Vol. 17, No. 3, 2022

swiss academies
of arts and sciences

swiss academies
reports

swiss-academies.ch

Swiss Energy System 2050: Pathways to Net Zero CO_2 and Security of Supply

Basic report

ABOUT THIS PUBLICATION

PUBLISHER AND CONTACT
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RECOMMENDED FORM OF CITATION
Boulouchos K, Neu U et al. (2022) Swiss Energy System 2050: Pathways to Net Zero CO_2 and Security of Supply. Basic report. Swiss Academies Reports 17 (3)

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The preparation of this report included the creation of the concept/storyline, first chapter drafts by the Commission and external experts, a first draft of the overall text, several revisions of the draft, the review by about 30 external experts, discussions with the reviewers, the incorporation and implementation of the feedback, a final review by the Commission and the finalisation.

1st edition, 2022

ISSN (online) 2297–1572

DOI: doi.org/10.5281/zenodo.6967084

With this publication, the Swiss Academy of Sciences contributes to the SDG 7, 12 and 13.
> un.org/sustainabledevelopment/sustainable-development-goals
> eda.admin.ch/agenda2030/en/home/agenda-2030/die-17-ziele-fuer-eine-nachhaltige-entwicklung.html

Swiss Energy System 2050: Pathways to Net Zero CO_2 and Security of Supply

Basic report

Content

1 Context and (grand) challenge

This report aims at assessing pathways and formulating recommendations for the transformation of the Swiss energy system necessary to achieve the net zero greenhouse gas (GHG) emission target by 2050 (BFE 2017a) set by the Federal Council taking into account the Paris climate agreement. We examine the role and impact of the national energy system, define the main future challenges and formulate a holistic strategy to address them.

According to recent estimates of IPCC (2018), limiting global warming to 1.5°C with a 66% probability requires a 40–60% reduction of global CO_2 emissions by 2030 compared to 2010 and net zero emissions to be achieved between 2040 and 2055. In alignment with these recommendations, the Swiss Federal Council decided to extend the quantitative target to net zero GHG emissions[1] in the country by 2050 (Schweizer Bundesrat 2019). This is a highly ambitious goal, even more so since other requirements for the energy system – among them security of energy supply in all seasons, affordable energy and fair access to energy services for a competitive national industry – must be satisfied as well.

It is important to point out that a climate policy that wants to meet the net zero GHG emission target is a fundamentally different task than the past Swiss climate policy that only aimed at reducing emissions by 80 or 95%. This is mainly because it is the last 10 to 20% of the reduction that represents by far the greatest technical, economic, societal and political challenge (concerning e.g. aviation, shipping and industrial processes). Indicatively, aviation in Switzerland accounts for about 13% of CO_2 emissions and only low-CO_2 fuels can lead to its decarbonization. Providing such fuels at scale requires new large-scale infrastructure, with the associated investments, and commercialization of currently technologies with low readiness level (TRL). It is therefore not possible to simply extend the former climate policy in the sense of 'more of the same' in order to achieve the net zero target.

On top of the need for transformative climate action (see chapter 3) as considered until now, the net zero GHG target means a shift from a 'low-carbon' to a 'zero-carbon' system – or even 'below-zero' system with two additional important elements:

1. Developing measures, including technological innovation, for the reduction and elimination of the technically most difficult and most costly emissions to be avoided, e.g. emissions from aviation or the cement industry.
2. Developing measures, including technological innovation and resolving (international) governance issues for the removal of CO_2 from the atmosphere and transporting and storing it safely ('negative emissions technologies' NET), in order to compensate for the climate impact of emissions that cannot be avoided or only at very high costs. At the same time, the energy sector itself should aim at reducing emissions to zero without or with very little compensation from NET.

Along with speeding up the current energy transition, both tasks have to be considered and started straight away, because they are among the most difficult ones and are only at the beginning of their development.

There are a few other specific issues that have to be taken into account:

- The transition will not be possible without changes of consumption patterns, i.e. a reduced demand of services and products (often called 'sufficiency') which imply the use of energy in one or the other form. This might involve a fundamental rethinking of our way of life and how we organize societies.
- The whole production chain (including manufacturing and build-up of energy infrastructures) has to be based on renewable energy, including NET and grid infrastructures.
- Security of supply in the future Swiss energy system has gained much attention very recently, due among others to geopolitical risks. This is addressed to some extent in the context of sector coupling (see Chapter 7).

This report is based on the following underlying delimitations:

1. Although we are aware of many other Sustainable Development Goals (SDGs) that are important for Switzerland (BAFU 2018) as well as of adaptation challenges, we here focus on climate change mitigation, considering this to be the dominant challenge concerning the energy system. Possible synergies or trade-offs and conflicts with other SDGs are mentioned where appropriate, but are not quantitatively examined. Some related issues are discussed in the SRI research agenda (Wuelser et al. 2020) of the Academies.
2. We take the Paris agreement of the UN climate convention and the decision of the Federal Council to reduce CO_2 and greenhouse gas (GHG) emissions, respectively, to net zero GHG until 2050 as principal aim.
3. Since more than 98% of domestic GHG emissions of the energy system consist of CO_2, we focus on CO_2 and do not discuss non-CO_2 GHGs. However, we include CO_2 emissions from international aviation (although currently not included in the Paris agreement), since we can allocate these for Switzerland based on the

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[1] Net zero means that remaining emissions have to be compensated by extracting the corresponding amount of CO_2 from the atmosphere by nature based or engineered solutions].

fuel statistics of the Swiss Federal Office of Energy and they are disclosed in the GHG inventory.[2]

4. While we examine advantages and disadvantages of several technologies from different angles, we take into account constraints coming from the outcomes of recent public votes, such as the energy strategy 2050 (BFE 2017a) or the refusal of the CO_2 law.
5. We are aware of a large amount of imported 'grey emissions', caused by the production of consumer goods abroad (see **Figure 2** below), but we here concentrate mainly on domestic emissions, in line with the United Nations Framework Convention on Climate Change (UNFCCC) inventories. Main reasons are among others that it is difficult to properly allocate responsibility between consumers and producers and that it is very difficult to influence production processes in other countries. Moreover, concerning energy supply, with the replacement of fossil fuels the corresponding grey emissions (from oil and gas production and transport) will be eliminated, and in case of import of renewables including synthetic fuels the corresponding grey emissions will increase, but to a much lower extent than the decrease due to less fossil fuels (the import share will be lower than the current share of fossil fuel energy). On the other hand, Switzerland has the possibility to influence international climate action through its large financial sector and the corresponding worldwide investments or as a trading center for agricultural commodities, but this is not discussed in this paper.

Historically, rapid economic growth in the last century and associated expansion of the energy industry has led to a steep increase in environmental impacts in industrial countries, followed by a period where knowledge, capital and societal awareness and implemented policies as well as the increasing importance of the service sector led to a slower increase and in some cases to a kind of stagnation of these burdens. This development leads at first to a typical '**S**-shaped' trajectory of energy consumption per capita over time – and of the corresponding CO_2 emissions as well. As **Figure 1** shows, Switzerland has reached the end of the 'S' and recently started a slight decline, while the world as a whole is currently located around the place of the steepest slope and it can be expected that the development will follow patterns similar to the highly developed economies if no fast and concrete actions will be taken at the global scale. It seems obvious that for countries still on the rising part of the curve with strongly increasing energy demand (especially developing countries) it is much harder to reduce emissions than for those that have stabilized their energy demand.

From a global perspective Switzerland benefited from a large technological and economic expansion based on burning cheap fossil fuels, while developing countries should not follow the same path for their own economic expansion. From an ethical point of view, Switzerland due to its historical responsibility and the economic power should be more ambitious in its reduction targets than non-industrialized countries and, with its very good economical situation and technology innovation potential, take a leading role and support poor countries climate actions financially and technologically, as it is an obligation of industrialized countries in the Paris Agreement.

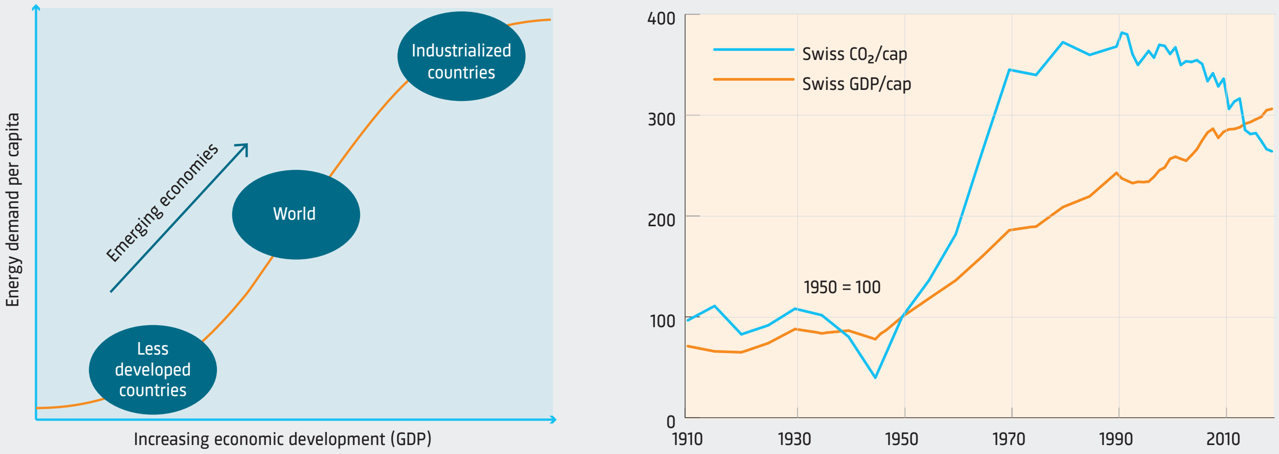

Fig. 1: Left: Qualitative S-shaped evolution of the energy demand per capita as a function of economic development (approximated by Gross Domestic Product per capita, GDP/cap). Position of different country/economy groups is shown indicatively in the graph. Wealthy countries show already a stagnation of final energy demand per capita and decoupling of economic growth (GDP per capita) and domestic energy demand. **Right:** annual evolution of CO_2 emissions and GDP per capita in Switzerland, both normalized to 100 in 1950 (when real GDP was 28,200 CHF/cap and CO_2 emissions were 1.77 tCO_2/cap): CO_2/cap exhibits also a kind of S-shaped curve, while the increase of GDP/cap is almost linear with time.[3] (Sources: BAFU 2022a, BFS 2021).

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[2] Besides CO_2 aviation emissions also contain short-lived climate forcers. The additional forcing of non-CO_2 emissions depends among others on the change of aviation emission rate during the preceding years and could be negative in case of decreasing emission rates in the future. Currently, with the increase of aviation emissions during the last 10–20 years, the non-CO_2 forcing is estimated to be about two times that of CO_2 (Lee et al. 2021, Neu 2021).

[3] All energy-related CO_2 emissions, including international aviation. Only domestic CO_2 emissions and energy demand have been considered; the issue of imported CO_2 and grey energy is discussed in the text.

Box 1: Developments of key indicators in Switzerland

Between 1990 and 2019 in Switzerland:

- Population has increased by 27% and the GDP by 56% (BFS 2021).
- End-use energy consumption has been essentially stable (between 225 and 250 TWh/a) during the last 30 years (BFE 2020b).
- CO_2 emissions have decreased by about 15% (BAFU 2022a).
- SOx, NOx and particulate matter (PM) concentrations, respectively, have decreased by 90% and 60–70%, i.e. atmospheric pollutant concentrations have decreased from a pronounced peak around 1980 to levels currently comparable with or lower than those in the 1950's (BAFU 2021b).

New renewable technology use, in particular from solar photovoltaics, has accelerated since 2010, and reached 4.7 TWh_{el} in 2020 (BFE 2020b), although its contribution still is less than a tenth of the total electricity demand.

However, it has to be taken into account that industrial production and the corresponding emissions – for numerous products like cars always in history – mainly occur abroad and that the (before the corona crises) most growing sector, international air traffic and shipping, is not included.

While in Switzerland overall energy consumption has started to decrease despite an ongoing growth of population and GDP (see Box 1), it should be pointed out that a considerable amount of 'imported' CO_2 emissions (non-domestic or so called 'grey' emissions) have been caused by the production of imported goods and services. These emissions have not decreased in the long-term and are now almost twice as high as the emissions within the country itself (see Figure 2) (BFS 2022). Only for transport and living the grey emissions are not much higher than the emissions in the country itself.

Of the grey emissions, about 25% come from energy carriers (Frischknecht et al. 2018). These will decrease with the phase out of fossil fuels. The other grey emissions are difficult to influence by Switzerland, apart from changing consumption patterns (longer use of products; preference of local goods) or to some extent through international procurement.

On the other hand, financial investments in foreign assets by Swiss institutions (including energy companies) or firms located in Switzerland may lead to a large quantity of further emissions. These investments constitute a considerable leverage to influence emissions abroad (although perhaps not directly those causing our grey emissions). However, the corresponding awareness e.g. in the banking sector seems to have grown in recent times.

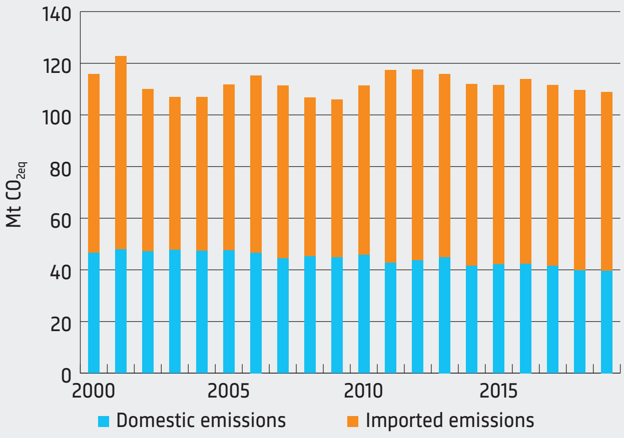

Fig. 2: Swiss greenhouse gas footprint resulting from Swiss final consumer demand: temporal evolution of the Swiss CO_2 emissions, caused by emissions in Switzerland (blue) on the one hand and by emissions due to production of goods imported to Switzerland (orange) (BFS 2022).

Recognizing the extraordinary complexity of the energy system we review in the following the current status of individual energy sectors with a special focus on their interrelations from an interdisciplinary point of view and extract relevant drivers for the intended change. Taking their developments in each sector during the last about 20 to 30 years on both the demand and the supply sides as a starting point, we thereafter project future developments according to current policies and identify relevant further actions necessary to meet the ambitious climate change mitigation targets. Integrating these requirements in a systems approach including some 'back-of-the-envelope' estimates it becomes evident that the challenge is much bigger than widely thought of and exceeds even the ambitious goals of the Swiss Energy Strategy 2050+. Achieving these goals will not be possible without urgent and coordinated actions within a coherent policy design that stimulates economic, technological and social innovation at multiple levels. The report attempts to formulate corresponding paths and necessary actions at the regional and national level with a strong recommendation for international coordination to the maximal extent possible.

2 Overview of the Swiss Energy System

The energy system is interconnected with the natural world and the anthroposphere. Using material and primary energy flows from the ambient, it provides through a cascade of conversion steps energy services, which are highly important for the well-being of human society. At the same time, it produces waste and pollutants that negatively impact the environment. **Figure 3** shows the main components of the Swiss energy system embedded between the socio-economic system and the environment. In addition there is a non-negligible influence of the technical and socio-economic development abroad.

The energy system involves different end-use sectors which provide economically highly important energy services. Useful energy in these sectors is supplied by a cascade of conversion steps from a variety of primary energy sources to secondary and final energy. At several stages of this conversion distribution grids and storage devices are crucial for securing the temporal and spatial availability of the appropriate energy carriers for the different applications. This cascade involves a number of different actors which all play a particular role in a transformation of the system (see **Figure 4**): Producers, retailers and consumers as well as policies define market prices and product specifications through multiple interactions like the interplay of demand and supply. Technology innovation and new business models lead to a dynamic evolution of the overall system, driven by policy-induced boundary conditions and regulations at the international, national and cantonal level. In view of the overarching decarbonization challenge and as a consequence of emerging digital technologies a continuous trend for the integration and interaction of sectors and actors has been manifested during the last years and this development can be expected to intensify in the next decades.

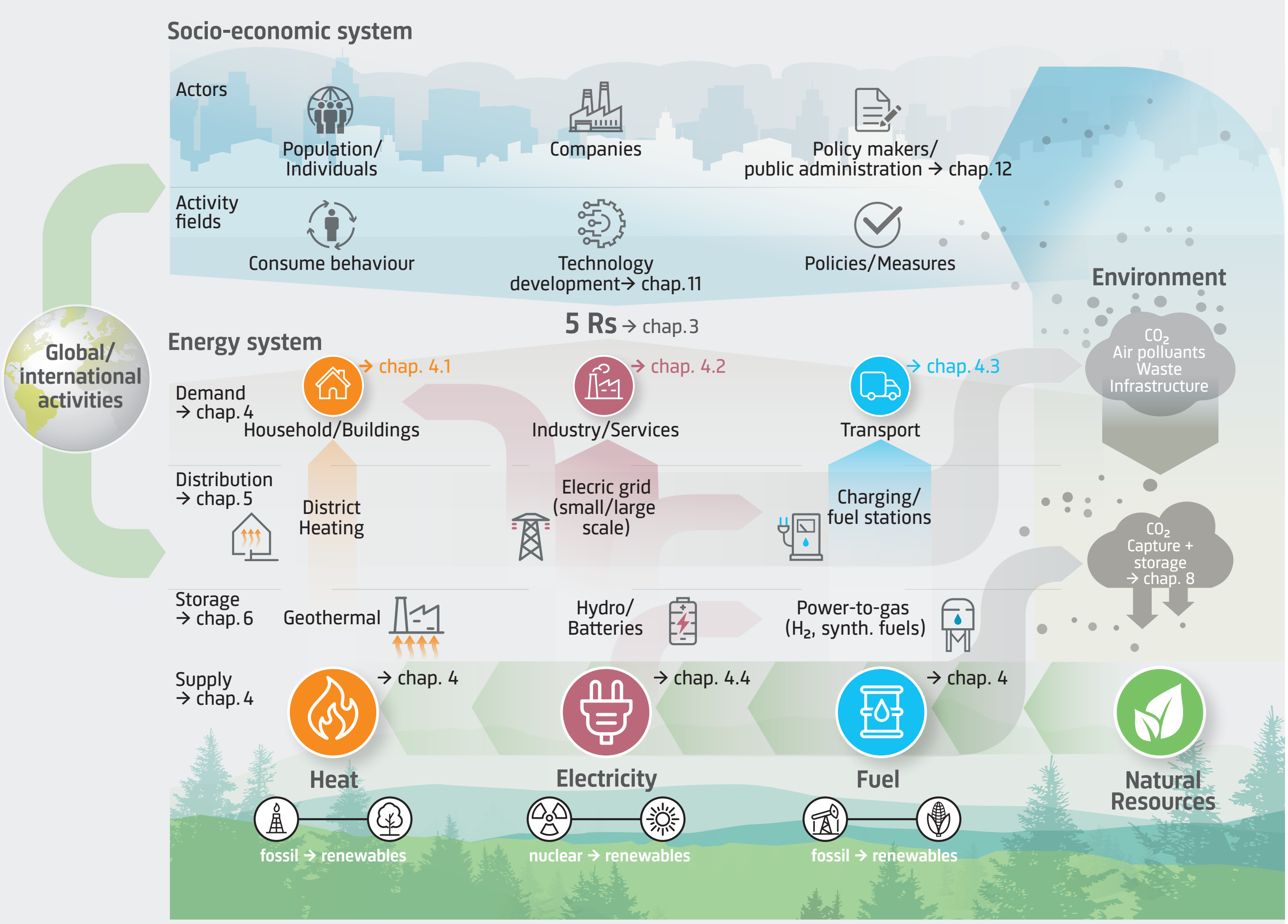

Fig. 3: Overview of the Swiss Energy Supply System. The numbers indicate the chapters where the different topics are addressed. Chapter 3 describes the fields of action where the socio-economic system can steer the energy system. Chapter 4 presents an overview of the factors influencing supply and demand. Chapters 5 to 7 point out the importance of the distribution and storage system, respectively, and the sector coupling. Chapters 8 and 9 contain information on the potential of negative emission technologies and the necessity to close material cycles. Chapter 10 describes possibilities of digitalization. Chapters 11 and 12 summarize possible transition paths towards a net zero GHG system and the corresponding policies needed. At last chapter 13 presents a number of recommendations for different actors.

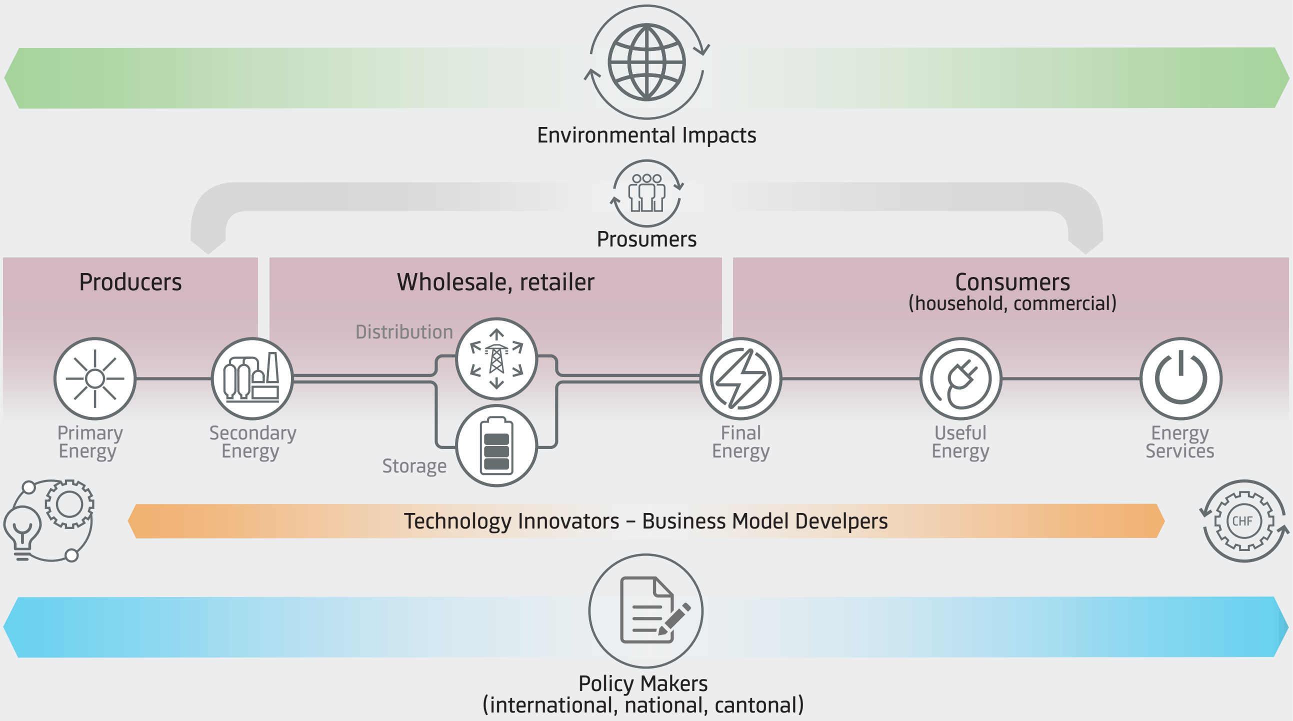

Fig. 4: The cascade of conversion steps and the involved actors.
The key parameters of the energy system are not static but their dynamic interactions with each other decisively shape its evolution over time. While energy demand is influenced (among others) by the economic and demographic development it also feeds back into the economy both directly through the corresponding business sectors and indirectly through its environmental impact. When addressing issues related to the required transformation to a net zero CO_2 energy system, these interactions may be adverse to the strategic goal (representing **hurdles**), in which case they must be counteracted by specific measures (requiring **actions needed**). General hurdles are for example the long-term investments or uncertain energy prices in the future. In chapters 4 and the following ones we will examine such demand and supply trends and identify the main hurdles and actions needed and derive corresponding recommendations, first for the individual energy sectors, with a specific focus on electricity as this is anticipated to form the backbone of the future energy system. Subsequently we will analyze cross-cutting issues related to new infrastructure like storage, distribution grids and ultimately the emerging coupling among the various energy sectors. We will then discuss negative emissions options, the necessity to close material cycles, socio-economic action fields and point to important dynamics along the transformation path before deriving recommendations for policy makers.

3 The 5R concept for reaching the net zero goal in 2050

The transformation of the Energy System towards the goal of net zero requires a holistic approach. In the following, we consider for this purpose five different fields of action, which we refer to as the **5R concept** as illustrated in **Figure 5**:

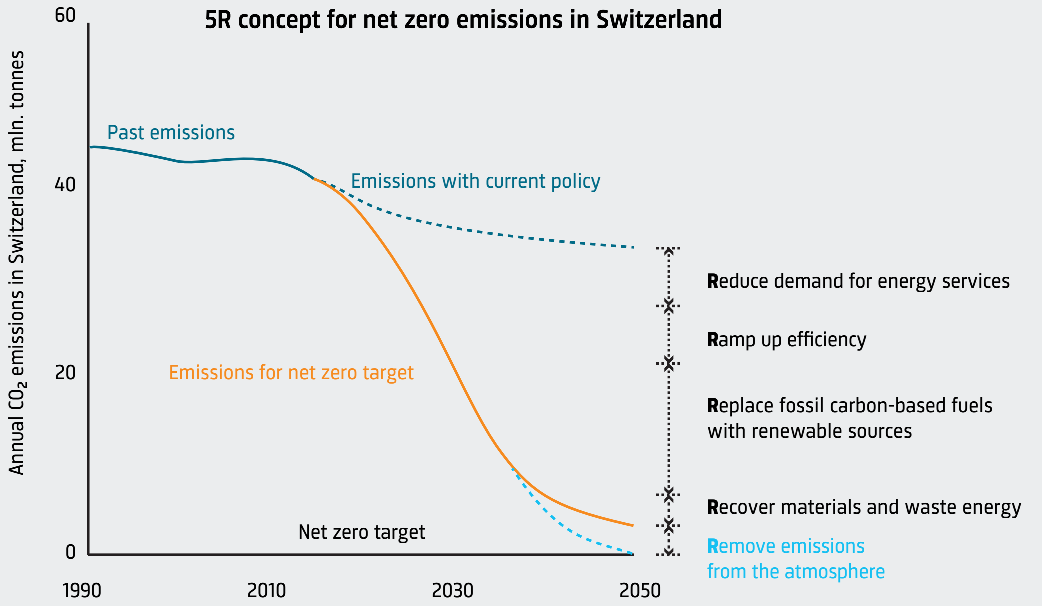

Fig. 5: Qualitative illustration of a synergetic strategy portfolio towards decarbonization of the energy system. The potential emission reductions due to each of the 5Rs are only indicative and are assumed to be implemented in parallel rather than sequentially. The removal and sequestration of CO_2 is seen as the 'last resort' for emissions that can hardly be removed for technical reasons or due to very high costs.

R1: Reduce demand for energy services ('sufficiency'): Reduce demand refers to the reduction of the demand of energy services by end-users for example by the reduction of consumption (in contrast to reduced demand by efficiency gains).

R2: Ramp up efficiency: Increase energy conversion efficiency of equipment, machines, industrial processes, cars etc. (for example use waste heat in case of electricity use) as well as CO_2 efficiency in hard to decarbonize sectors (for example by capture and sequestration of CO_2 from point sources [Carbon Capture and Storage CCS] like industrial sites).

R3: Replace fossil fuels: Replace carbon-based fossil fuels by energy sources with no or low net GHG emissions.

R4: Recycle CO_2 and materials: Captured CO_2 is reused for different energy and non-energetic applications (CCU); recycling of materials, particularly also those used in energy production like solar cells.

R5: Remove CO_2 from the atmosphere: Use negative emission technologies, which remove CO_2 from the atmosphere, for example by chemical processes ('direct air capture') or biological processes (afforestation etc.), and sequester it in a permanent storage. Using biomass as energy source combined with carbon capture and storage (CCS), called BECCS ('Bioenergy and CCS') is also considered as negative emission.

It is very important to note that all five fields of action must be exploited as much as possible in order to achieve net zero.

With its energy and climate strategies as well as a number of laws, particularly the CO_2 and energy legislation, Switzerland aims at following a path to net zero GHG emissions. However, the currently implemented measures and instruments will not be sufficient to reach the target, as **Figure 6** indicates. With its recently published climate strategy (BAFU 2021a) the Federal Council has outlined how it plans – based on the newly developed 'Energy Perspectives 2050+' – to reach the aim of net zero GHG emissions in 2050. As a comparison, **Figure 6** also shows the corresponding reduction paths and recently defined aims of the 'Green New Deal' of the European Union.

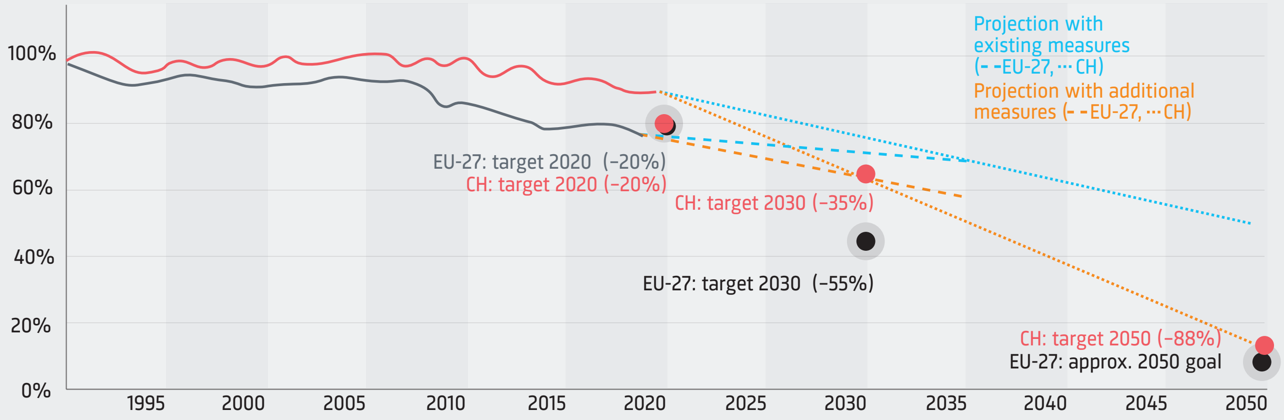

Fig. 6: Comparison of emission development (starting point 1990) of emissions and reduction targets and paths for Switzerland (Energy Perspectives 2050+; BFE 2020a) and the EU (EEA 2021a). The red and grey lines show the development since 1990 for Switzerland and the EU, respectively. Blue lines show the trajectories that will be reached with measures that are currently implemented or in the political process. Orange lines show the trajectories aimed at by additional measures (EU) and by the climate strategy based on the Energy Perspectives 2050+ (Switzerland), respectively. Red points show the Swiss targets without negative emissions. Black points represent the new aims of the EU with their 'Green Deal'.

Successful implementation of the **5R concept** requires a recognition and clear picture of the complexity of the energy system in order to define main fields of action. We try to provide such an overview in the following chapters, indicating 'actions needed' in the different **R** areas.

4 Assessment of individual energy sectors

The individual economically important sectors exhibit different amounts of CO_2 emissions and to some extent different trends over time as **Figure 7** illustrates. It is important to note here that the four major energy sectors (households, services, industry and transport) are in the focus of our considerations, while the vast majority of non-CO_2-GHGs are not energy related. Those will be important for the new Swiss net zero GHG target but are not considered here as explained in the beginning. The individual sectors also have different potential and technoeconomical possibilities for emission reduction, as the reduction paths according to the Energy Perspectives 2050+ of the Federal Office of Energy shows in **Figure 7**.

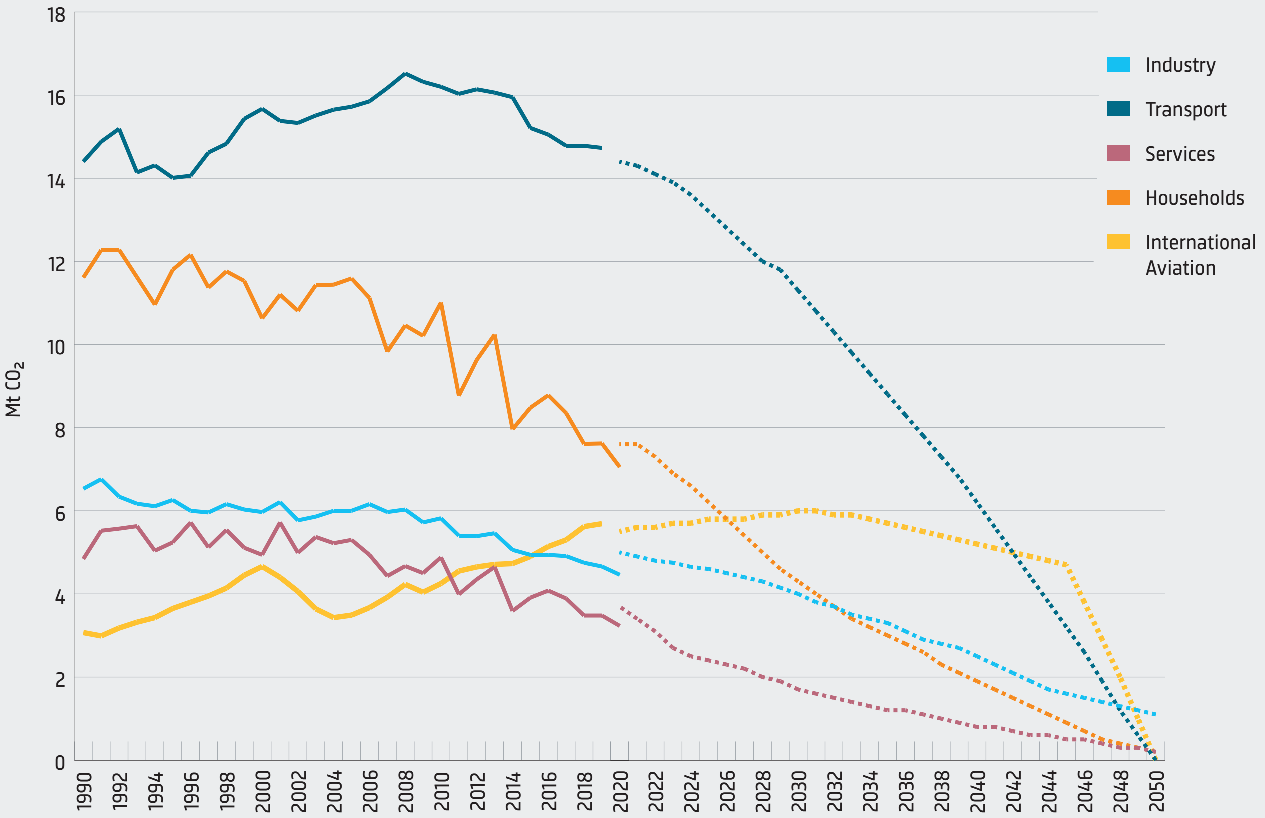

Fig. 7: Evolution of CO_2 emissions from energy use (excluding for example emissions from industrial processes) by sector (from GHG inventory; BAFU 2022a) as well as the expected evolution to reach the zero GHG emission target as projected in the Energy Perspectives 2050+ (scenario ZERO A; BFE 2020a). Development of emissions from international aviation as given in the Energy Perspectives 2050+, though it is conceivable to either have a more gradual substitution of fossile kerosene or to reach zero emissions much later than 2050. Observed values for transport and international aviation of 2020 have been omitted due to the strong influence of the pandemic.

4.1 Residential buildings

Box 2: Households 2019 (BFE 2020b)

Importance
- 27% of total final energy demand (63 TWh)
- 33% of electricity consumption (19 TWh)

CO_2 emissions (BAFU 2022a)
- 7.6 Mt CO_2 (18% of total CO_2 emissions incl. aviation)
- Evolution: 1990–2019: reduction of CO_2 emissions by about 35%

Demand evolution
- 1990–2018: electricity demand almost doubled, oil consumption decreased by 60%, natural gas quadrupled, the renewable heat increased by 60%.

Heated area, evolution 1990–2018 (BAFU)
- +48%

The energy demand in the sector involves electricity and energy for heating, cooling and domestic hot water in buildings. Heated area in buildings has increased over the last decades due to population and economic growth but the trend is weakening (INFRAS et al. 2018).

Technologies for efficiency increase (up to a factor of almost 3 for heating energy) are meanwhile well established in new buildings and the same is true for switching to near zero CO_2 energy carriers (solar heat/air and geothermal heat pumps with electricity from renewable sources). But in the stock, these technologies are still not standard. In view of climate change a substantial decrease of heating demand in winter and increasing cooling demand in summer must be expected (Gonseth et al. 2017, Settembrini et al. 2017). Nevertheless, wide spread use of heat pumps will increase the electricity demand in winter substantially (s. Appendix).

Basically, due to long investment cycles and other hurdles listed below, the renovation rate is much too low to achieve the climate targets in time. We have to find ways (incentives, regulations etc.) to speed it up considerably.

Hurdles

- The low energetic renovation rate in the order of 1% per year, depending on the depth of measures included, due to several reasons (long life-time of buildings, large investment needs with long payback time, principal-agent dilemma etc.).
- Limited knowledge of private owners and installers on energy costs and technical options of renewable energy and refurbishment (heating systems based on low-carbon energy carriers require higher upfront investments).
- The subsidies for renewable energies such as brine-water heat pumps and refurbishment are not sufficient for a middle term return of investment.
- Difficulty to achieve consensus on actions in buildings with multiple ownership (Stockwerkeigentum) and often split incentives: tenants, with limited authority to decide, pay the energy bills but landlords determine the building's energy efficiency (the 'principal/agent' problem).
- Due to financial, psychological and transaction costs, it is a challenge to motivate elderly owners for renovations; at the same time, they often are not able to get an increase on their mortgage to renovate their building.
- The limited availability of highly efficient geothermal heat in several locations, also due the necessary minimal distance between boreholes and to constraints with regard to impact on ground water (could be reduced by novel methods, such as smart heating grids with central heat pumps).
- The limited feasibility of air source heat pumps due to noise restrictions and the necessity of sufficient installed power (noise from air source heat pumps has decreased considerably though).
- The limited access to biomass (availability, space and air quality requirements).
- Lack of strategic energy planning and economic feasibility, especially in smaller communities for district heating.
- Difficulties to renovate a building, for example due to monument and heritage or landscape conservation restrictions.
- The situation of buildings with different existing heating systems (for example of different renovation standard) or limited ability to adapt buildings' internal heating system from high to lower temperature complicate optimized solutions for these buildings.

When evaluating policies, pay attention to

- CO_2 emissions per heated area will become a more important concern than energy use.
- In addition to reducing CO_2 emissions during operation, the future focus must also be on the CO_2 emissions of the construction process and the materials (circular economy).
- With regard to heating systems: take CO_2 emissions for building construction into account (retrofit (Sulzer et al. 2019) vs. replacement by new building).
- Electricity demand for heat pumps in winter will increase, but also electricity demand in summer due to cooling needs.
- Avoid using biomass for low-temperature heating purposes since this energetically valuable renewable resource should be used rather in other sectors, namely power generation (combined with heat), industry (middle- to high-temperature processes) or transportation (e.g. long-haul transport). However, if heat pumps are not feasible, biomass (wood chips) or biogas/biomethane would be a reasonable option.

- In densely populated areas, district heating and cooling systems rather than individual solutions enable benefiting from economies of scale in producing or transforming energy; low-temperature networks increase the energy-efficiency.
- Heat from incineration of non-biogenic waste is not neutral in terms of GHG emissions, meaning that these emissions need to be compensated by negative emissions or prevented by CCS.
- The requirements to obtain subsidies for the refurbishment of building envelope are sometime too difficult to fulfill so that most projects only focus on the replacement of the heating system.

Action needed

R1 (reduce demand):

- Lowering of room temperature; reduction of heated area.
- increased use of passive measures to reduce demand: operational energy and emissions, especially shading, adjusting window-to-wall ratios, natural ventilation etc.
- Engage in societal discussion relating wellbeing to energy services (challenging norms and expectations around comfort).

R2 (efficiency) and **R3** (replace fossil):

- Incentives for renovation investments.
- Promotion of life-cycle-costs consideration and information of intermediate actors on advantages of new technologies.
- Wider use of digital technologies to monitor and improve real-world building operation vs. design specifications (which requires engineering expertise that has to be spread in engineering schools); reduction of stand-by-consumption.
- Systematic energy planning in all types of communities (country, cantons, regions, communities, quarters).
- Ensure that best available low-CO_2 technology is used in new buildings and – wherever possible – in renovations (for example for heating, cooling, ventilation, lighting, equipment/devices), including storage systems and load management) through cantonal construction norms
- Installation of reversible heat pumps for combined heating and cooling (Plant replacement and new installations) where possible.
- Utilization of builiding envelope surfaces for solar energy generation (cost effective, surfaces are available, synergies with retrofit and construction, i.e. material savings).

R4 (recycle):

- Implement the principle of circular construction which will lead to a reduction in the embodied energy and CO_2 of buildings.

Recommendations

(H: High impact; P: priority measure; –: medium impact and/or priority)

- (H) Set limit values for CO_2 emissions per habitable surface for new buildings and renovations, respectively (better than prohibition of technologies, leaving open how to meet the limit depending on the specific circumstances of a building, e.g. isolation vs. replacement of heating system). Adapt these limits regularly according to technological development, preferably done via associations like SIA (policy, SIA norms).
- (H) Adapt monument and landscape conservation restrictions in environments already influenced by energy installations, with converse enhancement of restrictions in areas very valuable for biodiversity or landscape protection (policy). This may include a national priority planning (Akademien der Wissenschaften 2012).
- (H) Increase the CO_2 levy on fossil fuels with careful design to increase acceptance (compensation mechanisms) (policy).
- Increase the incentives for energy saving renovations with special focus on rental housing (because a large part of the population is renting and has no influence on renovation activities) to guarantee middle-term return on investment (policy).
- (H) Improve energy related literacy of households: provide easy understandable information on energy use aspects like behavior of neighbors; make mandatory the transparency about energy use and costs of household equipment (policy, energy labels) and embodied energy; provide information on the possibilities of (digital) monitoring options and design specifications (policy, energy companies).
- (–) Provide consulting services for renovations (energy/building companies).
- (–) Include knowledge on low-carbon technologies and increase corresponding sensitization in occupational training of all relevant professions (architects, construction industry, heating/air conditioning/ventilation [HVAC] and plumbers, janitors, etc.) (educational institutions).
- (–) Make design for disassembly in construction mandatory and therefore pave the way for circular construction.

4.2 Industry and services

Box 3: Industry and services 2019

Industry

Importance in 2019 (BFE 2020b)

- 18% of total final energy demand (42 TWh)
- 30% of total electricity demand (17 TWh)
- 53% of energy demand is for process heat (22 TWh)

CO_2 emissions 2019 (BAFU 2022a)

- 11.3 Mt CO_2 (incl. waste incineration and non-energy use; 27% of total CO_2 emissions incl. aviation; of which 4.7 Mt CO_2 from energy use)
- Evolution: 1990–2019: reduction of CO_2 emissions from energy use by about 30%

Gross Value Added, evolution 1990–2019 (BAFU 2022a)

- +68 %

Services

Importance in 2019 (BFE 2020b)

- 16% of total final energy demand (38 TWh)
- 30% of total electricity demand (17 TWh)
- 48% of energy demand is for space heating (17 TWh)

CO_2 emissions 2019 (BAFU 2022a)

- 3.5 $MtCO_2$/y (8%)
- Evolution 1990–2019: reduction of CO_2 emissions by about 30%

Heated area, evolution 1990–2019 (BAFU 2022a)

- +34%

Gross Value Added, evolution 1990–2019 (BAFU 2022a)

- +95%

In both sectors part of the energy demand is related to heating of buildings to which considerations of Section 5.1 apply. Quite important though is the electricity demand in both sectors while in industry process heat is a major contributor to CO_2 emissions.

CO_2 emissions decreased steadily in both sectors between 1990 and 2019, though more slowly compared to the trend in the household sector. Since electricity in Switzerland has been so far practically CO_2-free the development is dominated by the heat demand.

In services increase of efficiency in space heating has overcompensated the business expansion, while in energy-intensive industry fuel costs together with a partial switch from oil products to natural gas have contributed to the reduction in CO_2 emissions.

Quite important are also general trends particularly with regard to the structure, competitiveness and potential outsourcing of manufacturing activities abroad (or vice versa as a consequence of increased automation in production).

Increasing CO_2 prices for heating fuel have proven to be effective in industry and can be continued and intensified when intermediate reduction targets have not been achieved. An increase of CO_2 prices and making the emission path for the plants in the Emission Trading System (ETS) more stringent would yield an economically feasible savings potential of 16–19% in energy demand (6.7 to 8.3 TWh) and CO_2 emissions (1.7 to 2.1 $MtCO_2$/y). Concerns about competitiveness compared to foreign companies may not be that important, especially if EU adopts a carbon border adjustment mechanism.

Hurdles

Industry

- Significant efficiency potentials (particularly with regard to electricity use) are not sufficiently exploited because life-cycle costing is not systematically used.

Services

- Increased digitalization/automation in the future may lead to a measurable increase of electricity demand.

Pay attention to

- The required amount of renewable energy for full decarbonization will be very high (s. Appendix). In addition to the flexible hydro power, renewable chemical energy carriers must be available to provide power on demand for industrial processes.

Actions needed

R2 (efficiency):

- Provide life-cycle cost calculations /investment-calculations.
- Support knowledge transfer for efficiency increase in industry.
- Use combined optimization of chips/IT-devices with cooling and space heating in data centers.
- Switch to non-fossil fuels for industry heat.
- Implement high-temperature heat pumps in applications where needed.
- Implement Carbon Capture and Storage (CCS) or similiar technologies for emission intensive industries (e.g. cement industry, industrial high temperature processes).

R3 (replace):

- Substitute fossil fuels with low or zero CO_2 energy.

R4 (recycle):

- Promote cascading waste-heat use in industrial environments.

Recommendations

- (H) Increase the CO_2 levy on fossil fuels, with careful design of compensation mechanisms for households and firms to increase acceptance (policy).
- (H) Support research and development of solutions for processes where low-CO_2 technical solutions are missing and difficult to find (cement industry, high-temperature processes) (policy, research funders).
- (P) Develop strategy for deployment of CO_2 from CCS including transport and storage of carbon.
- (–) Promote adoption of existing low-carbon technologies (for instance via performance standards and voluntary sharing of best practices; SIA norms etc.).
- (–) Provide life-cycle costing of industrial processes (policy, technical norm setting).
- (–) Support waste-heat use and material recycling (policy).

4.3 Transport/mobility

Box 4: Transport/mobility 2019 (BAFU 2020b)

Importance 2019 (BFE 2020a)

- 37% of total final energy demand or 87 TWh (of which: 82 TWh fossil, 2 biogenic, 3 electricity; 23 TWh for aviation)
- 5% of total electricity demand (3 TWh)

CO_2 emissions 2019 (BAFU 2022a)

- 20.4 Mt CO_2 (48% of total CO_2 emissions incl. aviation) (of which 10.8 Mt are from passenger cars and 5.7 Mt are from aviation).
- Evolution: CO_2 emissions from road transport peaked around 2008 and declined by 10% until 2019, reaching 1990-levels.
- Aviation emissions increased from 1990–2000, then decreased slightly until 2010 (due to '9/11' and financial crisis) and from 2010–2019 increased by about 35%.

Modal split (BAFU)

- 20% of people mobility (person km) are through public surface transport (slightly increasing)
- 37% of freight surface transport (ton km) are by rail (slightly decreasing)

Transport is a highly diverse sector involving people and freight at several modes (public/private, road/rail/aviation/shipping) with quite distinct characteristics, including different conditions for cities and rural areas involving demographic aspects and spatial planning. As Figure 7 illustrates, the sector exhibits the highest CO_2 emissions and emissions are still at the level of 1990, while most other sectors show a decline for quite some time.

Demand for freight and people transport services has steadily increased and is currently projected to increase in the future. During the last 25 years, modest efficiency increase measures in the dominant sector of individual motorized mobility have at least compensated the growing demand, so that CO_2 emissions have started to decline, though very slowly. Heavy-duty freight transport on the other hand shows slightly increasing demand with a trend towards stabilization, but efficiency potentials have been already strongly exhausted since fuel represents a major share of total ownership costs (about $^1/_3$). The heavy-duty freight tax LSVA had a considerable effect on the shift to rail transport until now, but it should be further adapted. Even more challenging is the increasing demand in international aviation (data from flights outbound from Switzerland in GHG inventory) and in international shipping. This is not included in the national inventories, but has to be resolved to reach the net zero target. In particular for international shipping, it is very complex to fairly allocate the emissions to Switzerland with no international ports for ocean-going ships.

The transformation to a net zero CO_2 transport sector must involve demand containment, shift to transport with higher efficiency (technically and higher use to capacity) and lower emissions, rapid electrification, increase of powertrain efficiency, reduction of vehicle weight and ultimately a switch to low or zero CO_2 energy carriers. For all these steps, there are explicit hurdles and a coherent strategy is necessary to overcome them. Moreover, since power markets are organized at an European scale and supply chains span the entire world, the international dimension of a transformation of transport (as well as all sectors) becomes evident. Demand containment can also be supported by spatial planning that reduces travel distances e.g. to working places, shopping facilities etc.

The anticipated emergence of autonomous driving could be a mixed blessing: if 'Mobility as a service' (Maas) can be widely applied the benefits will be obvious: better use of vehicles, increase of road capacity without extension or reduction of area demand for inactive vehicles (ARE 2021). If on the other hand autonomous vehicles will be privately owned, the growth in transport demand will be substantial, as costs will decrease and convenience in use will be improved, a common rebound effect. In such a case, competitiveness of public vs. individual transport will probably suffer and the same could occur for rail vs. road freight transport. In general, digitalization will be accompanied by trade-offs between energy efficiency increase per unit mobility service and a stimulus for increased demand. The net outcome of these competing effects is very difficult to assess.

Decarbonization of the transport sector requires that ultimately both power-generation and vehicle/powertrain/infrastructure manufacturing are practically CO_2-free.

While for individual transport electric drive is much more efficient (based on life-cycle assessment) than using synthetic fuels (hydrogen, synthetic methane etc.), the latter will still be important for long-haul transport and aviation (Cox 2018).

Hurdles

- The high purchasing power and willingness of consumers to pay, because mobility is an important part of our lives and the way our society is organized (including the urban/rural divide).
- Cars and the countryside single-family houses are still a status symbol.
- Marginal costs of mobility services are low (in particular for cars) and the share of fuel to the total ownership costs in the individual mobility sector is low.
- Missing CO_2 levy as well as historically adverse socioeconomic developments (tax exceptions for commuters, urban/spatial planning etc.).
- In long-haul transport (heavy-duty freight on the road, shipping, aviation), alternatives do not exist yet at a useful scale, but some are emerging. In particular, direct electrification of commercial aviation will not be feasible for decades. The indirect electrification (hydrogen and synthetic fuels) route is currently commercial at early stage, exhibits very low round-trip efficiency (from electricity to propulsion energy) and leads to a large demand for additional power generation and very high costs (EASAC 2019, EU 2018) (s. Appendix).
- For nearly complete fuel substitution, drastic costs and efficiency improvements will be necessary, but it will take time due to lock-in effects in existing assets, and the investments in infrastructure will be quite substantial.

Pay attention to

- Shifts to active mobility (cycling, walking) can as well improve public health, reduce chronic diseases and thus reduce health costs. However, the energy and CO_2 savings potential through increase of slow traffic is rather limited (a few percent of the total CO_2 emissions of the mobility sector; Boulouchos et al. 2017) .
- A reduction of individual motorized mobility demand by 20% through a shift to public transport would mean about a 75% increase in demand of person km of public transport capacity with corresponding costs.
- Prevent unintended effects (e.g. increased mobility due to more convenient transport services).
- Efficiency increases of non-electric mobility can contribute to a CO_2 reduction of the part of the market share that is not covered yet by electric vehicles.
- Even in the case of electrification legislation should provide incentives for light-weight/reasonably sized and powered vehicles.

Actions needed

R1 (reduce demand):

- Encourage and support more ‘active’ mobility (walking, cycling).
- Encourage and support more distance working, tele-conferencing.
- Enable and support more compact urbanization, less urban sprawl to reduce distances traveled.
- Limit investments in road infrastructure: keep functionality, but without increasing attractivity.
- Use digitalization possibilities: smart-working (home office, flexible times), smart cities (15 min. city), smarter logistics in road-freight transport by avoiding induced demand.

R2 (efficiency):

- Make fuel-efficient, light vehicles more attractive for buyers.
- Encourage higher car occupancy rates.
- Better filling of freight-transport vehicles.

R3 (replace) (EASAC 2019, EU 2018):

- Direct electrification of cars and short-/mid-haul transport (light-duty lorries, urban busses) through battery drives (BEVs).
- Indirect electrification through synthetic fuels (H_2, hydrocarbons; NH_3 for shipping) produced by net zero CO_2 electricity for mid-to-long-haul transport modes, in particular aviation and shipping.
- Develop and promote drop-in fuels from biomass for long-haul transport (particular aviation).

R4 (recycle):

- Enhance and facilitate recycling of batteries.

Recommendations

- (H) Implementation of tax instruments to reduce energy demand and emssions. Increase acceptance by information (e.g. about the environmental effectiveness of the tax and the use of generated revenues for environmental purposes and social cushioning); carefully design instruments to avoid disadvantages for remote domiciles or low income households (design of redistribution); consider congestion taxes, which are generally better accepted (policy).
- (P) Facilitate the diffusion of efficient electric cars by fostering the needed infrastructure (charging stations), for example via building regulations (policy).
- (–) Develop the heavy vehicles fee further (policy).
- (–) Reorganize the mobility tax system by shifting flat rate costs to costs linked to fuel consumption.
- (–) Support the development of low-CO_2 alternative fuels produced by renewable energy for long-haul transport and aviation and prescribe the use of a gradually increasing part of these fuels (policy, research funders).
- (–) Increase the capacity and improving multi-modality of public transport (including night train options) as alternative to individual transport (policy).
- (–) Facilitate the use of human powered mobility (HPM) by improving the infrastructure (for example separate lanes) (policy, mobility planning).

4.4 Electricity sector

Box 5: Electricity (BFE 2020c)

Importance 2019

- 25% of total final energy demand (58 TWh_{el} without grid losses)
- Power generation: 55% hydro (30% dams, 25% run-of-river), 36% nuclear, 6% renewable, 3% thermal non-renewable
- Storage capacity of dams: ~9 TWh
- Capacity of pumped hydro power: currently ~1.7 GW (2.7 GW including Linth Limmern and 3.6 GW with Nant de Drance soon)

Demand evolution

- Increase by a factor of 2.2 between 1970 and 2004, but stable thereafter (±2% fluctuation per year)
- Current sector partition: Households 33%, Industry 30%, Services 27%, Transport 5%, Others 5%
- Peak demand ~10GW

CO_2 footprint (g/kWh)

- Production mix ~20g/kWh
- Consumption mix 100–200g/kWh depending on year and season

Electricity demand in Switzerland has increased by a factor of 2.2 between 1970 and 2004, but has been more or less stable (±2% fluctuation per year) thereafter. The switch to more efficient appliances compensated the increase in demand for conventional electricity services originating from strong GDP growth.

Future developments will depend on the influence of rapidly increasing digitalization but even more strongly on the electrification of end-use-sectors (buildings, industry, transport) as a consequence of the need for drastic and rapid reduction of CO_2 emissions as well as the effctive speed of phaseout of nuclear and phase in of renewable energy. As will be shown later in the 'sector coupling' section such a development can – when completed – easily double the current electricity demand of the country, which will pose tremendous challenges on power generation capacities and transmission/storage infrastructure (s. Appendix).

The structure of power generation in Switzerland has remained essentially stable over the last decades with a recent increase of new renewable electricity but still at a low level. Nevertheless, future developments will pose big challenges to the supply side of the electricity sector. The phase-out of all nuclear power plants within the next 10–25 years will reduce the generation capacity by a substantial amount, which is already noticeable in the winter half-year. Net imports in winter were about 4 TWh on average over the last 10–20 years although the annual import-export balance of the country is rather neutral. This seasonal characteristic is expected to be even more pronounced when nuclear (with a distribution of 57% in winter and 43% in summer half-year) is replaced by solar energy (with a distribution of ²/₃ in summer and ¹/₃ in winter).

A realistic consideration of options for shaping electricity supply in Switzerland in the next few decades leads to a portfolio of power generation methods including – though striving for a reasonably high degree of domestic generation – targeted sourcing of renewable primary energy abroad, optimally within internationally coordinated (mainly European) efforts. However, recent developments with regard to the cooperation framework agreement with the EU make the feasibility of large scale imports uncertain, for technical as well as regulatory reasons (see chapter 5). This means that domestic electricity generation in Switzerland particularly in winter will become crucial.

Nevertheless, hydropower will continue to constitute the backbone of electric power generation in Switzerland in the next decades. Despite its limited growth potential (a few TWh if any) it will be very important as 'power-on-demand' asset through pumped hydro power plants. 40–45% of annual hydropower production is delivered by base-load 'run-of-river' power plants. In the future, system pumping could occur around noon and turbining during night to account for the temporal diurnal pattern of solar electricity. Climate change will lead to more river flow in winter and less in summer, which will slightly compensate the need to store electricity from summer to winter.

Nuclear electricity offers some important advantages, namely:

– very low LCA-based CO_2 emissions (5–40 g CO_2/kWh_{el} in 2050 according to BFE (2017b)
– base-load generation, with possibilities of load-following capabilities (Davis et al. 2018) which, however, if used regularly would lower profitability of plants (since plant construction costs are the main cost share).
– minimal landscape effects and high energy density of storable fuel

On the other hand, this energy supply option is associated with major disadvantages, namely:

– currently very high upfront capital costs with 'negative' learning curves over the last 10–20 years
– long investment cycles and 'lock-in' effects realistically over at least 70 years from design to decommission
– challenging risk assessment and respective perception with respect to accidents with low-probability high-damage potential.
– waste disposal challenge: though technically feasible, very limited social acceptance which resulted in currently only one long-term storage facility in Finland (El-Showk 2022)

In their taxonomy, the European Commission has classified investments in nuclear electricity (together with natural gas electricity) as supporting the Green Deal, but with a clear label as 'transitional' until a fully renewable energy system will be established (European Commission 2022).

Finally, Switzerland has made a decision, based on a public vote (2017), to gradually phase out nuclear power plants and to prohibit the built-up of new ones. Though any public vote can be reversed if new insights become available, timescales for such a process (if any) will most probably be quite long and the issue will remain hotly debated.

Notwithstanding emerging new developments (small modular reactors SMRs, Generation IV), none of these concepts can be expected to be ready within this decade. Moreover, Generation III+ power plants with some advanced safety advantages are at the market introductory stage (with a few plants in operation worldwide), exhibiting substantial delays in commissioning and very high cost overruns of plants built in Europe and the U.S. Given that safe and cost-efficient operation of new concepts must have been demonstrated before a favorable decision can be made (if at all) in Switzerland, it is highly unlikely that any new nuclear power plant can be put into operation in the country well before 2050.

However, the continued operation of existing nuclear power plants as long as they are secure is an important factor to support security of supply in the transition phase.

Solar electricity has by far the highest potential for additional electricity generation in Switzerland. It provides currently around 3% of Swiss electricity with growth having been substantial during the last years (Deschaintre and Jacqmin 2019). Further development will depend among others on market conditions and policy instruments, but also on technology breakthroughs in a next generation of high-performance-low-cost PV technologies which are applicable on surfaces of buildings and transport vehicles, in battery costs and overall performance as well as the costs of upgrading local distribution electricity grids for utilities. Indicatively, if we want to generate 25 TWh of solar electricity, this would require 20–25 GW installed capacity. Modeling experiments of the Swiss electricity grid indicate that with up to about 15 GW peak PV power no batteries for storage are necessary (Gupta et al. 2020). From then on required battery storage capacity increases roughly linearly with PV power. At 25 GW installed PV about 50 GWh battery capacity would be necessary. Recent studies show however that curtailing 40–50% of the peak PV power (occuring over very short periods of time) reduce the annual energy yield of PV by typically only 10 max. 20% (Remund et al. 2022). For Swiss conditions a typical economic optimum between investing in battery capacity and employing curtailing lies around these values. The requirement for local storage capacity through stationary batteries in order to relax the need for costly enhancement of the distribution electric grid can be further reduced to very low levels if the availablity of the majority of e-cars for being charged around the period of peak PV production can be exploited. For this purpose the wide implementation of digital technologies and corresponding business models offered by utilities is an absolute necessity. Such demand-side management (electric vehicles, heat pumps) in general can help absorb peak influx of solar electricity.

The power generation potential and the corresponding challenges of renewable primary energy sources is listed in Table 1:

Table 1: Performance characteristics of electricity supply options for Switzerland. LCA-based CO_2 emissions in 2050 from BFE (2017b) unless otherwise stated.

Electricity supply	Performance characteristics
Hydropower	**'Realistic' potential** In the order of today's about 35 TWh_{el}, up to 10% more. **Advantages** – Run-of-river offers base-load. – Dam-hydro offers flexible dispatch. – Pumped-hydro offers short-term storage (charge-discharge). – Very low LCA-based CO_2 emissions of 5–15 gCO_2/kWh_{el}. – Reasonable costs (LCOE) and low marginal costs. **Disadvantages** – Potential expansion quite limited. – Limited acceptance when landscape and other environmental aspects are in conflict with new projects. **Other comments** – Mature and proven technology. – Limited learning curves with respect to efficiency and costs.

Solar PV	**‘Realistic’ potential** 25–67 TWh_{el} (Scartezzini et al. 2021, BFE 2019). **Advantages** – Reasonable costs (LCOE) with almost-zero marginal costs. – Wide social acceptance for rooftop or utility-scale installations in Mittelland. – Quite low LCA-based CO_2 emissions of 7–71 $gCO_2/kWh_{el.}$ **Disadvantages** – Stochastic generation with around 1000 full-load hours (FLH) in Mittelland, up to to 1500 FLH in some parts of the Southern Alps. – A massive expansion of PV installed power would require substantial short-term storage capacity (batteries). – Unfavorable seasonal pattern in Switzerland (70% in summer and 30% in winter respectively in Mittelland, unfortunately in positive correlation with hydropower). **Other comments** – Uncertain social acceptance of large-scale installations in the Alps. – To achieve an installed PV power of about 35 TWh in 2050 vs. about 3TWh today requires an annual. expansion by about 1.2 GW/y on average in future (vs. 0.7 GW/y today). – Alpine PV production has a better summer/winter distribution of electricity production.
Wind	**‘Realistic‘ potential** 2.5–7 TWh_{el} (ARE 2020). **Advantages** – Favorable seasonal pattern (up to $^2/_3$ in winter half-year). – Quite low LCA-based CO_2 emissions of 5–30 gCO_2/kWh_{el}. **Disadvantages** – Stochastic generation with rather low FLH even in favorable locations (2000–2500 FLH). – Needs short-to-mid-term storage. – Debated social acceptance due to landscape, noise and other environmental effects (Joubert et al. 2018). **Other comments** – Currently high investment uncertainty due to extremely long lead times from design to installation. New legislative/procedural streamlining concepts may improve the situation.
Geothermal	**‘Realistic‘ potential** Up to 4.5 TWh_{el} (BFE 2017b). **Advantages** – Base-load capabilities. – Appropriate for winter generation due to coupling with large heat amounts. – Rather low LCA-based CO_2 emissions 27–84 $gCO_2/kWh_{el.}$ **Disadvantages** – So far limited social acceptance of deep geothermal (petrothermal) version. – Seismic risks (petrothermal and deep hydrothermal), especially in densely populated areas. – Hydrothermal installations offer lower temperatures and therefore very low electric efficiencies. – Potential location conflict between large heat use and acceptable power plant sites. **Other comments** – Very few large-scale market-deployed projects internationally. Economic feasibility uncertain at this stage.
Combined Cycle Gas Turbine (CCGT) Powerplants	**‘Realistic‘ potential** Up to 5 TWh_{el} per powerplant (CCGT2+1 with net electric output >1.5GW). **Advantages** – Good dispatch capabilities (less than half an hour response time). – Quite low investment costs. – Fast lead times to high power installations. – Open cycle gas turbines appropriate as ‘peakers’ as insurance against shortages at very few FLHs. – Technology adaptable to H_2 use. – Fast build-up. – If equipped with CCS, rather low LCA-based CO_2 emissions of 70–100 gCO_2/kWh_{el}. **Disadvantages** – High (though much lower than for coal) LCA-based CO_2 emissions of ~360 gCO_2/kWh_{el}. – For this reason limited social acceptance in Switzerland. – If load-following operation, then need for large quantities of gaseous fuel storage (not existing yet). – Operating costs depend on fuel price and are rather high. **Other comments** – Net plant efficiency of latest technologies reaches 62–64%. – Feasibility/acceptance of CCS is rather limited. – Technology is appropriate for use of H_2 or synthetic methane, but sufficient quantities will be available rather on the long-term only. – To some extent still advantageous for LCA-based CO_2 reduction when used together with heat pumps and electric mobility.

Decentralized Combined Heat-and-Power (CHP) Plants	**‘Realistic‘ potential** Single-digit TWh_{el} (if biogenic[4]) **Advantages** – Excellent dispatch capabilities (response time around 5 min.). – Rather low investment costs. – High total efficiency of around 90% (heat and electricity). – Appropriate for mid-/high-temperature industrial process heat when operating at high FLH. – Substantial co-benefits for relaxing the distribution e-grid requirements. – Well adaptable to renewable gaseous fuels, with then very low LCA-based CO_2 emissions. **Disadvantages** – Electric efficiency alone lower than for CCGT. – Need for appropriate heat sinks in close distance for larger, more efficient installations. – High sensitivity to fuel costs. – If supplied with natural gas, high LCA-based CO_2 emissions of 340–468 gCO_2/kWh_{el}. **Other comments** – Large amounts of renewable gases are expected to be available only on the long-term. – Prospects for use of fuel cells if their investment costs can be reduced substantially and their lifetime extended.
Nuclear	**‘Realistic‘ potential** Typically up to 10 TWh_{el} per (large) powerplant. **Advantages** – Base-load operation. – load-following capabilities possible. – Very low LCA-based CO_2 emissions of 5–40 gCO_2/kWh_{el}. – Minimal space requirements. – Quite low marginal costs. **Disadvantages** – Very high specific investment costs. – Negative learning curves in the last years: massive delays and cost overruns for the new Gen. III+ projects in Europe and U.S. – Very long decay times of concentrated but highly dangerous radioactive waste. – Possible proliferation risks. **Other comments** – Challenging risk assessment due to very seldom accidents but with potentially very large consequences. Overall matter of normative decisions. – Waste disposal technically possible, but low social acceptance. – Swiss public vote prohibits new power plants. – New technologies (Generation IV, SMR) in development, not market-proven yet.
Imports	**‘Realistic‘ potential** Between 2010–2019 net winter import were on average 4.1 (0.7–8.7) TWh_{el} (BFE 2022). A ‘realistic potential‘ is difficult to estimate as it depends on future transmission capacities, market and EU-Swiss relationship. **Advantages** – Can in principle offer relief for winter electricity shortages. – Transmission lines are technologically sufficient (in the order of 10 GW with prospects for expansion) – European electric system expected to provide low LCA-based CO_2 emissions in the long-term future. **Disadvantages** – Current electricity generation in Europe (EU-27) has LCA-based CO_2 emissions of ~250 gCO_2/kWh_{el} (EEA 2021b) but these are expected to be substantially reduced by 2030. – Political/regulatory challenges at the interface between the EU and Switzerland (missing framework agreement) lead to high uncertainties. – Neighboring countries may face similar seasonal pattern challenges in the future. **Other comments** – Economists agree that integration of the Swiss to the much larger European system with a highly diverse generation portfolio is beneficial in terms of both costs and security of supply (if a legal framework is established).

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[4] According to two WSL/SCCER-BIOSWEET studies (Thees et al. 2017, Burg et al. 2021), the total sustainable potentials for wood and manure are 50.2 PJ and 26.9 PJ respectively – i.e. 21.4 TWh in total – which with a 40% efficiency in CHPs would make 8.6 TWh of electricity and 10.5 TWh of heat. However, alternative uses of wood as well as economic and other constraints for manure (wide distribution, difficult collection and exploitation, conversion losses from primary to secondary biomass) would substantially reduce their actual energetic potential.

Given the expected massive increase in electricity demand on the way to full decarbonization, other options beyond the two major future contributions by hydro power and direct solar electricity use will be important. Candidates, alone or in combination, for this are:

- Electricity imports from the European system: depends on the availability of renewable energy in Europe and the integration of Switzerland's electricity market into the European one (which is currently rather diminishing due to political reasons). This may lead to risks for security of supply and requires therefore a reliable legal framework for embedding Switzerland in the European grid-system.

- Massive expansion of solar electricity in combination with electrolysis (potentially by electricity generated abroad) and storage/distribution infrastructure of hydrogen and/or synthetic hydrocarbons: electrolysis may relieve the pressure for enhancing electricity grids to absorb peak solar electricity input and most importantly allow long-term storage of large electricity amounts, thus counteracting the anticipated seasonal imbalance.

- Increased exploitation of wind energy can contribute to the generation of renewable electricity in winter. The population might accept wind mils more readily if the affected inhabitants have a fair share of the revenues and are involved actively and early in the process.
  Non-nuclear thermal powerplants: either large-scale Combined Cycle Gas Turbines (CCGT) with peak power of currently up to 800 MW_{el} for a power plant with one turbine and one steam cycle (1+1), and up to 1.5 GW_{el} for a (2+1) power plant or decentralized Combined Heat and Power (CHP) installations with up to 20 MW_{el} peak power. The former have net plant efficiencies up to 64% for the latest technologies on the market (prior to grid losses), while the larger CHPs achieve electric efficiencies of 45%–50% with another 30% of medium-temperature heat (appropriate for several industrial processes) and about 15% of low-temperature heat which is suitable for district heating networks (all figures relate to the biggest engines of GE, Ansaldo and Siemens). As a kind of 'insurance' against unforeseen shortages of electricity supply, open-cycle gas turbines ('peakers') can be considered for emergency power generation. These assets have electric efficiencies of close to 43%, no heat use, but low investment costs and therefore potential economic viability.

  If such thermal powerplants are operated with Natural Gas (NG), they may have a justification only as transitional devices to close the gap between demand and supply when (and if) earlier phase-out of nuclear power plants occurs in parallel with an insufficiently fast expansion in particular of solar electricity.

  Prospects for contributing to net zero electricity generation in the mid-to-long-term can be realized for CCGTs when large amounts of 'green' H_2 (mainly imported) become available. Recent developments, also from Swiss manufacturers, have shown that large (H-class) gas turbines can be efficiently operated with CH_4/H_2 mixtures of varying composition and prospectively with pure H_2 (Bothien et al. 2019). CHPs can be operated with biomethane or Synthetic Natural Gas (SNG) without adaptations while lately industry announced 'H_2-ready' CHPs within the next few years. Such local installations can use H_2 from power-to-H_2 systems.

  Fuel-cells can become interesting alternatives to combustion engines due to their even higher electric efficiencies in CHPs if their high investments costs can be reduced substantially.

  In principle, the generation of electricity from CHPs is limited by the local availability of heat sinks, either for buildings heating or industrial processes. According to the Energieperspektiven 2050+, appropriate heat sinks include industrial processes at temperatures lower than 400 °C and district heating, ranging in total between 7 and 10 TWhth, leading to a comparable electricity potential.

  In addition, biogenic electric generation is subject to the limited availability of sustainable biomass. For example, according to the Energieperspektiven the total biomass potential in 2050 is about 37 TWh_{ch} (14 imported, 23 domestic), which could theoretically provide up to 16 TWh_{el}. However, it is expected that there will be a competition for this high-exergy[5] source with other end-use energy sectors and, given the heat sinks limitations, a realistic potential lies in the order of single digit TWh_{el}. It is also worth noticing that there is a debate about whether burning woody biomass can be considered climate-neutral due to the long 'payback' times of newly planted trees (EASAC Bioenergy, Forest bioenergy update: BECCS and IAMs).

- Observe the evolution of nuclear energy technology. Should a new technology (Generation III+, IV, small scale plants SMR) be established with intrinsic security that has been demonstrated in commercial use over a longer period (e.g. one to two decades), progress in nuclear waste disposal (including accepted disposal sites) and economic competitiveness, nuclear energy could in the long-term be part of the production mix.

Current electricity markets are characterized by the necessity to match demand and supply at any time in a given control domain as large-scale electricity storage capacities have been marginal so far. At least until cheaper and more efficient storage options and smart management on

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[5] Exergy denotes the ability of a given energy form to create work (mechanical or electrical). The exergetic value of heat is higher the higher its temperature is.

the demand side will become widely available, the flexible dispatch of power generating assets will be crucial. Such dispatch follows the merit-order principle. This means that at any point in time, reduction of demand removes the generator with the highest marginal costs from the dispatch scheme and vice-versa in case of increasing demand.

Given the integration of the Swiss electricity system with the European one, import electricity to the country may be produced by quite different sources. Until recent market conditions, where CO_2 price was low, coal-fired power plants produced at very low marginal costs (also due to extensive subsidies) and were thus more competitive not only than gas-fired plants, but in some cases even against hydropower. With current and foreseen higher CO_2 prices, coal-fired generation will have higher marginal costs and will thus be displaced even by gas-fired powerplants.

Hurdles

- Rapidly increasing digitalization and the electrification of end-use-sectors (buildings, industry, transport) can – when completed – easily double the current electricity demand of the country.
- The current growth rate of new renewable electricity generation is insufficient to reach net zero emissions target in the longer run by 2050.
- The replacement of nuclear power plants mainly by solar energy poses a big challenge of seasonal storage from summer to winter in addition to requirements for short-term storage of fluctuating solar energy.
- Limited public acceptance of wind and to some extent geothermal energy and opposition of environmental protection groups to heightening of hydro power dams and construction of greenfield hydro power plants.
- The massive increase in renewable electricity demand (electrification of cars, heat pumps, synthetic fuels, cooling, further digitalization) will be difficult to achieve and needs the concurrent use of several options.
- The low technological development of several key components for electrolysis and storage/distribution infrastructure of hydrogen and/or synthetic hydrocarbons and in particular the currently prohibitive costs for synthetic fuels, making very high CO_2 prices necessary in order to be competitive against fossil fuels.
- The limited availability of biomass does not allow to replace natural gas by biogas to a large extent.
- The current market situation is inappropriate because storage and distribution (grid) costs are not adequately reflected in electricity pricing.
- Current heavy subsidies of coal-based power generation lead to very low electricity prices in an open market, thus increasing the demand for subsidies for wind and solar electricity, which – despite enjoying very low marginal costs – cannot recover their capital costs during their limited operational time.

Actions needed

R1 (reduce demand):

- Internalization of external costs for all power generation technologies including supply, storage and distribution.

R2 (efficiency):

- Market design that remunerates the storage capacity and operational flexibility of hydro power.
- Increase matches between demand and availability of renewables by demand management.
- Consider CCS/CCU if gas plants have to be installed as transitional technology until sufficient renewable power is available.

R3 (replace):

- Development of predictable regulation/policy instruments for decision-making at the side of investors in coordination with international, in particular European, policy in the sector.
- Introduce concept of community/district owned power generation plants if these are space-demanding or affect natural scenery (non roof PV and Wind).
- Technology innovation to bring down further costs of renewable generation methods (for example for roof top solar in Switzerland) and enhance applications on surfaces of buildings and transport vehicles.
- Information/communication for consumers and local prosumers on potential benefits/savings on the basis of new policy instruments (for example ‘Eigenverbrauchsregelung’).
- From a global perspective it would be cost-efficient to invest in large scale solar and (off-shore) wind (at 4 to 7 ct/kWh) instead of expensive domestic solutions, provided that grid infrastructure will be provided in time and regulatory conditions for Switzerland will be improved.

Recommendations

- (P) Consider market instruments that remunerate storage and on-demand production capacities (policy)
- (P) Provide incentives for ‘back-up’ capacities to ensure electricity supply in winter. Fossil ‘back-up‘ capacities should also pay the CO_2 tax.
- (P) Due to acceptance and environmental issues of other energy sources focus primarily on a strong increase of PV and its integration in distribution grids and storage capacities; for other technologies, follow open and transparent decision processes with intense public engagement.
- (–) Develop a long-term strategy for the – mainly international – supply of the increasing demand of low-CO_2 electricity that is needed to phase-out the use of fossil fuels, including long-haul transport and aviation (policy; energy companies).

5 Distribution grids/networks for heat, electricity and fuels

Distribution networks or grids are linking demand and supply over space. They are an important part of the energy system, in particular for electricity but also for heat (district heating) and some fuels (gas). Heat networks are mainly used on the local or small regional scale for district heating. Gas networks today are used for the distribution of natural gas but in the future might also be used for district heating, the transport or distribution of biogas, synthetic fuels and hydrogen or captured CO_2 to be reused or sequestered. The electricity grid will gain in importance and face numerous challenges with widespread electrification of transport and increase of heat pump use, increased variability of energy production due to the increased share of renewables and a decentralization of electricity generation down to the building scale.

Gas grid

Natural gas supply covers 20% of residential buildings of Switzerland (BFS 2017). In many urban areas a transition from natural gas consumption to district heating is ongoing in order to reduce CO_2 emissions. Due to the limited production capacities of renewable biomethane of about 4.5 TWh per year, the gas grid will strongly diminish in the long term. However, the natural gas grid may be an important asset because some energy transition trajectories may require distributing renewable gases (methane, hydrogen) to consumers. This infrastructure should be preserved to a certain extent at least until the energy transition has evolved in such a clear direction, for example substantial electrification, where chemical energy will not have to be distributed to consumers. In future if CCS will be implemented to a substantial extent there will be the need of a dedicated infrastructure to transport CO_2 from the carbon capture to the reuse or storage locations (see chapter 7).

Heat

District heat networks make sense where renewable heat supply sources as for example biomass, waste incineration power plants, solar thermal, low-temperature heat from mid-depth geothermal systems, waste heat from large data centers or water reservoirs are readily available. In addition, it should be a priority to employ combined heat and power (CHP) generation whenever possible, instead of heat supply only. Electrification of heating via heat pumps is a competing option to heating networks, but also might have some limitations in densely populated areas. On the economic side trade-offs between economies of scale and higher efficiencies on the one hand and investment costs for the building of a distribution network on the other hand have to be considered. While such investments can be optimized when a completely new residential area is built up, the situation is much more complicated, where existing buildings and heating equipment are diverse and in different phases of their lifetime. Local authorities/utilities must engage in a dialogue with stakeholders to find viable solutions in this context.

Electricity

The electricity grid is classified in four different voltage levels, where higher levels traditionally serve to transmit high power flows from centralized power plants to various locations of concentrated demand, from where electricity is distributed to individual consumers at lower voltages. Due to the increasing share of local small/medium-scale generation (solar, wind, CHP, small hydro) controllable and centralized electricity generation is progressively displaced by distributed stochastic renewables located primarily in distribution grids. This impacts the planning and operational practices of both distribution system operators and transmission system operators. Handling the possibly resulting bi-directional flows, the impact on voltages and the need for balancing of these resources requires increased coordination between the system operators of the different voltage levels.

An increased implementation of advanced control schemes, sensors and related digital technologies in distribution grids is crucial for an increased transparency and an efficient operation of the power grids down to the low voltage levels (e.g. smart meters have by far not reached their full potential yet). Flexible management of appliances operation at the consumers end, like electric vehicle charging or heat pump operation as well as solar PV control, provide the means to avoid violations of grid restrictions but require additional investments in hard- and software as well as social acceptance. On the other hand, the flexibility for electricity production and consumption emerging from the aggregation of many distributed energy resources (DER) can support the upstream operations of the high voltage transmission grids and create new business opportunities for financing the installation of DER. Direct current (DC) based technologies might become important for high-voltage transmission grids but likely less so for local or regional grids, at least in the near future.

Recently, important challenges from changing EU framework conditions have emerged. Due to the lack of an electricity agreement, Swissgrid is limited in terms of influencing developments in the European electricity market and is prevented from participating in the coupled electricity markets. Switzerland currently is not considered when the cross-border capacities provided for these electricity markets are calculated. This has led to an increase in unplanned flows through Switzerland – with a negative impact on grid security. In addition, the access to important control energy cooperation arrangements seems to be threatened or at risk. An electricity agreement with the

EU will be crucial for power supply and grid security in Switzerland.

An additional issue should be assessed at least in the midterm: due to the increasing direct use of decentralized power generation the main function of the electricity grid shifts more and more from a means to access electricity to a backup system for times with low own production. This might be better reflected for example by a flat rate for grid access instead of an additional price related to the amount of consumed power as it is today.

Hurdles

- Costs of installing district heat networks in an environment of disperse heating systems of different age and different technical efforts to change a heating system (e.g. in houses with individual warm water boilers on every floor to a central warm water distribution system).
- Impact of distributed resources on grid flows and voltages in distribution systems and corresponding needs for balancing.
- Missing integration in the EU electricity market which creates uncertainties in import capacities and grid security.
- Some of the high voltage power lines have been confronted with public opposition.

Actions needed

R2 (efficiency):

- Preserve a basic gas distribution system for a time where biogas or later on synthetic natural gas or hydrogen become more widely available or for transport of CO_2 from carbon capture.
- Planning of adequate regulating power capacity.
- Leverage information and communication technologies to support the efficient operation of distribution grids.
- Enhance the coordination between transmission and distribution system operators.

R3 (Replace):

- Support expansion of district heat systems with low-CO_2 energy.
- Support the joint installation of energy storage and renewables with holistic consideration of both the investment costs and the sustainability goals.

Recommendations

- (P) adapt the pricing/tariff design to account for the changing role of the main grid supply.
- (–) Long-term planning of local or regional district heat networks to facilitate investments in renovation or set up of heating systems in buildings (community policy).
- (–) Stronger integration in the EU electricity and energy system (policy).
- (–) Consider the importance of the gas grid for repurposing for transport of CO_2 or renewable gases (policy/industry).

6 Energy storage

Storage of energy is linking the demand and supply over time. For many decades, storage challenges have been to store base-load energy from nuclear and river plants from low usage time (night) to high usage time (mainly done by hydro reservoir power stations). Nowadays and in particular in future storage is needed to transfer power from times of high renewable production (sunny times and windy times) to times of lower production, the main challenge being seasonal storage from summer to winter.

Mobile applications use energy storage technology on a small scale (capacity) and large numbers since the mass deployment of mobile phones. On a large scale, pumped hydro storage is the only technology around for 150 years, simply because fossil energy was a much cheaper ‘energy storage’. Pumped hydro was of interest since it allows the coupling of unflexible, large-scale electricity production with the 24 hrs pattern of electricity consumption and secured the business case in the past. With increasing (cheaper) electricity supply during the day, coming from Wind and PV, the arbitrage diminishes.

At the current level of installed PV and wind, together with the remaining fossil and nuclear power generation, production and consumption during 24 hrs match quite well. In future, however, with solar-and wind-based power supplies, the energy supply system calls for a flexible connection with variable consumption. The elements of flexibility are 1) comprehensive energy distribution grids (chapter 5), 2) sector coupling and demand-control (chapters 7 and 10) and 3) energy storage.

The combination of all three elements leads to a cost-optimized system. Demand-control requires strong engagement and thus strong efforts of the individual, but is an effective measure for large single source consumers like industry. Grid expansion and large-scale storage require investments and research but do not interfere with the habits of individuals.

For storage, there are two central questions:

1. What capacity is needed for which duration of storage and
2. what are the technologies available for mass deployment along the timeline of the transition?

Direct (power-to-power) electricity storage on short-to-medium time scale

For counterbalancing supply and demand day-night or even for a couple of days, proven and established storage technology is available, either as pumped hydro bidirectional systems or batteries. Round-trip efficiencies are 80-85% for batteries and 75–80% for pump-hydro, while storage periods are typically in the order of minutes, hours or a few days at the most.

Pumped hydro is only feasible under specific geographic and market conditions, but the technology is mature also for large power systems in the order of 1 GW and more per installation. Initial investment costs are high but recoverable over the very long lifetime of the asset.

Batteries have emerged as local, small-to-medium-scale applications with storage capacities between a few kWh and a few MWh. Even up to 300 MW resp. 1200 MWh were achieved recently. Their lifetime is in the order of 10 years, and the number of cycles is limited depending on the operational strategy (mainly depth of discharge). Specific costs are still high, but technological progress related to costs and overall performance was impressive in the last few years. Experts expect that the learning curves are steep, also driven by the market growth of electric mobility. Surely, optimization potential for durability, reliability, and cost exist, depending on the specific technology, but in general, such storage devices are on or close to the market-readiness.

Long-term heat storage

Heat pumps can cover the heat demand for hot water and space heating in rural areas. In densely populated areas, air-to-water systems or ground-probes-to-water systems might not be feasible due to noise issues or unsustainable heat depletion in the ground. In such cases, long-term heat storage systems, for example underground storage of excess summer heat, would help decrease the electricity demand of heat pumps in winter and facilitate the thermal regeneration of the underground.

The heat storage solutions for such situations are currently close to market readiness. Several dwellings in Denmark get their space heat from large storage lakes (heated with solar energy in summer up to temperatures of 80 °C).

Pilot project phase-change (Water to Ice) heat storage facilities supply heat to single-family houses and community buildings in Switzerland and prove their usefulness. Other heat storage systems, using latent heat, stored in concentrated lyes are not yet demonstrated in a residential situation but explored in the labs of applied engineering and research groups in Switzerland.

Short-term heat storage supports the energy transition as a pivotal component for sector coupling, and the corresponding section provides more details on this technology.

Long-term chemical energy storage

An energy production deficit from the sources PV, wind and hydro of some weeks in October-November and February-March may result in the long run, depending on the acceptable wind capacity and available energy imports. Switzerland requires long-term energy storage in significant amounts to mitigate such a shortage. From the present perspective, only the chemically stored energy fulfils this requirement, as the usable storage capacity of pump storage plants is limited and battery systems lead to high storage costs if operated for seasonal storage. For this purpose and to reduce GHG emissions of the demand sectors of the energy system (for example aviation), synthetic production of fuels from renewable energy is an option.

Based on the simplified scenario that Switzerland's national electricity production stays the same for 2050 but self-supplied by renewables only (without nuclear energy), we present an ‘order-of-magnitude’ estimation for long-term storage, neglecting the estimated 11 TWh of electricity for the transport sector and the part for operating the heat pumps: With a large capacity of PV installed, Power-to-X becomes most valuable for balancing the lowest grid level, which is due to its current layout most vulnerable to imbalances. The magnitude of installable PV is a politically sensitive topic. On pure geographic (supply-side) and physical considerations (demand side), about 25 TWh/a net from PV can replace the currently installed 3.3 GW (25TWh/a) capacity of nuclear power. Here any compensation of losses for seasonal storage is excluded. On the supply side, various assumptions have to be made (like the efficiency of the cells, installation on vertical surfaces, etc.). The estimated PV potential ranges from 28 TWh to 67 TWh. If wind power is an option, even the conservative PV scenario shows that required power to replace the nuclear capacity is obtainable but demands a seasonal balancing strategy. An estimation shows that the required 25 TWh of PV sourced energy has a seasonal production split of 63% in summer and 37% in winter. This characteristic requires that roughly 13% of the annual production in PV needs to be shifted seasonally (3.25 TWh net). Based on the 25 TWh estimation and considered overall storage losses (50%), about 32 TWh of new renewable electricity are required, of which 7 TWh are for the seasonal shift. This consideration largely excludes the controversially discussed wind energy, which has a better production characteristic in winter, mitigating the storage challenges (Kober et al. 2019).

Power-to-X allows for the described seasonal shift. Starting from Power to hydrogen, various liquid and gaseous fuels become available. Yet, experts debate that the required number of full-load hours to reduce the cost for hydrogen production, as the first process step, is challenging to achieve if excess electricity from PV or wind is used only (1000 full-load hours). Although hydro power and PV operate at different voltage (= grid) levels, a connection to (running river-) hydro power is helpful to achieve enough full load hours. Therefore further investments in transformers and other infrastructure are required. The economics depend not only on the capital costs but also the operating costs, mainly the electricity. Any price component added to the price for electricity (grid fee, taxes, etc.) challenges the business case for Power-to-x plants. The players in the field demand an exemption from grid fee for the electricity stored in power-to-gas if done in a system stabilizing fashion (according to the regulation for pump storage) for this very reason. Besides the cost for Power-to-X, a key question is the source of CO_2 for the production of CH4 or liquid synthetic fuels.

For power to hydrocarbons, to be part of the solution and not part of the problem, the CO_2 has to come 1) out of the atmosphere, 2) from a biogenic source or 3) as a dual-use of CO_2 captured from a non-renewable source like calcination of limestone forcement industry, waste incineration (apart from biowaste) or centralized power generation. Since the latter two are 'waste streams', there is no or negative price associated with the raw CO_2. Depending on the technology, the plain CO_2 from sources 2) and 3) needs to be purified, creating additional costs. CO_2 pricing is an enabler for all three sources creating additional revenues, compensating for the cost of treatment of raw CO_2. While CO_2 taken out of the air is unlimited in supply while at considerable cost (today: about 600 CHF/ton), sources 2) and 3) are less expensive but limited in supply. Studies estimate the maximum potential from the 'waste stream' sources to 7,314,000 T/a, resulting in a storage capacity of about 39 TWh/a (CH4). If the society becomes CO_2 neutral or even CO_2 negative in the long run, the CO_2 available from waste incineration plants significantly declines. Assuming a reduction of waste-born CO_2 by 50% and neglecting the cement plants, the methane storage potential drops from 39 TWh/a (7,314,000 T/a CO_2) to 13 TWh/a (2,482,000 T/a CO_2), based on the energy content of CH4. This estimation assumes a conversion efficiency from power to methane of more than 27% to store the required energy for the seasonal shift described previously. The storage capacity for methane in Switzerland is little more than 1.6 TWh, including the gas storage cavern in Étrez, France. Eight times this capacity is needed to store the energy for the seasonal shift as methane to compensate for the nuclear power Switzerland uses today (Kober et al. 2019).

Power to hydrocarbon also provides plug-in fuels for today's long-distance transportation and the heating sector. Today's gas market has a volume of 39 TWh, with the highest demand between October and April. The CO_2 capacity in Switzerland as of today matches this demand. In future, with the broad dissemination of heat pumps, the gas demand for (home) heating purposes will decrease. Power to methane is an option for the mid-term. In the long run, Switzerland would need cheap CO_2-air-capture or carbon-free energy carriers to meet the requirements for seasonal energy shift.

Hurdles

- Mid-to-long term storage of high-temperature industrial heat is not realistic.
- Low efficiency of chemical 'round-trip' storage of electricity.
- Huge amounts of renewable hydrogen needed.
- The expansion of various storage facilities in Switzerland is inhibited, among other things, by the unequal treatment with regard to network charges (compared with pumped storage plants).
- Possibly limited CO_2 amount available from CCS or direct air capture to produce synthetic fuels.
- Missing public acceptance of large pumped hydro or other large and well visible installations.
- Large material flows and the associated conflicts with other environmental goals in connection with battery systems.
- Missing integration in the EU electricity market which creates uncertainties in import agreements, particularly in times of low energy availability.

Actions needed

R3 (replace):

- Enhance short-term storage capacities, also at utility and residential scale.
- Support the development and implementation of long-term electricity storage systems and capacity at the seasonal scale, at large scale if possible.
- Integration of battery energy storage systems into power distribution grids and transmission grid reserve.
- Large scale deployment of renewable fuels.

Recommendations

- (–) Incentivise the heightening of reservoir dams to make even better use of the important Swiss hydropower storage infrastructure; the current storage capacity of almost 9 TWh, of which 6.5 TWh are effectively used, might be increased by up to 2 TWh (Schleiss 2012, Fuchs et al. 2019) (policy).
- (–) Provide incentives to support seasonal heat storage to integrate higher shares of renewable energy in the heating sector (policy).
- (–) Explore locations and provide instruments to establish (seasonal) storage infrastructure for renewable gases (industry).
- Support further research for more efficient and less costly storage options.

7 Sector coupling

Box 6: Nomenclature regarding zero CO_2 fuels

Zero CO_2 fuels can be produced by:
a) biomass
b) solar thermo-chemical processes
c) electrolysis using renewable or nuclear electricity
d) fossil fuels (e.g. steam methane reforming) with CCS

When talking about c) we refer to e-fuel. When the hydrogen is combined with recycled CO_2 to create methanol or hydrocarbons, or with nitrogen to create ammonia, etc., we talk about synthetic fuels (see **Figure 8**). In the context of LCAs, all these fuels cannot be precisely zero CO_2; the term would be correct only if in 2050 all energy and industrial processes were 'defossilised' (i.e. would involve no net-positive emission of CO_2 in the atmosphere).

Concept introduction

The decarbonization of the energy system requires first a wide electrification of several end-use sectors and second close links between electricity on the one hand and chemical energy carriers on the other. Long-term storage over weeks, months or seasons will be important due to the expected seasonal fluctuation of solar electricity, and synthetic fuels can enable such storage if zero CO_2 electricity can be made available for their production. Very high energy density requirements in heavy-duty, long-haul transportation (in particular in heavy-duty trucks, ships and in aviation) as well as in reliable, steady energy supply for industrial processes can then be met by these synthetic fuels.

Furthermore, in view of recent developments in the co-operation framework agreement between Switzerland and the EU and of the difficulties for establishing a European transmission grid the availability of large amounts of imported electricity in future is uncertain. Therefore electric (e-)fuels or solar-chemical fuels will be needed, since the amount of necessary power generation for this most likely cannot be supplied through domestic renewable energy. Appropriate locations to generate electricity for electrolyzers are those with high solar and – mainly – off-shore wind potential and much higher number of full-load hours than feasible in Switzerland/Central Europe. In contrast to imports of electricity, synthetic fuels can be transported and distributed over long distances partially using existing or repurposed infrastructure at very low costs.

In addition, 'Power-to-Heat' concepts can be useful in providing heat for industrial applications at medium temperatures. An important element in this concept are short-term heat storage systems at different temperature levels. On the one hand, low-temperature heat and even cold storage can relieve the load from the grid by operating heat pumps when electricity is readily available to fill storage for domestic hot water supply or cold storage for air conditioning. Such storage systems based on phase-change processes or based on water are market-ready (Schmidt et al. 2020). Rooftop PV, in combination with heat storage, can cover the heat demands of in-shop bakeries and frozen food sections of grocery retail. Other industrial sectors require process heat at increased temperature levels, heat pumps for temperatures up to 165 °C are on the market. High-temperature, high power heat storage concepts for temperatures up to 550 °C are at a technology readiness level (Schmidt et al. 2020). The underlying concept allows for customizing the temperature to the application in a wide range. Heat storage systems do not require precious metals or catalytic material and are more economical than batteries. In this sense, coupling the sectors electricity and heat provide an excellent flexibility option.

This anticipated development, as conceptually illustrated in **Figure 8**, is called **sector coupling** and will increase the complexity of the overall system and the interactions among commercial, public and private market players and stakeholders substantially. For its realization technologies like electrolyzers, methanation power plants and refineries for synthesis of higher hydrocarbons, management of CO_2 cycles and large-scale fuel cells must be brought to maturity and commercialization. Investments in new or repurposed infrastructure will most likely be very high and the concrete transitional path largely unknown. Substantial technology innovation will also be necessary and policy-driven boundary conditions will be decisive drivers of such a transformation.

More concretely we anticipate that there will be on the one hand a need for additional electricity for the electrification of cars, Light-Duty Vehicles (LDV) and buildings heat. On the other hand there is a need for large amounts of electricity for producing chemical energy carriers for long-haul transport (in particular shipping and aviation) and industry heat as well as for long-term (seasonal) storage. For the direct electrification domestic power generation could cover a substantial part of the needs, dominantly through massive expansion of Photovoltaics (PV).

Available domestic sustainable biomass and in addition any imported one shall be preserved as energy carrier for high exergy applications (industry heat, power/heat generation in winter and long-haul transport, particularly aviation), but its potential amount will not be enough to cover the entire demand for chemical energy carriers.

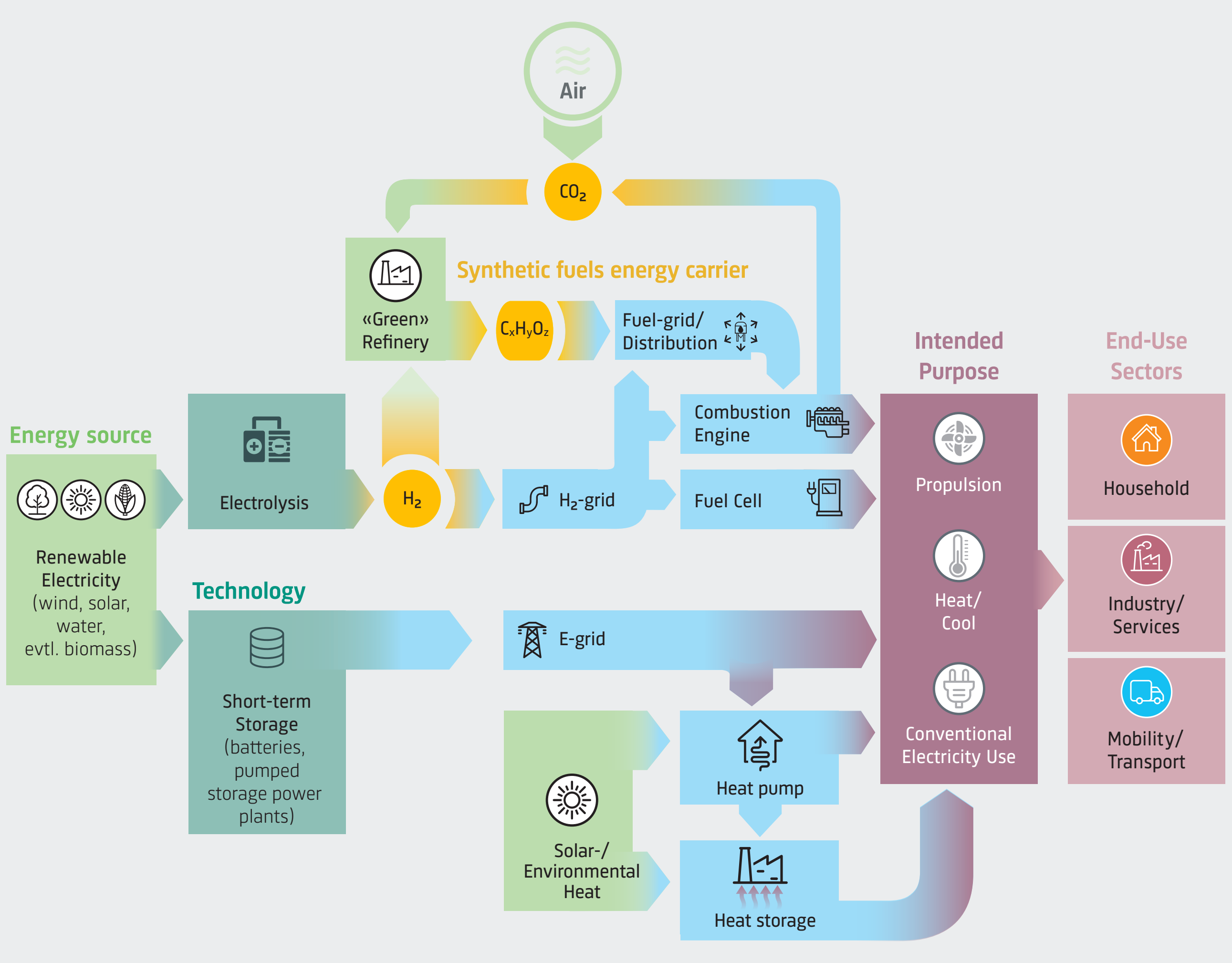

Fig. 8: An example of sector coupling indicates on the one hand the electrification of the various end-use sectors and on the other the manifold interconnections between electricity and gaseous energy carriers (simplified illustration).

Key Indicators of Swiss Energy Studies

Scenarios for the future evolution of the energy system are continuously generated, assessed with complex optimization methods and revised in the light of emerging insights. Among the most recent relevant works for Switzerland we highlight several White Papers from the 'Energieperspektiven 2050+' (EP2050+, BFE 2020a), elaborated in a mandate of the Swiss Federal Office of Energy (BFE), and from the Swiss Competence Centers of Energy Research (SCCERs), and the final report of the Joint Activity Scenarios and Modelling (JASM, Marcucci et al. 2021), to which several SCCERs have contributed. Several scenarios of the last two studies set normative targets for the Swiss Energy System in 2050, ranging from net zero CO_2 through net zero GHG (thus requiring net-negative-CO_2 emissions), around mid of the century. In the present work we use in addition two scenarios developed and quantified in a simplified 'back-of-the-envelope' approach to contextualize the findings of the aforementioned detailed models of JASM and the EP2050+. For more information on these two reports (including some international studies), please consult the **Annex** of this White Paper. For the background of the 'back-of-the-envelope' analysis, please consult the **Appendix** at the end of this report.

The EP2050+ involves a main 'ZERO Basis' scenario, around which three different perturbations with varying degrees of direct (ZERO A) or indirect electrification (based on gaseous or liquid renewable chemical fuels, ZERO B and ZERO C) are analyzed. The JASM report uses three different modeling approaches (SES-ETHZ, STEM-PSI, SES-EPFL), of which we include in the following the first two for reasons of better comparability. Within each model, several scenarios have been assessed, based on different assumptions with respect to autarky, boundary conditions for energy imports, degree of international cooperation, etc.

The 'back-of-the-envelope' approach spans two widely different scenarios for the Swiss energy system in 2050. Both use the same heuristics for the demand side of all end-use energy sectors, but differ in the design of the supply side and therefore in the configuration of the sector coupling. Both scenarios do not allow for electricity im-

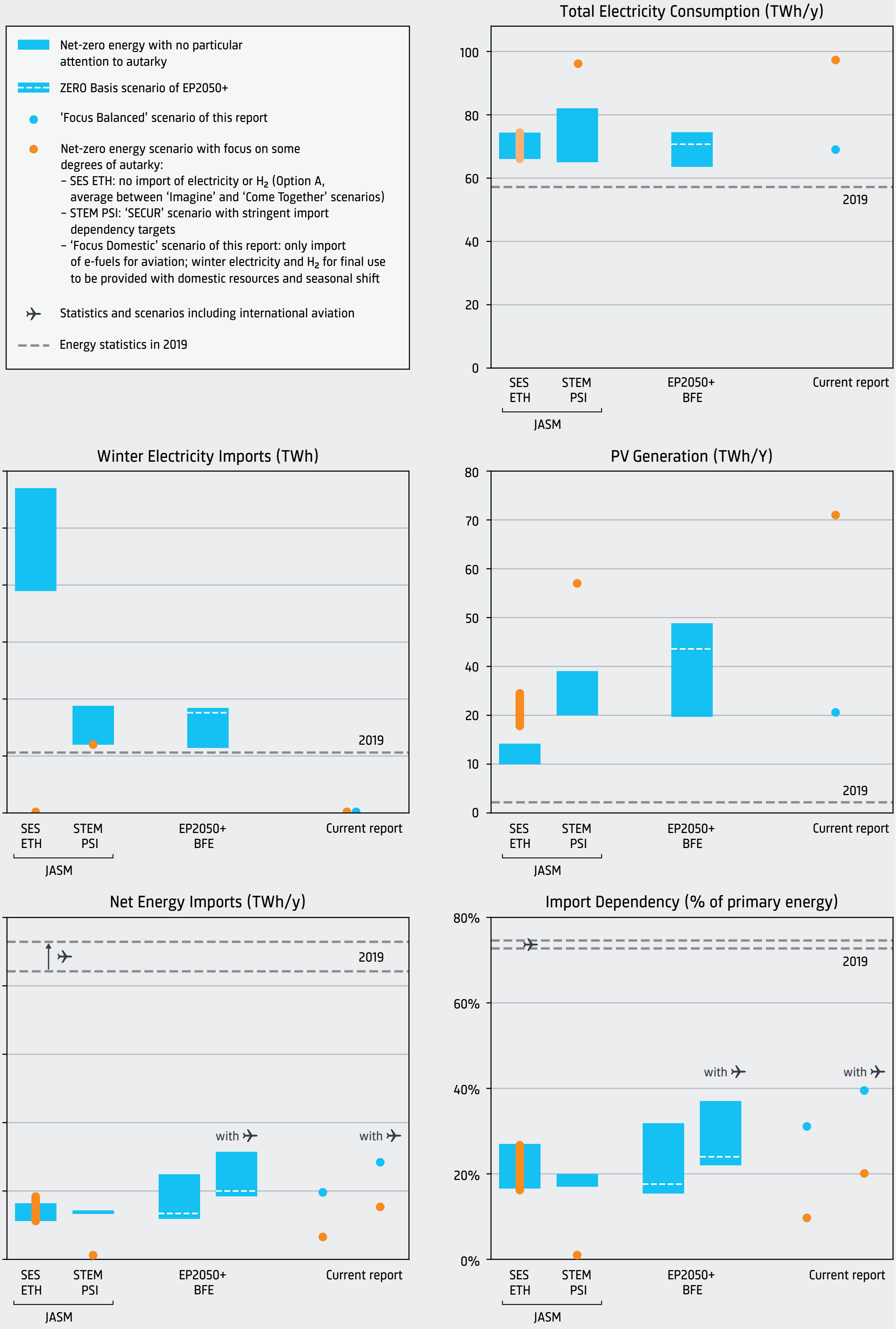

Fig. 9. Key 'performance parameters' of the Swiss energy system in 2050 according to estimates from various studies and scenarios: total electricity consumption, winter electricity imports, PV generation, net energy imports and import dependency (ratio of net energy imports to the gross (primary) energy supply).

ports even in the winter half-year due to the aforementioned uncertainties (with respect to the embedment of the Swiss in the European electricity system) and are in this sense very conservative.

The first scenario, called **'Focus Domestic'**, allows for imports only of renewable jet-fuel and considers massive expansion of photovoltaics to drive electrolyzers creating H_2 for three purposes:

a. industrial processes (mainly for heat)
b. propulsion of heavy-duty trucks (fuel cells or IC-engines)
c. long-term storage for seasonal shift (PtH_2 in summer and H_2 to electricity in winter, using either CCGT or fuel cells).

The second scenario, called **'Focus Balanced'**, relies for all three above sectors (a, b, c) on H_2 that shall be imported, being generated at appropriate locations worldwide based on least-costs for production (including transport). Alternatively, synthetic natural gas (SNG) can be considered for the same purposes if its lower transport/storage/distribution costs would overcompensate the higher production costs (consider also already existing NG infrastructure).

Figure 9 shows the comparison of the models and scenarios described above with respect to key 'performance parameters' of the Swiss energy system. It is worth noticing thereby that only the EP2050+ and 'back-of-the-envelope' estimates include the anticipated energy demand for international aviation in 2050 (jet-fuel demand for 17 TWh in the former and 22 TWh in the latter).

The figure shows, quite interestingly, that scenario estimates for all considered studies are in a similar range, while the span of predictions within each study may be quite large. In particular, there is evidence that more 'autarky'-oriented scenarios (in orange in Figure 9) can be clearly distinguished from those which include international cooperation and import/export volumes of both electricity and fuels. The former scenarios are characterized by significantly higher total electricity consumption, substantially higher power generation through PV and to a certain extent (much) lower net energy imports. It is however noteworthy that overall energy import dependency, although following similar trends as the net energy imports themselves, drops in all estimates quite substantially from about 75% today to between 20%–40% in 2050 and is thus dramatically reduced.

E-fuels: how much, where from and at which cost?

In the following we will provide rough estimates of the amount of electricity needed to produce 'zero-CO_2' fuels in Switzerland and in favorable locations worldwide with different generation technologies. Installed power generation capacities and those for electrolyzers will be given and cost projections will be drawn from recent literature.

Estimates of the amount of e-fuel imports vary widely among the scenarios and studies introduced above. Indicatively, in the EP2050+ a range between 29 (ZERO A) and 48 (ZERO B) TWh is given. On the other hand, our 'Focus Domestic' yields 22 TWh e-kerosene while according to the 'Focus Balanced' scenario another 33 TWh H_2 is required on top of the 22 TWh for aviation, leading to a total of 55 TWh. The two ranges are therefore quite similar to each other and for the sake of simplicity we may assume an 'average' scenario consisting of 22 TWh jet-fuel and 17 TWh H_2 for the subsequent considerations. Using electricity-to-e-fuel efficiencies of 0.37 for kerosene and 0.55 for (liquified) hydrogen (Stolz et al. 2022) we obtain a total electricity demand of **90 TWh_{el}**.[6]

According to the top-right plot of Figure 9, the Swiss electricity consumption in 2050 in different scenarios ranges between **64–97 TWh_{el}**. Therefore, the electricity generation required for the production of e-fuels abroad will be at least in the same order of magnitude as the entire Swiss electricity consumption.

In **Table 2** key-numbers are derived for the production of 39 TWh (22+17) of e-fuel energy depending on the site for electricity generation and on the power generation technology. It is evident that the production of such an amount of e-fuels is out of the question in Switzerland due to space requirements and costs for PV electricity as well as very low FLH, which would lead to excessive investment costs for electrolyzers. Furthermore, it is hardly conceivable that about 12 nuclear power plants like Gösgen would be a realistic option (though perhaps in unpopulated areas other sustainability criteria can be met). Most appropriate sites would obviously be therefore those with high FLHs in extremely sunny or windy areas. In contrast to the Desertec concept, however, such installations should rely on substantial added value in the locations and countries considered, which means that H_2 and synthetic fuels (perhaps as 'syn-crude') would be produced on site.

Therefore, it is clear that production of such e-fuels cannot be dedicated only to Switzerland, but must be part of an international strategy that will gradually replace existing fossil fuel production infrastructure if it can create corresponding markets also for transport and distribution. Additional major requirements are the mobilization of financial means at very large scale as well as an appropriate 'geopolitical' framework for ensuring security of supply including diversification of sources. This means the establishment of a well coordinated international policy and cooperation is needed. On the other hand, new opportunities for technology-oriented companies would arise, since new infrastructures and businesses would be created.

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[6] Excluding energy consumption for transport of the e-fuels to Switzerland

Table 2. Alternative options for producing 39 TWh of e-fuels (22 jet-fuel, 17 H_2, representing the average of the ‘back-of-the-envelope’ scenarios of the current report), resulting in **90 TWh$_{el}$** of annual electricity demand. Installed peak capacities for power generation and electrolyzers and needed surface area depend on the power generation technology and on the production site.[7] In reality a combination of these as well as other pathways will have to supply the required fuels.

	Full-load hours	**Peak capacity**	**Surface area [km × km]**
PV in Switzerland	1100	82 GW	36 × 36
PV in Middle East	2400	37 GW	18 × 18
Off-shore Wind EU	4100	22 GW	64 × 64
Wind Patagonia	5800	16 GW	44 × 44
Nuclear	7500	12 GW	Extremely low

Referring to potential costs of e-fuels in 2050, **Figure 10** provides recent estimates for liquid hydrocarbons (Fischer-Tropsch, FT) and H_2 including transportation costs for different production sites and delivery to Germany (Fraunhofer IEE 2021). It appears that the lower production costs of H_2 are by large compensated by increased transport and distribution costs. The numbers have to be viewed with caution since learning curves for not yet commercialized technologies exhibit a certain degree of uncertainty. It can be observed that there is a large diversity of geographical areas and countries from which e-fuels can be sourced, meaning that the geopolitical risks can be mitigated to some extent. Furthermore, the estimated global potential of e-fuel production is 57,000–69,000 TWh (Frauenhofer IEE 2021). Since the Swiss population in 2050 is projected to be about 1000 times smaller than that of the world, a fair share of this e-fuels potential for Switzerland would be 57–69 TWh, which is in the range of the ‘back-of-the-envelope’ estimates for Switzerland (22–55 TWh). Nevertheless, the full deployment of this potential will certainly be quite a challenge.

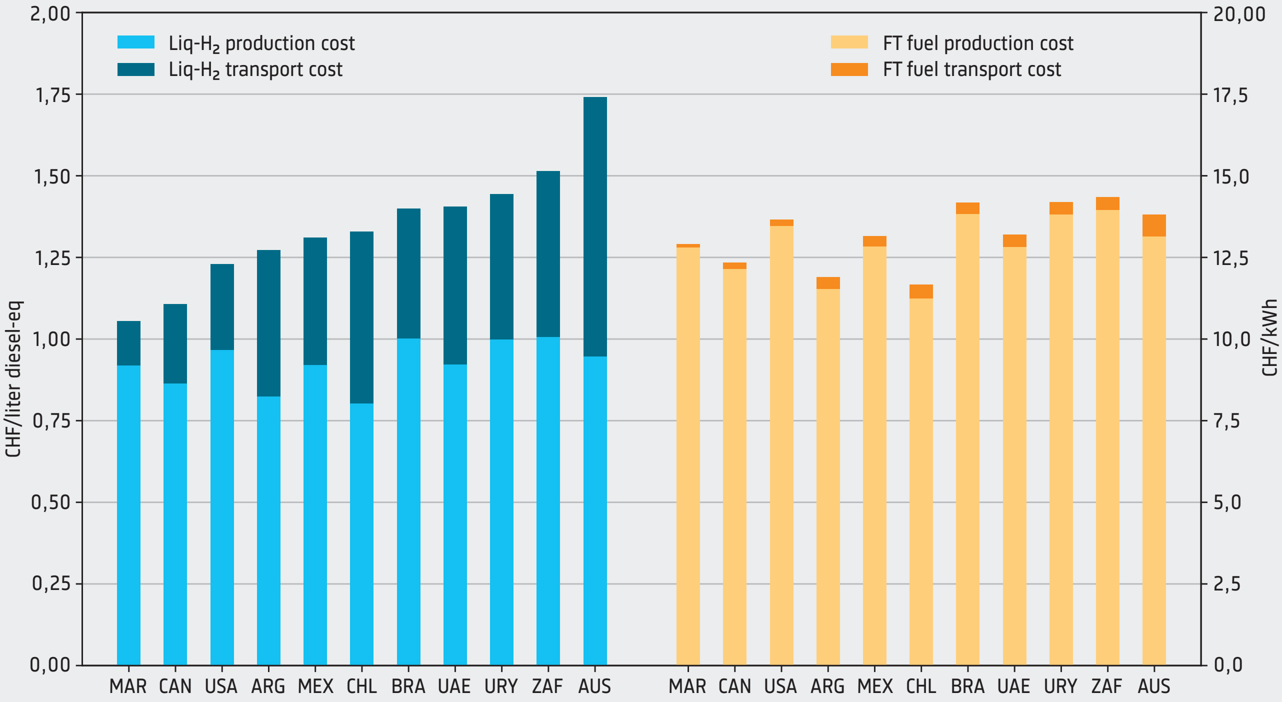

Fig 10. Production costs of liquid Hydrogen (Liq-H_2, on the left) and Fischer-Tropsch fuels (FT fuel, on the right) in suitable foreign countries and their total import costs to Germany in 2050. Left y-axis in CHF/liter of diesel-equivalent and right y-axis in CHF/kWh for both fuels (1 liter of diesel-eq = 10 kWh; 1 € = 1.04 CHF). The expensive transport of liquid hydrogen makes closer locations (like Morocco) much more convenient than further ones (like Australia) despite the similar production costs (Fraunhofer IEE 2021).

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[7] Sources: IRENA 2021, ESMAP 2020, WindEurope 2017, Fraunhofer IEE 2021, IEA 2020

Having said this, it is worth examining what the total costs of imported fuels for Switzerland would be in 2050 compared to today. In 2019 Swiss households and companies have paid for fuel imports around **7 bill. CHF** (BFE 2020b), the vast majority of which is fossil fuels and a smaller part from nuclear. Even in the 'Focus Balanced' scenario with 55 TWh of imported e-fuels and assuming an average cost of 1.30 CHF/MWh the total cost of e-fuel import would also be about **7 bill. CHF**. In addition, there will be imports of biomass and a higher electricity consumption by about 20% (~58 to ~69 TWh/y), so the total energy expenditures for Switzerland are expected to increase somewhat. On the other hand, the real GDP of the country is projected to increase by 38% between 2020 and 2050 (unpublished estimate of Seco, see BFE 2020a). Therefore, it can be expected that the overall energy costs per GDP for Switzerland will not substantially increase.

Notwithstanding these macroeconomic considerations, individual energy sectors like aviation and perhaps industry would have higher energy costs. On the other hand, the cost for fossil fuels is expected to increase substantially due to very high CO_2 prices around 2050 or to account for the required Carbon Capture and Storage (CCS) costs. Assuming the same fossil fuel price as in the near past (0.50 CHF/liter = 50 CHF/MWh) and a synthetic fuel cost of 1.3 CHF/liter (= 130 CHF/MWh, see Figure 10), these fuels will be competitive for a CO_2 price in the order of 300 CHF/tCO_2.[8]

Hurdles

- 30 years are an extremely short time for the imperative and unprecedented overhaul of the Swiss energy system.
- Sector coupling requires among others a close coordination between the electricity and fuel industries, with substantial redistribution of revenues and market shares between 'winners' and 'losers'.
- The potential for massive expansion of zero CO_2 power generation is difficult to exploit
- Technologies, markets and policy instruments for a cost-efficient worldwide system of supply of zero CO_2 fuels is at its infancy.

Actions needed

R1 (reduce demand):

- Contain the demand increase of energy and mobility services (in particular aviation).

R2 (ramp up efficiency):

- Exploit all efficiency increase potentials in buildings, transportation, industry and conventional electricity use.

R3 (replace):

- Close collaboration of national with international policy, at least with European policy (s. recent announcement of the EU-hydrogen strategy that includes also synthetic fuels and long-term storage).
- Management of lock-in effects and avoidance of stranded assets (for example investments in technologies that will be or have to be replaced) must be a key-priority of future energy policy; provide very clear corresponding signals to the business and investors community as fast as possible.
- Massive expansion of PV power generation at much higher pace than today (at least 1 TWh_{el}/year)
- Establishment of short-term storage (batteries in addition to already operating/planned pumped-hydro power plants) and enhancement of distribution e-grids.

Recommendations

- (H) Encourage/promote investments and international financial partnerships in new large-scale energy infrastructure worldwide.
- (H) In particular develop agreements with countries having large resources of low cost renewable electricity in coordination with large energy companies to establish a geopolitically resilient system of production, transport and distribution of synthetic renewable energy carriers worldwide.
- (H) Put in place policy instruments that encourage efficient use of low-carbon energy in all end-use energy sectors.
- (–) Internalize external costs of the Swiss energy system, while carefully considering interests of specific vulnerable segments of the population/economy at the federal level.
- (–) Joining efforts to enhance European collaboration in production, storage/conversion and transport of renewable electricity (policy; energy companies).

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[8] 1 liter of FT hydrocarbon leads to about 2.65 kg of CO_2 emissions

8 Negative emissions options

A 100% decarbonized energy system is very hard to achieve until 2050, and even more for some waste. The consequence of closing the remaining gap of residual emissions to the net zero GHG target is that some use of **negative emission technologies (NET)** will most probably be unavoidable.

Negative emission technologies include any process intentionally induced by human activity and reducing CO_2 concentrations in the ambient air, be it technically or biologically for example through afforestation. Therefore, carbon capture and storage (CCS) at non-biogenic point sources or carbon capture from ambient air combined with re-use (CCU) indeed reduce emissions and may replace fossil fuel use, but they do not reduce the ambient CO_2 concentration and therefore do not compensate for emissions that already happened, which would be the goal of negative emissions. While CO_2 capture from concentrated source is thermodynamically much more favorable than from air, even in the latter case the required energy per kg CO_2,[9] if coming from fossil-free sources, would release no more than 50 LCA-based gCO_2 emissions.

Some biological negative emission options like afforestation, wetland restoration or soil carbon sequestration have been practiced for decades to millenia, although not with the intention to remove carbon from the atmosphere (IPCC 2022). Most negative emissions technologies, however, are at an early readiness level, they are risky, costly, require significant new infrastructures, investments, and international cooperation. Moreover, they have significant socio-economic effects with many unresolved questions concerning governance (rules, regulations), justice, responsibility for financing, maintenance or any kind of side effects etc. In order to keep their life-cycle emissions low and thus the removal efficiency as high as possible, negative emission technologies also need to be fueled by low-carbon energy, e.g. from renewable sources. This introduces additional challenges related to technology innovation and business models but also in particular concerning social acceptance. Sensible choice of options and engaged dialogue and communication with key stakeholders and international negotiations will be important. Hence, negative emission technologies can be regarded only as 'last resort' technologies and used only to remove residual emissions from difficult to decarbonise sectors, but they cannot replace the other 5R actions (Figure 5, p. 8).

Main negative emission options are:
- Direct CO_2 capture from the ambient air by chemical processes and permanent storage underground or by chemical binding in rock formations (Direct Air Carbon Capture and Storage, DACCS).
- Biological fixation through the increase of biomass in plants or in the soil, e.g. through afforestation, reforestation, forest management, enhancing carbon content in soils through adaptation of soil management or the production and sequestration of biochar. However, these options can only be used once in a certain area and have to be maintained infinitely (if a forest burns or is cut, this will be like an emission of CO_2, unless cut wood is used in buildings and stored again for a long time). Thus, it only gives time to find permanent solutions (either emission reductions or permanent NET options like DACCS).
- Bioenergy, i.e. power or heat generation using biomass, in combination with point source carbon capture and storage (BECCS). Waste incineration plants with CCS also generate negative emissions, as about half of the material incinerated is biomass.

Other options are discussed, like enhanced geochemical weathering, wetland restoration or the carbonation of concrete aggregate using biogenic CO_2. The removal effect of ocean fertilization, which appeared to be a possible mechanisms, is now more or less abandoned.

The main requirement of negative emissions options is their permanency, i.e. the storage underground must be safe and possible CO_2 release only very small over long time scales, carbon content of soils has to be kept high constantly far into the future or additional forest must not be cleared or burnt later on (and otherwise be counted as new emissions). Mainly for biological storage, this is a difficult condition to assure and thus such negative emissions are rather uncertain.

Other problems relate to:
- Public acceptance e.g. of underground storage, ethical challenges or governance issues (these increase with international options): who pays for it? who is responsible for risks and side effects anywhere in the world, particularly, if the technology is implemented at a global scale? Control systems/certificates for permanence are necessary.
- Afforestation or BEECS, for which the technology is already available but both are often in competition with food production and might alter local or regional climate and involve high water consumption or other environmental impacts (some of them might also be positive). Also considering land use it has to be kept in mind that on the same area PV can supply about 40 times the amount of energy than the growth of biomass as energy source.
- High energy or water consumption: most technologies, especially direct air capture, but also measures involving cultivation and thus fertilizing, need a high amount

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[9] About 0.3 kWh_{el} + 1.7 kWh_{th} @ 100 °C corresponds to about 1 kWh_{el} (Fasihi 2019)

of energy, which also leads to CO_2 emissions if not coming from renewable sources.
- Upscaling: To be effective on a global scale, measures have to be implemented on a very large scale, where effects might be very different than at the small scale.

The DACCS method has on the one hand the advantage of allowing to decouple emission source and site of capture and it has less non-cost constraints than any other NET method (IPCC 2022). On the other hand, it requires much higher energy (though to a large extent at low temperature levels) and water input and at the current stage of technology costs per ton of captured CO_2 are much higher than CO_2 capture at the source. Development of DACCS methods is yet at the stage of pilot and demonstration units, but learning curves could be steep. As of 2021, there are some more than ten plants worldwide, with a scale of $ktCO_2/y$ or smaller (IPCC 2022).

Biological sinks have – besides the problem of permanency – the basic constraint of limited potential in the long-term. Area on Earth is limited, therefore forest areas or soil carbon content cannot be increased endlessly, which would be necessary if some carbon emissions cannot be avoided. For this reason, too, biological sinks can buy some time only for emission reductions but they are not a permanent solution to compensate unavoidable emissions. DACCS or BECCS are not limited as a process, because they can capture CO_2 for an unlimited period of time (while forest stops to bind CO_2 when mature), but there might be limitations in storage possibilities.

The potential for the main options of negative emissions in Switzerland is rather limited:
- The area for additional afforestation is not very large
- Swiss forests are among those with the highest carbon pools in Europe (in biomass as well as in the soil), i.e. to increase the C pool in forests is difficult, but there is a high risk of loosing them (e.g. due to climate change…)
- Agroforestry seems to be a promising option, but the potential is still uncertain
- Enhancing soil carbon is difficult: grassland are carbon sinks, but cultivations are carbon sources. However, to increase grassland means livestock farming which is itself more carbon intensive than agriculture.
- CO_2 storage in Switzerland is challenging: The storage potential in aquifers appear modest, but efforts to identify such appropriate locations are ongoing.

In the longer term every country has to reduce its territorial emissions as far as possible since compensation certificates from reducing emissions abroad will get rare when the world approaches net zero. However, international cooperation for establishing NET might make sense in the long-term but poses as well major challenges, e.g. concerning responsibilities. At least DACCS activities are in principal independent of location and can be placed near storage possibilites or at places with high renewable energy availability or even better both. Other options for negative emissions abroad are:
- Biological sinks: afforestation projects abroad are, despite being possible, very inefficient compared to the prevention of the still widespread clearing of primary forests, particularly rain forests and the prevention of draining peat soils.
- CO_2 storage: transport of CO_2 to one of the large storage hubs that will be established by the European Commission in collaboration with the Norwegian government in the North Sea might become a valuable option, since CO_2 has already been injected at a scale of million-ton CO_2 per year for more than 20 years successfully and safely there. These projects are supposed to make storage volumes available to third parties from 2023 on. However, under which conditions and at which prices sufficient storage volumes for the needs of most European countries will be created is difficult to estimate and needs international negotiations as well as an appropriate and cost-affordable CO_2 transport infrastructure (see gas grid in chapter 5, p. 22). If CO_2 prices will increase enough, also market mechanisms might contribute to exploitation of NET.

Hurdles

- Uncertain permanency of storage options (especially biological sinks).
- Public acceptance, ethical challenges and governance issues.
- Low technical maturity of DACCS.
- Competition with food and possibly bioenergy production and other environmental goals and potential environmental impacts of biological sinks.
- Limited potential in Switzerland for biological sinks and carbon storage.
- Large upscaling at a global scale is needed, with high risks and unknown side effects at that scale.
- Avoidance of possible ‘cheating’, like double-counting, adding avoided and removed emissions.

Actions needed

R5 (remove):
- Further development of DACCS technologies (Switzerland is currently in a leading position).
- Contribute to the establishment of an international accounting and governance framework for NET, based on scientific grounds.
- Analyse potential challenges of international negative emission and carbon storage as well as CO_2 transportation options and possibly negotiate promising options.
- Establish a sound methodology for quantifying long-term effectiveness of all potential NET, based on Life Cycle Assessment.

Recommendations

- (P) Initiate and support research on NET (technical research).
- (P) Initiate and support research and a stakeholder dialogue on socio-economic issues like acceptance, governance, ethical and justice issues related to NET technologies (research).
- (P) Further quantify the NET potential of different options (research).
- (P) Although CO_2 storage and/or reuse will be probably necessary, it is most probably preferable not to rely on this path but rather see it as a kind of 'safety net' (policy)
- (–) Experiment with policy incentives for carbon capture (e.g. like tax credits in U.S.).
- (–) Initiate early enough discussions and agreements on safety, liability issues with regard to international CO_2 pipelines.
- (–) Join and/or initiate international research, cooperation and negotiation concerning international or global governance and responsibility issues related to NET activities, (policy).

Carbon capture (CCS) for mitigation

As mentioned above, carbon capture and storage at non-biogenic point sources is an option for reducing emissions, which is technically much easier and therefore much more efficient than negative emissions. Among those are:

- In Switzerland, concentrated emission of CO_2 fit for point source carbon capture and storage comes from cement manufacturing (3 to 6 Mt CO_2), waste incineration (3 to 6 Mt CO_2) as well as (at much smaller scale) sewer and biogas plants, with a realistic total counting to about 15–20% of annual Swiss CO_2 emissions. Related capture technologies 'off-the-shelf' do exist but storage potentials are limited (s. above).
- Reuse of CO_2 to produce chemicals may be optimal from the point of view of sustainability but overall cycle efficiencies are very low, electricity demand is very high and costs well above those of fossil fuels. From a thermodynamics point of view, production of H2 has a higher efficiency compared to synthetic hydrocarbons; these offer however the advantage of very low 'downstream' distribution costs due to the existing distribution infrastructure and easy adaptation to the end-use devices.
- Use wood primarily as building material and not in the short term for energetic purposes. A Swiss study from WSL has shown that the largest carbon storage can be achieved when forests are exploited, the wood is used in buildings (carbon storage) and at a much later time is burnt in power plants to produce heat and power.

9 Closing material cycles

The closure of material cycles is highly relevant for the energy system in three aspects:

1. The prevention of waste in the first place
2. Recycling/reuse of materials embedded in the components and infrastructure of the energy sector, which usually reduces the amount of 'grey' energy invested in the energy sector (and recycling/reuse of material in general lowers the energy demand of primary materials)
3. The use of municipal and industrial material as a source of electricity and heat on the basis of its calorific value – with trade-offs between that use and the desirable recycling or prevention of that waste

The anticipated future evolution of the global energy system, characterized by an increasing share of renewables in the primary energy, leads already now to a growth of demand for precious, rare materials. Since their mining and processing not only requires a significant amount of energy but often has severe negative environmental impacts, it is even more important to minimize their waste in the future.

Sourcing of these materials may be subject also to geopolitical constraints and corresponding diversification strategies must be developed with long-term fair trade agreements with the countries of origin.

While the energetic use of waste is advantageous for the domestic energy sector, the main effect of recycling and reuse refers to the countries involved in mining and processing as these typically take place abroad.

The energetic use of domestic waste in Switzerland is relevant (with a heating value potential of 15-20 TWh) and can increase in the future (from about 5 TWh heat and electricity gain today), if the efficiency increase potential can be exploited through a) favorable incinerator sites with large heat demand like in industrial plants or b) in district heated networks and allocation of waste of high energy content to power plants with largest energy recovery efficiencies (Haupt et al. 2018). However, power generation from waste is inefficient. For example separate collection of wet biomass and biogas production independently from waste incineration could increase the efficiency, and there is a large untapped potential to use manure energetically via biogas (Burg et al. 2018).

Furthermore, waste prevention is even more effective than the improved energetic utilization of waste materials, with regard to CO_2 as well as energy use. Eliminating for example all avoidable food waste in Switzerland would lead to savings of more than 5 Mio. tons of GHGs (approx. 10% of Swiss emissions), which is about 10 times higher than the related savings potential based on the energetic use of waste (Beretta et al. 2017). However, rebounds (impacts from spending the money saved through food waste prevented) could partially offset the environmental benefits from waste prevention.

For technical products, an improved product design is needed that facilitates an automated, widely applicable recycling process and thus the direct reuse or material recovery. This requires to avoid the mixing of different materials and the use of hazardous substances as far as possible (Wiprächtiger et al. 2020)

Actions needed

R4 (recycle):

- Targeted technology development for improved product design and waste prevention.
- Develop technology design that facilitates material separation of compound elements when recycling; this includes banning hazardous substances from products, which represent a barrier to recycling (for example flame-retardants in thermal insulation or hazardous additives in plastics).
- Clean source separation and waste prevention, which involves important behavioral aspects that must be addressed through socioeconomic and policy measures (information, support, incentives, legislation).

Recommendations

- (H) Prevent waste where possible
- (P) Improve product design:
  - Design products in a way that facilitate direct reuse or material recovery.
  - Align product design where possible to avoid a mixing of different materials and enable automated, widely applicable recycling processes.
  - Avoid the use of hazardous substances where possible.
- (–) Determine the environmentally most beneficial value retention process and treatment option for each waste stream via Life Cycle Assessment, and provide incentives to implement the most sustainable option.

10 Digitalization

Digitalization with regard to the energy system transformation supports the management of increasing complexity and offers a large potential for needed changes. Digitalization can be structured in three main domains (see Figure 11): a) physical measuring equipment, i.e. sensors, linking the physical to the digital world also referred to as digitization; b) energy data infrastructure, i.e. storing, processing, transmitting, connecting and accessing different data; c) market applications, i.e. control and automation of process, reduction of current market barriers and transactions costs, new value generation and consumer empowerment. Cyber security plays an important role as an overarching domain. Digital technologies, such as Cloud Computing, Distributed Ledger (DLT), Application Programming Interfaces or Machine Learning/Artificial Intelligence (SFOE 2019, SBFI 2021) can typically be allocated to one or even more of these domains.

Digitalization affects the whole energy system holistically (Galus 2019). It has strong impacts and the different sectors (chapter 4), networks (chapter 5), storage (chapter 6) as well as sector coupling (chapter 7) and negative emission technologies (chapter 8). Digitalization offers the great potential to interconnect these energy domains and optimize planning and operation based on digital measurements, analysis and control (IEA 2017). As ubiquitous sensors provide data based on internet-of-things technology, insights are generated by interconnecting data sources and analysis based on novel techniques like data science. Based on such analysis, optimization potential is identified, decision making is supported and automation expanded through machine learning and artificial intelligence in every part of the energy value chain (Zhou et al. 2015).

Moreover, digitalization will also change how energy markets function today. Digitalization pushes forward platforms (Becchis 2019) and puts the consumer into the center. Currently, most energy markets lack consumer involvement as they are dominated by oligopolistic structures with little transparency (Fehrenbacher 2016). Obviously, digital technologies like DLT bear the promise of change adapting centralized market structures to a decentralized nature of the energy system. An example are peer-2-peer markets with no intermediaries, which hence put consumer in charge of producing and trading energy (Zhang 2017). As such decentralized market structures need careful coordination with energy networks, information technology, data exchange and automation become crucial in networks, i.a. smart grids (Heer 2018, Montero 2019).

Pay attention to

- Energy demand of digitalization (there are only few studies (e.g. Andrae & Edler 2015) estimating the increase of electricity demand due to digitalization, with huge uncertainties) which contrasts possible efficiency gains through digitalilzation (Fraunhofer 2019). The

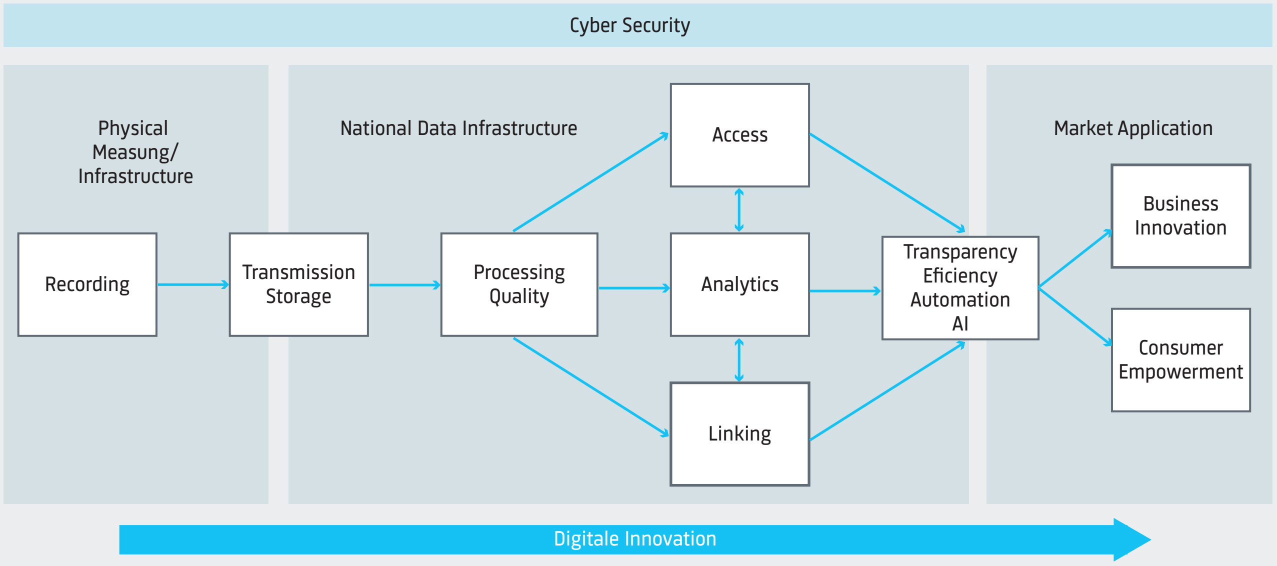

Fig. 11: Conceptual model for digitalization (SFOE)

balance largely depends on the emissions of electricity production (Bitkom 2020).

Hurdles

- Missing interconnection of and limited access to data collections in the energy sector.
- Reliable and good quality data at a national, cantonal or community level.
- Lack of monitoring and automation in distribution networks.
- Concerns on privacy and cyber security as well as complexity of their management.
- Missing interoperability between digital products and product platforms.
- Lack of transparency in energy markets and energy infrastructure management.

Actions needed (Thema 2019)

- Establish standardized interfaces and foster data exchange as well as automation between data silos, i.e. build and strengthen a national energy data infrastructure.
- Make more data of the energy system publicly available from involved stakeholders on national, cantonal and regional level (open data).
- Create a national energy data space where consumers can actively exert control.
- Increase transparency delivering more insights into parts of the energy value chain.
- Community building in the area of standardization and interoperability.

Recommendations (Thema 2019)

- (–) Create a regulatory framework in order to build up a national energy data infrastructure that is neutral and allows consumers to control their data (Becchis 2019).
- (–) Establish guidelines and regulations for utilization of data (traceability, transparency, operator of data infrastructure, access of data, etc.).
- (–) Foster more open data in the energy system (aggregated data of public interest like grid/capacity/workload data or data on cantonal/community level on energy production/demand/prices).
- (–) Strengthen cyber security for a more integrated and digitalized energy system.

11 System change and transition pathways

The path toward net zero GHG emissions requires major changes in existing systems such as electricity, transport, heating, industrial production and consumption patterns (Markard 2018). Such changes are referred to as sustainability transitions (Köhler et al. 2019). Experiences have shown that transitions can take several decades and are often confronted with substantial resistance. In the case of climate change, we are running out of time. We have to react swiftly and profoundly because negative impacts and costs accumulate the longer we wait. This chapter highlights three characteristics of low-carbon energy transitions that are important for accelerating the transformation.

First, technical changes and non-technical changes are closely intertwined, e.g. technical changes also imply social changes. Transitions include new technologies, e.g. around wind and solar energy, batteries, electric vehicles or hydrogen and synthetic fuels. These technological changes, however, are accompanied by transformations in business models, supply chains, markets, policies, regulations or standards. For the low-carbon transition, very importantly also consumption practices, lifestyles and social norms will have to change. Studies have shown that standards and expectations around indoor comfort can be contested {Sahakian 2021). New forms of work and communication may reduce mobility needs. New design practices and information services may help to create circular material flows, and new cross-sectoral business models may improve the flexibility of energy supply.

Second, transitions involve innovation and decline, winners and losers. While the role of innovation is widely understood and accepted, decline tends to be overlooked. Decline is about shrinking markets and industries, and it might also include the deliberate phase-out of specific products, or technologies. For example, we want to speed up the replacement of oil heating systems or conventional cars to make room for low-carbon alternatives such as heat pumps or electric vehicles. Phase-outs are of key importance for system elements with a long lifetime. Think of buildings, grid infrastructures, trucks, or ships (**Box 7**). For example, every fossil fuel heating system that is installed today, or every new car, will be used for the next 15+ years. The longevity of these and other assets makes systems slow to respond, which is why we might need technology bans or phase out policies (see **Figure 12**). Such instruments though may lead to stranded assets with severe consequences for investors in these assets.

Third, transitions are highly contested. Stakeholders hold different, often conflicting values with regard to climate change, clean air, energy prices, landscape, biodiversity or existing jobs and industries (Markard et al. 2016, Rosenbloom 2017). Incumbent firms, holding today's economic and political power often seek to protect their business models and they often have the resources to sway political processes in their interest. One arena where ideological or interest related conflicts become apparent is policy making. Carbon pricing policies and hence higher consumer prices, for example, have faced quite some resistance in the past. Moreover, in the Swiss direct-democratic context, the transition will even require a more explicit change in values and preferences, which enables to win political majorities among the population to introduce the aforementioned policies and regulations. In contrast to other countries, citizens need not only to accept the transition and related measures passively but more actively, for example in votings. Strategies to overcome resistance are to support the development and diffusion of low-carbon alternatives but also develop new ways to better inform, sensitize and engage stakeholders and a diverse population (in relation to urban/rural, age, gender, language, socio-economic status, etc.).

Once alternatives are visible, and new business opportunities exist, it is possible to form strong alliances in favor of a next generation of (more stringent) policies such as those that target decline or more radical innovation. To accelerate the low-carbon energy transition, we need a mix of policies, stimulating both innovation (for example through subsidies or emission standards) and manage decline (for example through accompanied technology bans or phase-out policies). Policies to manage and incentivize the decline of incumbent technologies must address challenges associated with financial interests of long-term investors and, in particular, negative socioeconomic impacts on jobs and employment.

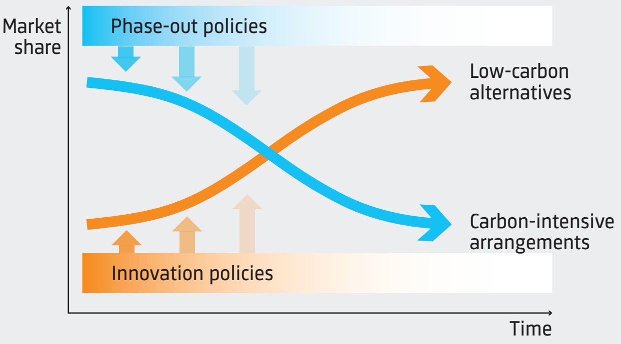

Fig. 12: Schematic representation of a key strategy to overcome resistance against transition and system change (Graph: Jochen Markard)

The low-carbon energy transition will unfold differently in different places. Transition pathways will vary across countries (Geels et al. 2016, Lindberg et al. 2019) but also across sectors. Even when the goal is clear (for example net zero in 2050) the paths are not. There is high uncertainty about new technologies (for example hydrogen and synthetic fuels) and the strategies for different sectors (for example decarbonize cement production, use low-carbon building materials such as wood). However, these uncertainties should not be a reason to delay action.

In addition to political and business interests, transition pathways are also shaped by existing infrastructures, geophysical resources, and societal preferences:

- Existing infrastructures with life-times of up to 100 years for buildings create lock-in effects where the corresponding techniques and energy infrastructure is fixed and a replacement out of a normal renovation cycle needs extraordinary investments (s. Box 7).

– Pathways of individual countries depend on history, available resources and ‘game changing events’: Norway, for example, with its vast hydro-power resources, decided to further electrify transport. Germany, in contrast, has decided to massively expand generation from wind and solar. Switzerland can draw lessons from both cases, due to its favorable position regarding hydro-power, while also facing challenges with expanding wind and solar.
– Societal preferences play a major role in the development of pathways, especially in the direct democracy of Switzerland, where at least half of the voting population has to be convinced of the chosen political actions and measures. The development of worldviews and social norms will be crucial here. This is difficult to steer, but with appropriate instruments they might be influenced.

More concretely the Swiss energy system is already following a transition pathway, characterized by an increasing demand for transport services, a reduced one for buildings heat, a gradual replacement of oil products by natural gas and in particular heat pumps in the heat sector and continuous reduction of energy related atmospheric pollution. Wind and solar electricity show declining costs, the electric vehicles market share is on the rise. We see established business models under pressure, an increased orientation to energy services rather than selling products and an increasing role for ICT and digitalization. These developments are, however, rather gradual and their pace is by far insufficient for meeting the net zero goals. A strong acceleration of these, in principle mostly positive, trends is absolutely necessary. As Box 7 indicates long life-time of crucial energy related assets create significant system inertia with respect to the required pace of transformation.

Box 7: Lifetime of exemplary energy assets

- Buildings in Switzerland: up to 100 years
- Energetic renovation cycles: 40 to more than 60 years (and beyond)
- Cars: 15–20 years
- Ships/airplanes: 25–30 years
- Power generation plants: 25–50 years
- Refineries, e- and gas-grids etc: more than 50 years
- Configuration of industrial/manufacturing processes: diverse, but for some more than 20 years

Hurdles

– Knowledge of problems does not necessarily lead to problem solving action.
– Technological and non-technical changes do not develop hand in hand or at the same speed.
– Long lifetime of major assets, including large-scale infrastructure.
– Conflicting interests between incumbent businesses and newcomers.
– Difficulty to phase out fossil fuel related industries and established products.
– Policies are perceived as costly, mainly in the short-run, by e.g. threat for existing jobs, increased prizes and uncertainty.
– Change needs additional effort; there are many possible arguments against new climate policies.
– Lack of consistent long-term policy signals; long-term effects are not taken into account for today‘s decisions.
– Lack of policy attention to managing the required decline of carbon intensive technologies.
– A fragmented and partially incoherent set of policies at regional (cantonal), national and international levels.
– Potential conflicts with other environmental and/or sustainability goals.
– Decisions on investments are not based on full costing (including external costing).
– Changes cannot only be left to individual decisions, collective action is an important driver.

Actions needed:

R1-R4:

– Foster societal consensus for low-carbon transition by dialogue, objective knowledge generation, education and communication and develop binding long-term policy targets.
– Implement comprehensive policy mixes that target innovation and manage decline.
– Adapt policies to specific sectoral circumstances and to the progress of the transition (for example the maturity of alternatives).
– Account for questions of social justice in the transition, including rural/urban divide, socio-economic, age and gender diversity.
– Continuously monitor and adapt policy mixes (policy learning).
– Ban carbon-intensive technologies where mature and low-cost alternatives exist (for example heating with oil).
– Foster and support occupational retraining of workers from technologies that will disappear to new technologies that expand rapidly.
– Create strategic alliances and strengthen the voice of those businesses and industries that benefit from the transition; show the potential for new, high-qualified jobs.
– Experiment with new financing tools for low-carbon innovations (e.g. venture capital competitions, research prizes and crowdfunding platforms) to attract new types of investors and support startup companies (Gaddy et al. 2016).
– Experiment with, showcase and promote new practices and lifestyles (ideas and social norms).
– (Re)design urban and infrastructure planning processes.
– Evaluate synergies and trade-offs of actions with other sustainability goals.

Recommendations:

- (P) Formulate long-term predictable/foreseeable (intermediate) transition targets with specific goals and milestones for different sectors (for example emission trading [ETS] caps).
- (–) Increase acceptance and feasibility with field experiments.
- (–) Adapt policy (instruments) to the different stages of the transition, use flexible instruments that adapt to the stage, account for societal justice.
- (–) Identify and support people in declining branches (retraining etc.).
- (–) Provide information and enhance awareness on financial risks of stranded assets.

12 Policy options

The main objective of a targeted energy policy should be in compliance with the Paris Agreement and the net zero GHG goal of the Swiss Federal Council as well as in alignment with other SDGs. Also the recently announced EU policy and strategy developments (European Green Deal, including compliance with SDGs) should be taken into account as well. Related legislation, however, should be in accordance with other sustainability goals. Policy decisions addressing other environmental impacts like air or water pollution have proven to be effective and well accepted by citizens and business in Switzerland and most other European countries. The challenge to implement a successful climate mitigation oriented policy, however, is of a much larger, i.e. global, dimension and cannot be solved by one country alone. On the other hand, the clear engagement of every country is needed nevertheless, especially from rich countries like Switzerland as a role model. Until now, a number of policies have already been successful to a certain extent. The CO_2 tax for fossile heating fuels was introduced at low levels and increased several times if objectives were not met. It allowed to decrease fossil heating fuel consumption over time.

In the following we discuss the policy options for Switzerland with focus on the energy system as the dominant greenhouse gas source and the abatement of CO_2 as the by far most important greenhouse gas.

As discussed in the chapters before, when designing a policy portfolio, a lot of interdependencies and tradeoffs – like the shift to electric cars increasing electricity demand substantially – and hurdles, as for example the lock-in effects in infrastructure, have to be considered. In addition, preconditions and characteristics for emission reduction measures for mobility, the building sector, different industries and household/consumption are very different and need to be taken into account at the same time. Moreover, a number of important sector coupling concepts (e.g. fuel-electricity-storage) have to be incorporated. And last but not least, economic interests and incentives, social developments and behavior as well as acceptance of measures will be pivotal. Therefore, a carefully designed mix of different instruments adapted to the different circumstances, taking into account their diverse advantages and disadvantages (see Swiss Academies 2019), will be necessary.

The current mix of policy measures suffers from a lack of a coherent long-term decarbonization strategy over all sectors (including sector coupling) and thus does not provide the necessary planning reliability for investors and economy. There are political efforts to address this problem by defining concrete reduction paths until 2050, but currently there is only mid-term predictability in isolated measures. This situation may be partly due to the complexity and diversity of energy sectors and partly due to the difficult coordination among policy makers and other stakeholders at regional, cantonal and national levels.

The set-up of adequate sector specific instruments faces a number of challenges:

- In the **buildings sector**, insufficient consideration of Life-Cycle-Costs by individual owners and limited energy financial awareness yield to – from a long term societal perspective – inappropriate decisions on renovation cycles; the same applies to the split incentives problem between landlords and tenants. The set-up of standards might hinder the choice of the solution that is most appropriate for the location circumstances. In addition the housing sector is mainly regulated on the cantonal and communal level which are difficult to coordinate. Moreover, demand reduction also depends on the willingness and behavior of residents, which is difficult to influence. The diffusion of smart energy meter technologies providing direct feedback to consumers on their energy use may mitigate behavioral issues in the future but faces as well data privacy concerns, and long term energy reduction is not assured.

- **Industrial processes** are of very diverse character and since the sector is to a certain extent internationally 'mobile', issues of competitiveness depending on energy costs must be carefully addressed, at least as long as the international legislation is quite heterogeneous in this respect. The implementation of the European Emission Trading System (ETS) for energy intensive industry and the power generation sector, as well as the possible implementation of carbon border tax at EU level, are nevertheless promising instruments to improve this situation. For some industries (especially the cement industry), adequate mitigation technologies are still missing.

- Since the acceptance of price signals in the **individual mobility sector** is very low despite the very small share of fuel to the total ownership costs of cars, high CO_2 prices would be necessary in order to change consumption and vehicle choice patterns. Emission standards as already implemented should be further improved to complement price signals. Since it makes sense to take over the emission standards set in the EU, which comprises major car manufacturing countries, there is no reason for the current weakening of these standards through exceptions and dampening fleet calculations. Standards are only effective if exceptions are kept to an absolute minimum, if obeying the rules is strictly controlled and if non-compliance is adequately sanctioned. Attention has to be paid however to some perverse incentives: Assigning a zero CO_2 emission to electric vehicles and even more double or triple counting the share of electric vehicles in the overall standard of a fleet may lead to an unjustified competitive advantage of oversized, overpowered electric vehicles, which consume much more energy and emit much more CO_2 emissions in reality vs. legislation. Moreover, electric vehicles will also have to contribute to infrastructure costs somehow. The replacement of the tax on mineral oils is started to be discussed in Swiss parliament. An additional issue is the still high symbolic value attributed to car ownership.

- Though legislation based on **norms and standards** (like the limits of CO_2 per km for cars and vans/lorries) are better accepted than CO_2 levies, from an economic point of view they are estimated to impose higher costs on society than market based instruments, and they address only part of the problem, merely providing incentives for manufacturers to adjust their product portfolio. They are not useful though for steering demand in travelled distance per person as they do not influence operational costs. Similar inadequacies result from cantonal legislation on annual car ownership taxes, which are fixed costs. It would be much better (and meanwhile easy to implement) to reshape these as taxes on consumed fuel or energy, respectively, to increase the share of total costs. In this way fuel cost as part of the variable costs influence the decision of travelling by car or not more directly.

- In the **electricity sector**, the current remuneration of grid services (in ct/kWh) will be inappropriate, when (and if) decentralized generation and own consumption increase substantially because prosumers will be subsidized, if they do not bear the costs for such services. Only a regime transition to a price per guaranteed bidirectional power (in kW) will provide the right incentives for grid operators. In addition, existing market mechanism to reward 'power generation on demand'capacities do not provide appropriate price signals to a part of consumers/prosumers.

As already pointed out, the implementation and success of policy measures will largely depend on the perception, reaction and feedback from the side of diverse stakeholder groups, political parties, industry and citizens, in brief, the whole society (Dermont et al. 2017). One can distinguish between market, socio-political and community acceptance (Wüstenhagen et al. 2007). Market acceptance is influenced on the one hand by measures taken to compensate at least partly for negative effects for certain strongly affected branches but also by the broad public opinion on the necessity of climate change abatement and the necessary image cultivation of market participants. Therefore, a key question will be the acceptability of such policy measures, since virtually all present or planned policies assume that their implementation will achieve the emission abatement targets (Baranzini et al. 2017).

Socio-political and community acceptance is influenced by a) social-psychological factors and climate change perception; b) the perception of climate policy and its instruments; and c) contextual factors like the wider economic or political environment (Drews and van den Bergh 2016), in particular the post-pandemic and ukraine-war economic crisis. Thus, the frequent perception by the general public of environmental taxes being ineffective (Kallbekken & Sælen 2011) has to be addressed by the clear earmarking of revenues for environmental purposes (Dresder et al. 2006), the redistribution of revenues to consumers (for instance by lowering income or labor taxes) or by providing convincing information on the environmental effectiveness of a carbon tax, or a combination of those. The latter also reduces the demand for environmental earmarking, but generates a demand for using the revenues for social cushioning (Carattini et al. 2017). Two other points are very important – as shown by the results of extensive Swiss research activities:

- **Supply side:** early and continuous stakeholder and public engagement in the innovation process and when planning and siting infrastructure to build trust (Stadelmann et al. 2018, Huijts et al. 2012). Such engagement includes transparent information and an open dialogue on citizens' concerns, including the engagement of citizens already in an early or planning phase. Such processes should become legally binding, as the requirement of formal consultation and allowing for legal action already is (Chilvers et al. 2018).

- **Demand side:** informational measures to reduce or temporally shift energy demand which implies fundamental shifts in behaviors, practices, social norms, lifestyles, etc. (Filippini et al. 2019). The focus on conscious behavior shifts will not suffice but habitual behavioral patterns and related social norms rather need to be broken up. Essential for the success of interventions to reduce energy demand are the joint setting of goals, social exchange in groups, regular feedback and community building as well as to take into account the interaction between new technological artefacts, social norms and individual capacities (Abrahamse et al. 2005, Shove 2010). This can be achieved for example by experimenting in the field, living labs, real world labs, transition experiments with novel practices or by people experiencing new ideas and thus enabling an experiential and transformative learning process (Luederitz et al. 2017). A great potential lies in the close collaboration between public and private agencies when implementing informational measures (Moser et al. 2018).

Policy Options for the future

Market-based methods (such as a CO_2 tax) are economically effective instruments to reduce emissions and internalize the external costs of energy use (**Figure 13**). Simulations show that to reduce CO_2 emissions to one ton CO_2 per Swiss inhabitant in 2050 (which is a 76% abatement with respect to 1990 emissions levels) it is necessary to implement a steadily increasing, universal CO_2 tax for all sectors with a rate between about CHF 250–330 /tCO_2 in 2030 and reaching CHF 1500 and 2500/*tCO_2 in 2050. In the transport sector this is equivalent to a tax of CHF 0.60–0.75 CHF in 2030 and CHF 3.50–5.75 in 2050 per liter gasoline. It is important to note, that we expect only few fossil fuel powered cars in 2050, hence this tax will be payed by very few people only. Interestingly the level for 2050 exceeds the cost range of synthetic fuels expected around 2030. The remaining CO_2 mitigation to achieve net zero levels will obviously lead to even higher marginal costs as the related sectors (for example aviation and some industries) will be extremely difficult to decarbonize. If revenues are refunded back to households, the welfare costs can be limited to 2% of household consumption in 2050. Nevertheless, such tax levels would lead to substantial social redistribution effects and economical disadvantages for certain industries which have to be compensated to a certain extent (Babonneau et al. 2018, Bretschger & Zhang 2016).

Taxation of fossil energy carriers can be justified via-a-vis the voting population, if external costs of such fuels can be quantified and convincingly communicated. Box 8 illustrates the estimate of such costs on example of the Transportation Sector (ARE Report on external costs 2021). Also, the offer of reasonable alternatives for the rural area like e-car-sharing programs might increase the acceptance.

Box 8: Example of external costs in Transportation

External costs of transport modes (ARE 2021)

- Total external costs of Transport Sector 13.7 billion CHF
- Specific cost per unit transport service (pkm = passenger-kilometre; tkm = ton kilometre)

People
Road: private 7.8 Rp/pkm, public 6.6 Rp/pkm
Rail: 3.5 Rp/pkm
Aviation: 2.5 Rp/pkm

Freight
Road: 6.5 Rp/tkm
Rail: 4.5 Rp/tkm
Aviation: 8.5 Rp/tkm

However, market instruments will not be sufficient to reach the zero emission goal due to the low acceptance of sufficiently high carbon prices, and as discussed above, a carefully balanced set of policy instruments taking into account the peculiarities of the different sectors and societal preferences is necessary.

Hurdles

- Substantial increase of electricity demand through implementation of the main decarbonization options (electrification of cars, heat pumps, synthetic fuels).
- Lock-in effects in infrastructure, low renovation rate of buildings.
- Provision of the necessary planning reliability for investors and businesses.
- Insufficient information on life cycle costs and technical options of individual actors for the public.
- Some regulations and standards on cantonal and communal level for buildings might be in conflict with overarching national goals.
- The landlord/tenant problem in building renovation.
- Low acceptance of CO_2 taxes for individual mobility.
- Norms and standards foster continuous product improvements but do not steer the demand (in travelled distance per person or weight haul distance – pkm/tkm)
- Lack of reward for ‘on demand’ provision of electricity or storage capacities.
- Strong opposition from affected stakeholders against policy-driven early phasing-out of emission-intensive infrastructure, including claims for substantial financial compensation.
- Dependence on societal world views, which have their own dynamics and can hardly be steered.
- Possible disadvantages for low-income households which have not the money to switch technology.

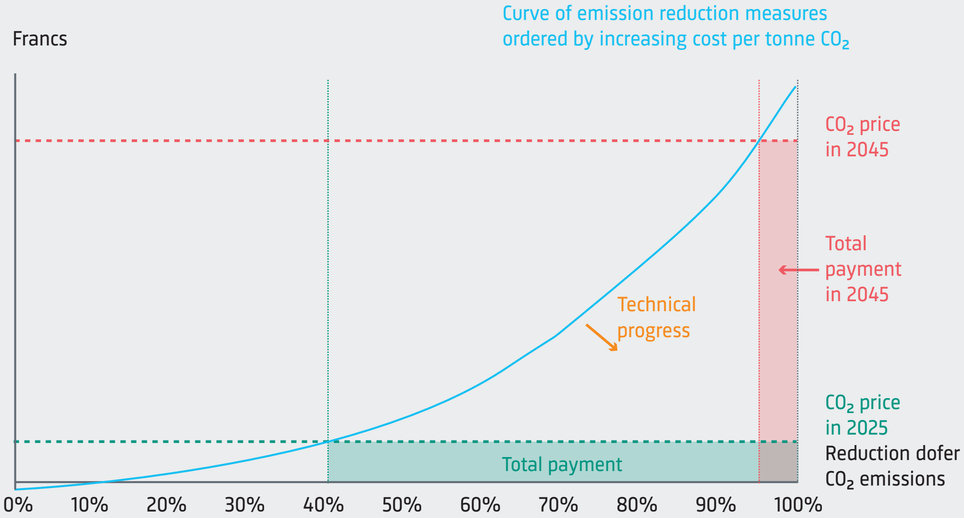

Fig. 13: Dynamic perspective on CO_2-reduction based on an increasing CO_2-price over time. The x-axis shows the percentage of eliminated emissions, the y-axis the CO_2 price. It is assumed that low cost measures are taken first (because they are economically viable), measures with highest costs only at the end. Emission reductions are realized when the CO_2 price is higher than the reduction costs. Technology Innovation will be important for lowering the mitigation costs and therefore the necessary CO_2 price, in particular for currently very expensive measures. It has to be noted that in the short-term, low prices will have to be paid by many; on the long-term high prices will only be paid by very few emitters. Note that the cost curve might look very different for different sectors: While the technological innovation and market penetration of photovoltaics has led to competitive prices and therefore comparatively low cost and this development is foreseeable for electric cars, decarbonization for aviation is quite far away and we are still in the beginning of technological development. (Graphic: Philippe Thalmann)

Actions needed (s. Fig 13)

- Increase the price/tax per CO_2 unit gradually to entail that a growing share of sustainable energy provision methods pass the threshold of net-profit even at the current state of technology. The perspective of increasing CO_2 prices will not only stimulate research and development in order to bring the costs of currently expensive CO_2 mitigation technologies down but also discourage investments in high-CO_2-footprint processes. Even at a constant technology performance a gradually increasing CO_2 price will lead on the short-term to small additional payment by many consumers, while on the long-term a large price will be paid by few.
- Address the missing awareness of individuals of life-cycle costs and corresponding savings related to investments in buildings or cars to foster the harvesting of the ‘low-hanging fruits’.
- Use nudges (method to influence the behavior of people without prohibition, command or economic incentive, for example make low-carbon consumption choices a default position by specific presetting of desired choice in selection processes).
- Enhance the technological and socioeconomic innovation capacity of the country (research and development over the whole chain) so that currently ‘too expensive’ products and services become competitive over time through steep learning curves with massive cost reductions and performance improvement. This decreases the height of a necessary CO_2 price.
- Subsidize research and product development for promising emerging technologies to enable a scale-up and corresponding learning curves so that their economic viability is enhanced fast enough (Acemoglu et al 2012).
- Create new financing schemes (for example venture capital finance, crowdfunding) to promote the development of new low-carbon technologies.
- Improve the acceptance of policy measures through a broad public dialogue on their impact on society, environment, earmarking of the revenues for environmental purposes or social/location-related cushioning.
- Improve the acceptance of new technologies through early and continuous stakeholder and public engagement in the innovation process and when planning and siting infrastructure.
- Enhance interventions to reduce energy demand involving social interactions like joint setting of goals, experimenting in living labs or transition experiments with novel practices with people experiencing new ideas.

Recommendations (Actors):

- (P) A gradual predictable increase of the price/tax per CO_2 unit (policy); it is important to use CO_2 levy incomes to support people who have not the (financial) possibility to adapt (policy).
- (P) Prefer emission standards instead of technology standards (policy).
- (–) Improve the awareness of individuals of life-cycle costs and corresponding savings related to investments in buildings or cars (polices).
- (–) Improve dialogue with the public on the effectiveness of policy measures (impact on environment, etc.) (policy).
- (–) Consider prescribing stakeholder and public engagement when planning and siting infrastructures, encourage financing schemes with sharing revenues with local population (policy).

13 Conclusions and recommendations

For a successful transformation of the Swiss (and global) energy systems towards climate change mitigation and sustainability in general a coherent but flexible portfolio of actions will be indispensable. These should be embedded in a **consistent long-term strategy** that should be based on the following pillars and targeted at specific stakeholders. These actions are based on the following *principles* (relating recommendations are given in brackets):

a. **Long-term predictability with certain flexibility (path to reach targets & monitoring):** To reach the target of net zero GHG emissions in 2050, a clear predictable reduction path comprehending all emission relevant sectors and transparent monitoring are key elements. Such a path that includes the development of necessary regulations, emission thresholds, tax levels etc. is also very important for economy and investment security. However, a certain flexibility might be needed, e.g. to relate strengthening of regulations to the development of emission reductions and arrival of new technology.

   [1 (CO_2 price), 2 (standards), 4 (electricity demand)]

b. **Mix of policy instruments:** Find a balance between steering policy instruments, including levies, and subsidies, although the former are economically more effective than the latter, and between redistribution vs. use of subsidies for environmental purposes. Adapt policy instruments to the different stages of the transition, use flexible instruments that can be adapted to the stage. Engage in a public dialogue about benefits of a transparent redistribution of collected charges to society; pay thereby attention to fair access for energy services and distribution of policy burdens on socioeconomically weaker segments of the population.

   [1 (CO_2 price), 3 (efficiency), 9 (financial), 10 (information), 11 (education), 13 (spatial planning)]

c. **Prefer standards over technology prescription (instruments, research & innovation):** Regulations and laws should in principal not prefer or exclude technologies, i.e. emission thresholds or standards should be preferred to prohibition.

   [2 (standards), 3 (efficiency) 12 (LCA), 14 (research)]

d. **Ensure competitiveness and security of supply:** When introducing or changing regulations, incentives or taxes, impacts on international competitiveness of the concerned actors and the implications for the security of energy supply should be considered

   [2 (standards), 4 (electricity demand), 5 (storage), 7 (EU cooperation), 8 (import), 14 (research)]

e. **Consider social aspects:** When designing policy instruments and emission reduction paths, social aspects like inequalities and distributional effects, early and continuous stakeholder and public engagement, acceptance by people, dialogue with population, taking concerns by population serious, awareness or necessary education are key for their effect and outcome.

   [1 (CO_2 price), 3 (efficiency), 10 (information), 11 (education), 12 (LCA), 13 (spatial planning), 14 (research)]

f. **International coordination and cooperation:** In several aspects, international developments and agreements/treaties will be crucial, especially in the electricity sector. Thus, corresponding negotiations and collaboration are an important part of decarbonization paths.

   [1 (CO_2 price), 2 (standards), 5 (storage), 6 (sector coupling/grids), 7 (EU cooperation), 8 (import), 14 (research), 15 (negative emissions)]

The following portfolio of *recommended actions* is complemented with possible target audience institutions in brackets:

1. **Implement CO_2 price mechanism:** Design and implement a predictably increasing CO_2 price mechanism with intermediate transition targets across all energy sectors, preferably through a market-oriented trading scheme (cap and trade) in agreement with international developments (e.g. integrate importers of fossil fuels in the ETS trading scheme – as has been done for aviation. In case of direct CO_2 pricing mechanisms (compensation regulations or CO_2 levy) avoid disadvantages for remote domiciles or low income households (e.g progressive redistribution; compensation mechanism for remote areas), to increase acceptance (▶ SFOE/FOEN, parliament)

2. **Set CO_2 emission standards:** Set continuously tighter CO_2 emission standards (to guide suppliers decisions) for buildings, mobility sectors, industry, electricity appliances; leave however the technologies to achieve them to the decision of market participants, thus being ‘agnostic’ to concrete innovation alternatives. Adapt these limits regularly according to technological development, preferably done via associations like SIA (▶ FOEN, SIA [buildings standards], Cantons [MUKEN])

3. **Efficiency first:** Put priority on efficiency even before considering substitution of incumbent energy carriers (energetic renovation of buildings, then installation of heat pumps; contain excessive demand for mobility services and oversized/overpowered cars before turn-

ing to electrification). (▶ EnergieSchweiz, Cantons, utilities)

4. **Account for increasing electricity demand:** Face (and act on) the indisputable fact that electricity demand in the country will substantially increase in view of the necessary deep 'defossilization' and that the electricity supply must be heavily expanded and be available over time and space, with specific consideration of the winter half-year. Support the integration of photovoltaics, which has by far the highest quantitative potential in Switzerland, in distribution grids and storage systems. Consider synergies and trade-offs with other sustainability goals. (▶ utilities [renewables, grid], Cantons [hydro])

5. **Deploy large storage capacities:** Encourage/support enhancement of daily and seasonal electricity and heat storage capacity and adaptation of the electricity grid. Consider market instruments and incentives that remunerate storage, electricity supply in winter and on-demand production capacities, e.g. for hydro power/reservoir dams and wind. Push on stronger integration in the EU electricity and energy system. (▶ utilities)

6. **Sector coupling/optimize energy grids:** Support – through regulatory instruments – coordinated investments in centralized and decentralized energy supply that are optimally connected through expanded electric heat and chemical energy carrier grids. Promote to this end advanced digital technologies, recognizing thereby that full realization of 'sector coupling' will be crucial for success. (▶ SFOE, parliament)

7. **Enhance cooperation with EU (in particular for electricity):** Align national with international, in particular European, policies and regulations, while considering specific important geographic, socioeconomic and environmental characteristics of Switzerland. With emphasis regarding electricity exports and imports an integration in the European electricity system is of crucial importance. (▶ SFOE, social partners, EDA [diplomacy])

8. **Strive for securing the import of renewable fuels:** Initiate intense cooperation with key international public/private stakeholders to secure a cost-effective and geopolitically resilient, potentially 'win-win' worldwide sourcing of renewable primary energy. This shall aim at producing, transporting and distributing of imported chemical energy carriers (hydrogen and based thereupon synthetic fuels) for long-haul transport, industrial processes and long-term/seasonal availability for electricity generation 'on demand'. (▶ EDA [diplomacy])

9. **Mobilize the financial sector:** Facilitate the mobilization of substantial resources and know-how of the Swiss financial sector to enable the necessary large scale investments in electricity generation and storage, new chemical energy carriers and the related infrastructure at a global scale. Consider policies that contribute to limiting the risks associated to investments in renewable energy. Better inform investors about financial risks associated with stranded assets. (▶ SECO, SNB)

10. **Improve information and communication**: Extend the dialogue (which is already done by SwissEnergy) with consumers on technical, environmental, and economic aspects in the climate/environment/energy nexus, in order to promote the 'literacy' of citizens, specifically in a country like Switzerland, in which political decision making is often based on public votes. Nudges could be used where 'low-cost' effects can be achieved via known cognitive or emotional characteristics of individuals. (▶ EnergieSchweiz, Cantons, utilities)

11. **Adapt and strengthen Education/Training:** Educate, train and lever knowledge of key personnel (architects, technicians, consultants, facility and/or fleet managers) in charge of implementing new energy concepts relevant to the net zero goal in all end-use sectors. (▶ EnergieSchweiz, associations)

12. **Employ Life Cycle Assessments:** Whenever feasible, employ – prospectively – Life-Cycle-Analysis-based data on CO_2 emissions when setting future standards in order to avoid 'carbon leaking' and embodied emissions in – often imported – goods. LCA-based data is also important for informing the public. Ideally, a full LCA including other environmental effects should be used to evaluate alternative pathways. (▶ FOEN, SIA [buildings standards])

13. **Exploit the potential of spatial planning:** Develop solutions for optimized planning to solve land use conflicts, mainly between renewables and biodiversity/conservation/food production claims and requirements on a national level in coordination with cantons (e.g. decide in a stakeholder dialogue on priority areas for energy installations with best cost benefit ratio and facilitate permission practice there as well as at the same time on priority areas for biodiversity and landscape interests). Implement stringent spatial planning to limit urban sprawl. Increase the attractivity of human powered mobility. (▶ cantons, ARE)

14. **Address evolving research needs:** Continuously support both fundamental and applied research in energy and climate change mitigation technologies and behavior assessment, including for processes where low-CO_2 solutions are missing and difficult to find (e.g. cement industry, high-temperature processes, low-carbon lifestyles). Greater emphasis should be placed on models including societal transition dynamics and heterogeneous actors instead of the prevailing cost

minimization approach only. (▶ SFOE, academies [SAGW, scnat/TD])

15. **Develop and assess negative emission options:** Although 'negative' emissions (NET) will be probably necessary, it is preferable not to rely on this path but rather see it as a kind of 'safety net'. However, the corresponding technologies are not mature yet and have to be further developed towards commercialization. Explore CO_2 storage and transport possibilities, which are also necessary for CCS at point sources. Initiate a stakeholder dialogue on socio-economic issues like acceptance, governance, ethical and justice issues related to NET. (▶ SFOE, FOEN, SNSF)

16. **Embed energy in overall policy:** Take into account the energy consequences of decisions in other policy areas and vice versa, for example interdependencies of the energy system and other subsystems of society and environment (like fair access to energy services or landscape preservation). Interconnections to societal developments should be observed and societal developments should be understood as opportunities. (▶ Policy)

When implementing these recommendations it is very important to ensure consistency and coherence. Moreover, synergies and conflicts to other SDGs or environmental goals have to be considered carefully. We must nevertheless recognize that there will continue to be trade-offs and deviating individual preferences and values that shape collective decision making. In a democratic society such partially opposing views must be mediated and conflicts resolved within the institutional political framework. For this purpose the information and education role of science striving for transparency and 'eye-level' dialogue with citizens will be of paramount importance.

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Annex: Comparative reflection on recent studies of the energy system future

In the following we distill insights from a few selected recent energy systemic studies and reports on the future energy system, in particular in view of the Paris climate agreement targets and on the necessary transformation paths towards net zero CO_2 emissions. We then reflect critically on these insights based on the findings of the present White Paper. We consider thereby studies referring to the global (worldwide), the European and the national Swiss conditions.

Global

The most recent report has been issued by the International Energy Agency and provides a roadmap for the Global Energy Sector in order to achieve net zero by 2050 (IEA 2021). Key findings thereof are summarized in the following:

- The challenge is enormous, the transformation path narrow but the 'window of opportunity is still open'.
- Electrification of the end-use sectors is indispensable but not sufficient for achieving the ambitious net zero in 2050 goal.
- Increase of energy efficiency is a key component in the portfolio of measures, while behavioral change will be useful but is playing a lesser role.
- Developed economies must achieve the net zero target slightly before 2040, leaving space for emerging economies to adapt until mid of the century
- Decarbonization of the electricity sector must be realized much earlier (between 2035 and 2040), while end-use sectors should achieve this around 2050
- This will require overall investments of 5 trillion USD by 2030, adding an extra 0.4% a year to the annual global GDP growth
- This implies among others a four times higher capacity addition for solar and wind electricity in 2030 (1000 GW) compared to 2020 (close to 250GW). Similar capacity expansions apply to the electric grid and its substations
- CO_2 emissions from existing heavy industrial assets (legacy) would according to normal life-time last beyond 2050; it is therefore relevant to use shorter investment and refurbishment cycles (of less than 25 years) to limit such cumulative, inertia based CO_2 emissions
- Intense international cooperation on policies, technologies and markets will be of paramount importance; following a 'low-international cooperation' path would result in net zero achieved around 2090 (vs. 2050) and with double as high cumulative emissions; this will have a severe impact on global warming compared to the intense international cooperation case
- Around 2050 annual CO_2 emission savings in the net zero pathway relative to 2020 will rely to about 50% on technologies on the market, to about 45% on technologies under development and to around 5% on behavioral changes.
- Gradually increase of CO_2 prices will be crucial for a successful transformation; the necessary CO_2 price is estimated to be in developed/emerging economies around USD 130/90 in 2030, 205/160 in 2040 and 250/200 in 2050.
- Total energy supply for net zero will remain at the level of 2020 in 2050 with solar energy of about 550 EJ and with renewables (incl. substantial share of advanced bioenergy) dominating with about 70% contribution, nuclear at about 10% and fossil fuels at about 20%.
- Thus CSS and CCU processes will be very important, amounting at about 7 $GtCO_2$/year in order to achieve net zero.
- The estimated share of electricity in the total final energy will increase from 20% in 2020 to 50% in 2050.
- The final energy for transport is expected to decline by $^1/_3$ in 2050 (80 EJ) vs. 2021 (115 EJ) with an estimated distribution of about 50% for direct electrification, 25% for H_2-based (syn-)fuels, more than 10% biofuels and less than 10% fossil fuels.
- Quite interestingly the globally averaged household energy bill in the net zero pathway in relationship to the disposable income is estimated to constantly decrease in 2050 vs. 2020 from more than 4% to slightly below 2% in advanced economies, while it is expected to essentially stay constant around 4% in emerging markets and developing economies.

Europe

1. 'A systemic approach to the Energy Transition', Science Advice for Policy by European Academies (SAPEA 2021).

   The report is centered around 6 main policy options to facilitate the transition to a 'defossilized' energy system for Europe and 2050. These policy priorities are in summary as follows:

   - Shape an effective and efficient regulatory strategy. This may include some top-down command and control measures, but a significant part should consist of market pricing instruments, like the expansion of the ETS. Though CO_2-pricing should constitute the main pillar of internalization schemes, additional externalities should be accounted for (air pollution, different types of waste, large-scale risks etc.).
   - Support of technical innovation for basic research, demonstration, early-adoption and scale up since some technologies requested on the long-term are not developed or mature yet and private investments at this stage would be quite risky.

- When setting standards and supporting new technologies it is important to maintain technology diversity and let innovation decide about the final winner.
- A geopolitical perspective would remain important for the future European energy system. This should include beyond supply sources for low-carbon primary energy, also and in particular sourcing for new materials, which will be necessary at a very large scale.
- Strong system integration and adequate dealing with the associated complexity will be crucial for a successful transformation. Matching demand and supply over time and space when fluctuating renewable energy input will dominate, will be a key challenge. Nevertheless, wide electrification will be important for a cost-effective decarbonization. In particular in the transport sector electrification will probably be implemented either directly (batteries, electric road systems) or through synthetic e-fuels.
- Policy should stimulate behavior in addition to supporting technology innovation. This refers in particular to consumers in households and their established or emerging lifestyles, since a big share of greenhouse gas emissions is ascribed – directly or indirectly – to household consumption.

2. Decarbonisation of Transport (EASAC 2019)

   This report examines the European transport sector as a whole but focuses explicitly on road transport and in particular on the dominating role of motorized individual mobility (essentially passenger cars). It employs a systemic framework in order to assess decarbonization options using the 'Avoid, Shift, Improve and Replace' concept and states that as of 2018 announced instruments for achieving the Paris Agreement targets for Europe as a whole were not sufficient. The study argued for an inclusive approach for both direct and indirect (e- or solar-fuels based) defossilization, depending on short-, mid- and long-haul modes and for the consideration of Life Cycle Analysis (LCA), thus included embodied CO_2 emissions for assessment of different powertrains and energy carriers. Along this arguments and based on the concept mentioned above it derived 12 recommendations for (European) policy makers.

3. Decarbonisation of buildings (EASAC 2021)

   The report examines ways to rapidly decarbonize the energy supply to buildings, considering deep renovations to increase energy efficiency and substitution of fossil fuels as complementary measures. The study recognizes also the role that buildings can play in the future as exporters of electricity to other sectors (industry, transport) and hosts of electricity and heat storage devices. Worth mentioning is the expressed need to shift the focus of regulations from near-zero-energy to near-zero GHG buildings and the observation that embodied CO_2 emissions in buildings may be a substantial part of the life-cycle CO_2 footprint; therefore the timing and depth of energetic renovations must be carefully defined (though the need to accelerate renovation rates of existing buildings is undisputable).

Switzerland

There are two recent systemic reports in the energy field for Switzerland and one specifically for decarbonization of mobility, namely:

1. Transformation of the Swiss Energy System for a Net-Zero Greenhouse Gas Emission Society (JASM, Marcucci et al. 2021)

   This studies summarize findings from simulation and modeling work carried out at distinct levels and with different methodologies in the framework of a Joint Initiative integrating competences from several Swiss Competence Centers in Energy Research (SCCERs). Different scenarios mainly concerning policy priorities have been examined. The following key insights are obtained from this activity for 2050
   - Electricity generation will amount to about 80–100 TWh/year, therefore being substantially higher than today (around 60 TWh/year).
   - Photovoltaics will become the second pillar of power generation next to hydropower, reaching 20–30 or in the case of high priority for energy security even 45 TWh/year.
   - Imported primary energy is calculated to be close to zero for high energy security but to reach up to 40 TWh/year in the other scenarios.
   - Net zero CO_2 for 2050 must rely on substantial amounts of CCS, ranging from 8–18 Mt/year.
   - The range of H2 production varies significantly among scenarios with a peak around 30 TWh/year in the high energy security scenario (obviously domestically produced).
   - For different technoeconomic models employed average system costs for reaching net zero CO_2 in 2050 are estimated to 330–700 CHF/(cap. year) between 2020 and 2050 (depending on the discounting rate and other assumptions).

   It is important, however, to notice that decarbonization of international aviation is not included in the considerations of the JASM-study.

2. Energieperspektiven 2050+ (BFE 2020a)

   This study has been mandated by the Swiss Federal Office of Energy and elaborated by several private consulting companies. It will serve as guidance for the Swiss Government with reference to the further development of the Energy Strategy of the country and the energy-related obligations for meeting the targets of the Paris Agreement. It is important therefore to examine carefully the main outcomes of the report as well as agreement with and deviations from the present White Paper of the extended Energy Committee of the Swiss Academies of Sciences.

The report examines four possible pathways to achieve net zero CO_2 emissions of Switzerland in 2050. 'Zero Basis' emerged as most probable, feasible/acceptable and cost-effective path. Technology variants of it have also been investigated, namely:

'Zero A' with increased electrification, 'Zero B' with higher share of synthetic gases and 'Zero C' with higher contributions of liquid fuels and district heat grids. Specifically for the electricity sector the focus is on a transition path of renewable power generation expansion that is supposed to achieved a balance of exports and imports of electricity on an annual average basis in 2050.

The study uses a large and detailed data base for economic development, population evolution, GIS-based potential of renewable energy in different sectors and associated cost estimates to include these in an economic optimization model, including also anticipated efficiency increase and technology improvement trajectories.

Main interesting findings are briefly summarized in the following:
- all 'Zero-x' models yield higher electricity demand with Zero A the highest and Zero B and C with lower growth. Assumed efficiency increase in conventional electricity applications leads however to an overall growth of total electricity demand in the order of 10-18% only.
- Around 2050 annually averaged import-exports of electricity is achieved, however substantial import share in winter is critically high around 2035 (around 15 TWhel, or 40% of winter demand) and remains substantial (6–9 TWhel) in 2050. In view of this, the assumption of adequate market mechanisms and legal conditions for the unhindered exchange between Switzerland and the EU may become an important uncertainty.
- The dominant part of the demand increase of electricity is due to electrification of road mobility, while heat pump loads are rather small due to energetic renovation in buildings and technology progress.
- Synthetic (PtX) fuels (H2 and derivates) are not relevant in Zero A but higher in Zero B and C. Based on cost considerations domestic production will be limited (only H2), while liquid fuels will be imported. Chemical energy carriers are used mainly in transportation and some heating application but not to a substantial amount in order to provide electricity in winter, thus leading to the high necessary imports mentioned above.
- Substantial use of biomass is shown, at about 60% domestic and 40% imported. However the contribution to 'power-on-demand' through decentralized biogenic co-generation appears though to be low to moderate given the available about 35 TWh of secondary biomass potential.
- In order to achieve net zero GHG-emissions around 12 Mt CO_2 need to be captured and sequestered (more than 50% of it abroad).
- As an interesting comparison with the IEA report on the worldwide roadmap to net zero, prices for CO_2 in the 'Energieperspektiven' are assumed to be quite low (essentially at today's levels) until about 2030 and then increase up to almost 400 CHF/t in 2050; the IEA roadmap estimates around 250 USD/t for advanced economies in 2050.
- Overall the technology mix differences among the scenarios are rather small, and both final energy and CO_2 emission reduction trajectories are very similar to each other throughout the next 30 years.
- Results are quite different though among the various Zero-x scenarios when it comes to the total direct economic costs of the transition to net zero until 2050. These range cumulatively between 73 bio. CHF in Scenario 'Zero-Basis' and 121 bio. CHF in 'Zero-C'. On a per capita and annual basis they amount therefore to about 250 (lowest) CHF and 650 (highest) CHF and are thus comparable with the estimates of the JASM report.

3. Pathways to a net zero CO_2 Swiss Mobility System (SCCER Mobility 2021)

   The findings and recommendations of this report have been directly incorporated in section 4.3 'Transport' of the present report.

Conclusions

The mentioned reports use partially different assumptions and scenarios but they appear to converge on some key characteristics of the path(s) towards net zero CO_2 in 2050. While the IEA, SAPEA and EASAC studies are useful in order to provide the international view and some relevant boundary conditions, the JASM and 'Energieperspektiven' reports can be drawn for a brief comparison with the present report as follows:
- All three studies for Switzerland stress the importance of efficiency increase and rapid substitution of fossil energy carriers for the transition.
- They also yield higher amounts of electricity demand and a clear reduction of dependency on energy imports. On average the necessary electricity demand growth is lowest in the 'Energieperspektiven' and highest in some of the JASM scenarios, while the estimates of the present report span a similar range depending on the chosen scenario.
- Implicitly the three reports converge also on the importance of sector coupling and different types of electrification of the end-use sectors.
- Nevertheless, this report attempts to make explicit the role of policies in guiding consumer behavior and inves-

tor's decisions from a long-term strategic point of view and for this purpose it

- discusses widely potentials, hurdles and actions needed for succeeding in the transformation to net zero
- distinguishes clearly between a 'focus domestic' and a 'focus balance' scenario, which have different consequences for the role of the country in international sourcing of renewable chemical energy carriers
- does not consider any substantial imports/exports of electricity and any substantial contributions from wind and geothermal electricity
- includes in the analysis the highly relevant demand of kerosene fuel for aviation (though at a frozen level of today, therefore probably underestimating the future demand growth)

However, the present report does not include any estimates of costs.

Appendix: Back-of-the-envelope estimates

Appendix A: Estimate of electricity demand for Switzerland under conditions of sector coupling and full decarbonization of the energy system in 2050

1 Method and Assumptions

We assume that by 2050 CO_2 emissions from the Swiss energy system will be essentially net zero. Increase of efficiency at all levels and electrification of end-use sectors like buildings heat and transport (incl. aviation) are supposed to help achieve the this goal. Renewable energy carriers for heat and fuels (incl. domestic sustainable biomass) are considered as well, beyond electrification.

As a conservative assumption, we don't consider any increase in hydropower capacity. We additionally postulate the complete phase-out of nuclear energy before 2050 and that photovoltaics will contribute a major part of additional, domestically generated electricity, thus ignoring – as a conservative assumption – the limited potential of wind and geothermal energy. We differentiate thereby between winter and summer (half-years) demand and supply. Furthermore, we include the option (absolutely necessary as we are going to see) that renewable synthetic fuels will be produced (and imported from) abroad to a significant extent, assuming appropriate locations can be identified and used through proactive action in the frame of a coordinated (for example European) initiative. Candidate electricity generation technologies are wind (in particular off-shore) and solar PV in areas where up to 5000 and more than 2000 full-load hours respectively are feasible. In contrast to the former Desertec initiative the strategy here would include fuel production abroad and/or transport through mostly existing and re-purposed distribution infrastructure (pipelines, tankers, etc.).

It is even more difficult to estimate the future evolution of the energy demand in the individual end-use energy sectors. In order to do so we use in the following mostly the empirical data from 1990 to 2018, derive energy efficiency increase rates and/or electricity demand per capita and extrapolate them in the future until 2050. We take this method as proxy for incremental improvements without the disruptive influence of massive electrification that is expected to occur in the next three decades. Extrapolation of efficiency increase trends may be wrong in either direction, namely: on one hand low-hanging efficiency gains may have been already reaped to a significant extend, while targeted future policy (in particular high CO_2-prices) may provide an additional stimulus for efficiency increase.

In addition we consider population evolution according to BFS mid-range scenarios or – whenever possible like in ARE scenarios for transportation – the forecasted future energy services demand as well. In the specific case of electricity, we use as proxy for the future demand the per-capita data of the period 2008–2018 rather than 1990–2018, since in the last 10 years a much faster reduction of the corresponding parameter vs. the 25-years period has become evident. Difficult to predict is the net-effect of digital technologies: they may increase the electricity demand but in parallel lead to increased energy efficiency in the end-use sectors.

Furthermore, the relative benefits of electrification vs. incumbent end-use technologies (heat pumps, electric vehicles, PtX-processes for synthetic fuels etc.) are modeled with coefficients reflecting some – but not radical – improvements in current technology.

Finally, we must keep in mind that the electricity demand numbers below refer to final energy, which means that gross power generation would be at least 10% higher due to losses relative to grid transmission and short-term storage.

Given the mentioned uncertainties the total electricity demand in 2050 may deviate from the results derived below to quite some extent, but the numbers estimated in this way are illustrative enough to stimulate public debate and targeted policy action.

2 Estimated energy demand for 2050

a. Buildings Heat

Current energy demand for hot water and space heat are around 80 TWh. Assuming 2%/year deep energetic renovation rate from currently 120 kWh/m^2 to 50 kWh/m^2, 20% population increase translated in some growth of heated area but at 40 kWh/m^2 (Minergiestandard) leads to a total heat demand of about 51 TWhth in 2050. Of these, 27 TWh_{th} are covered by central-/decentralized heat pumps with a COP ('Coefficient of Performance', describing the efficiency of a heat pump) of 4.5 leading to an electricity demand of 6 TWh_{el} and ambient heat supply of 21 TWh_{th}. About 10.5 TWhth of useful heat shall come from biomass burners and 7.5 TWh_{th} from biomass-fed CHP devices (including district heating). Considering electricity consumption of heat pumps and supply by CHP, in both cases the distribution between $^5/_6$ in winter and $^1/_6$ in summer applies. The remaining 6 TWh_{th} are supposed so come from solar-thermal (3 TWh) and incineration plants (3 TWh).

b. Industry Heat

- We exclude here CO_2 from production of concrete (assuming CCS or similar for this process).
- Extrapolating past efficiency increase per 'industry value added' with similar annual growth of industrial output until 2050 we arrive at ~14.4 TWh of useful heat (vs ~22.5 TWh today), roughly equally distributed between summer and winter.
- This heat demand would be met for 5.4 TWh_{th} by hydrogen and for 9 TWh_{th} by biomass, leading to (with a 90% efficiency) a demand of 6 TWh of hydrogen and 10 TWh of biomass.

c. Transportation

— **Electrification of all passenger cars**

Currently 42 TWh fossil fuels; extrapolating past efficiency increase from 1990 to 2018 and using ARE scenarios for demand (extrapolating from 2040 to 2050) we would need ~38 TWh in 2050. Using an efficiency increase factor of 3 between a BEV and an ICEV (and grid and intermediate storage losses) we estimate **~12.7 TWh_{el}** demand in 2050.

— **All other road (mostly freight)**

Today's fossil fuels consumptions for light-duty vehicles (LDV) and heavy-duty vehicles (HDV):
LDVs: ~12 $\text{TWh}_{\text{foss.}}$, Eff. factor (BEV/ICEV) = 2.5
HDVs: ~6 $\text{TWh}_{\text{foss.}}$, Eff. factor (FCEV/ICEV) = 1.1

With an anticipated combined demand and efficiency increase extrapolation (resulting in a net increase of 12.5% until 2050) and the above efficiency factors we estimate for road freight a final energy demand of **5.4 TWh_{el}** for LDVs and **6 TWh H_2** for HDVs.

— **Aviation**

Extrapolating the past trend (1990–2018) of 1.4% increase of energy per year and capita to 2050 with the corresponding reference population growth the jet-fuel demand would increase from 22.3 TWh in 2018 to ~41 TWh in 2050 (!). This is clearly a non-sustainable path and given that strict legislation is expected in the future vs. the unregulated situation today we will use for the demand for renewable synthetic e-kerosene a 'frozen' value of **22 TWh e-kerosene** as today, being aware that this is a very optimistic assumption.

d. Other (conventional) electricity demand

Current (2018) final electricity demand: 57.6 TWh_{el}

Using 1990–2018 per capita demand data is not meaningful because there is a clear demand trend change in the last 10 years towards significant decrease of electricity demand per capita and year (1.3%). Extrapolating 2008-2018 trends and with the reference future population increase leads to a clearly reduced electricity demand for conventional services in the order of 45 TWh_{el}. Extrapolating the average trend of the last 10 years according to which about 55% of demand is in the winter-half year and 45% in summer and qualitatively considering climate warming and possibly some increased storage capacity of hydro-dams we use a demand of 23 TWh in Winter and 22 TWh in Summer (net, excl. grid losses and hydro-pump storage).

⟶ **Therefore:**

Electricity demand in 2050 estimated to (1+9+22) = **32 TWh_{el} (S)** and (5+9+23) = **37 TWh_{el} (W)**

According to the biomass discussion in Sec. 4.4, in principle there is a total biomass potential of about 37 TWh_{chem}, including about 16 TWh of imports (EP2050+). Considering the competition with other energy sectors, out of those 37 TWh_{chem}, we allocate 10 TWh_{chem} to high-T-heat for industry processes, another 15 TWh_{chem} as input to CHPs, delivering 6 TWh_{el} and 7.5 TWh_{th} and 11.7 TWh_{chem} for buildings heat (in boilers), all of them with 90% efficiency

Anticipated availability of supply before PV (w/o wind and geothermal as conservative assumption):

Hydropower: **18 TWh_{el} (S) + 14 TWh_{el} (W)**
Biogenic CHP: **1 TWh_{el} (S) + 5 TWh_{el} (W)**
KVA: **1 TWh_{el} (S) + 1 TWh_{el} (W)**
The sum of these sources is: **20 TWh_{el} (S) + 20 TWh_{el} (W)**
Thus the **gap** that needs to be covered is **12 TWh_{el} (S) + 17 TWh_{el} (W)**

3 Two Options for future energy supply

We distinguish in the following between two strategies for covering the electricity and fuel demand as estimated above for 2050. Both options rely on importing renewable jet-fuel from abroad. The first one, called 'Focus Domestic', examines how it would be possible to cover all other energy needs by domestic sources (primarily through massive expansion of PV and PtX), while the second one, called 'Focus Balanced', uses a smaller PV expansion without domestic PtX and relies on additional fuel imports for domestic winter electricity, propulsion of heavy duty vehicles (HDV) and industrial processes as well.

For both scenarios the demand for increased domestic power generation could be in principle relaxed somewhat through net imports from the European electricity system. Since however neighboring countries are expected to pursue similar goals with regard to their power generation portfolio, it would be wise not to heavily rely on this mechanism for securing power supply even under the assumption of full integration of the Swiss electricity system into the European one.

a. Scenario 'Focus Domestic'

Here we assume that Switzerland will import only renewable jet-fuel (**22 TWh** as of today, leading to a necessary electricity generation of about 60 TWh, based on a conversion efficiency of 37%) and produces domestically all directly needed electricity (conventional applications, heat pumps, battery electric vehicles) as well as all hydrogen needed for industrial process heat, propulsion of HDV (6 TWh H_2 each), and seasonal shift to account for the winter electricity demand.

The production of H_2 for these applications will make the installation of electrolyzers necessary. In order to cover the electricity demand in winter when all nuclear powerplants are phased out, besides PV, hydropower and biogenic CHP, H_2 will be re-converted to electricity through full cells or combustion engines (including combined cycle turbines).

Under these conditions the electricity demand to be covered by PV will – according to Section 2 – amount to 12 TWh in summer and 17 TWh in winter (29 TWh in total). According to Part B of this Appendix and typical seasonal availability values in Switzerland the surplus factor for the PV power generation will be 1.30, leading to 37.6 TWh of annual generation (24.4 TWh [S] + 13.2 TWh [W]), and the PV fraction for the electrolysis 0.33, leading to 12.5 TWh electricity to sustain the seasonal shift.

In addition, for the 12 TWh H_2 for HDV and industrial heat, assuming a H_2 production (including transport/distribution) efficiency of 60%, in total 20 TWh electricity will be necessary. In order to minimize the conversion losses, we assume that these 20 TWh will be produced according to the seasonal pattern of PV as input for electrolyzers (13 TWh [S] +7 TWh [W]).

This leads to a net annual PV generation of about 57.6 TWh (37.4 [S] +20.2 [W]). Estimating grid and storage losses (combination of batteries and pumped-hydro storage) leads to a gross annual PV production of 61 TWh.[10] Assuming 1100 FLH of PV in Switzerland (2/3 in 'Mittelland', 1/3 in the Alps) this requires 55 GW of installed PV.

Of the 57.6 TWh net-generated by PV, 32.5 TWh are to be fed to electrolyzers (25.5 TWh [S] +7 TWh [W]). It is worth noticing that about 1/3 of summer PV generation goes into direct electricity consumption and 2/3 serve to feed electrolyzers. If electrolyzers (assumed to be load-following PEM) could only use the FLH of PV, the 25.5 TWh in summer would require 36 GW of installed electrolzers capacity. This capacity is extremely conservative, because electrolyzers could run at any hour when the solar influx is higher than the electricty load minus run-of-river generation. Nevertheless, these required capacity renders this scenario extremly demanding and therefore unlikely to emerge.

b. Scenario 'Focus Balance'

Here we assume that domestic power generation (hydropower, biogenic CHP and PV) will cover 'only' the direct use of electricity (conventional applications, heat pumps and battery electric light-duty vehicles). Renewable chemical energy carries (H_2 for HDV propulsion and industrial processes and for complementing power generation in winter and renewable fuel for aviation) will be imported after being produced abroad by electrolysis. It is assumed that the production of such fuels will rely on electricity generation at favorable locations worldwide (with offshore wind and solar energy). For securing winter electricity production H_2 is supposed to drive combined cycle turbine powerplants.

As already mentioned above, also in this case an electricity demand of **12 TWh** in summer and **17 TWh** in winter remains necessary after exploiting the hydropower and biogenic CHP potential. We assume that of these 18.5 TWh will be covered by PV (12 TWh in summer and 6.5 TWh in winter), which means that a source for the remaining 10.5 TWh in winter will be necessary. With a net-efficiency of 55% for a mix of combined cycle powerplants (60% efficiency) and large fuel cells (50% efficiency) both subject to 7% grid losses, around 20 TWh H_2 will be required. This will add to the 12 TWh H_2 for HDV and industry processes to yield a total of 33 TWh H_2 to be imported. This will make approximately 60 TWh of electricity necessary, while for the 22 TWh imported jet-fuel about 60 TWh of electricity must be produced. In this scenario no electrolyzers will be needed domestically.

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[10] 50% direct consumption, 25% pumped-hydro, 25% batteries. Average losses = 5.4%

All told therefore, 120 TWh of power generation will be needed abroad and around **55 TWh** of fuels (H_2 and jet-fuel) must be imported in this scenario. This compares to 60 TWh electricity abroad for 22 TWh of imported fuels in scenario 'Focus Domestic'.

In both cases the net energy imports of Switzerland – including 16 TWh of biomass – will be massively reduced (by more than 83% in 'Focus Domestic' and about 69% in 'Focus Balancced') in comparison to today's situation in which we import around 235 TWh of fuels per year (160 TWh fossil and 75 nuclear).

Remark

It is conceivable that in competition to production of H2 abroad synthetic methane can be considered as well. Despite the lower conversion efficiency from electricity to fuel (incl. Direct Air Capture of CO_2) of no more than 45%, existing transport and distribution infrastructure may still provide cost reductions against the H_2-route. In such a case, the amount of imported fuels will be essentially the same, but the necessary electricity generation abroad would reach about 130 TWh_{el}.

Comment on security of supply around 2050

Assuming that a massive global need for synthetic fuels will lead to a diversified portfolio of sourcing worldwide, the import dependence of Switzerland in terms of energy carriers not produced domestically is a key quantity for the security of energy supply. Compared to currently around 220 TWh of imported fuels (150 fossil and 70 nuclear) energy imports are estimated to be about 22 TWh and 55 TWh H_2 (or CH_4) in scenarios 'Focus Domestic' and 'Focus Balanced' respectively. This is a massive reduction that helps to relax fears about energy supply risks.

Appendix B: Estimate of surplus power generation due to the need for seasonal balancing of PV electricity through 'Power-to-Power'(PtP).

The following parameters are important for this estimate:

α: share of electricity demand in winter half-year to the whole year

β: share of PV-electricity generation in summer half-year to the total year

γ: 'power-to-power' conversion efficiency for the amount 'δ' of PV-electricity that needs to undergo seasonal storage for meeting the winter and summer electricity demand.

Based on simple math we arrive at:

$\delta = \frac{\beta + \alpha - 1}{\gamma + \alpha^{(1-\gamma)}}$ (1) with a total efficiency $\eta = \frac{1 - \beta^{(1-\gamma)}}{\gamma + \alpha^{(1-\gamma)}}$

and the surplus factor $f = 1/\eta$ (3)

Executing a small-scale perturbation around typical parameter numbers α and β for Switzerland as well as γ according to foreseeable technology

($\beta = 0.6 - 0.7$, $\alpha = 0.55 - 0.6$, $\gamma = 0.28 - 0.34$)

leads to a range of total efficiencies in the range of

0.70 – 0.86

and to 'surplus factors' in the range of

1.16 – 1.43

These efficiencies can be lower and the surplus factors higher by about 10%, if parts of the summer PV-generation need short-term storage to lower peak capacity and increase operating hours of electrolyzers but they are remarkably high.

List of abbreviations

ARE	Federal Office for Spatial Development
BECCS	Bioenergy with Carbon Capture & Storage
BEV	Battery electric vehicle
CCGT	Combined Cycle Gas Turbines
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CHP	Combined Heat and Power
DACCS	Direct Air Carbon Capture and Storage
DC	Direct current
DER	Distributed energy resources
DLT	Distributed ledger technology
EDA	The Federal Department of Foreign Affairs
ETS	Emission Trading System
EU	European Union
FLH	Full load hours
FOEN	The Federal Office for the Environment
FT	Fischer-Tropsch
GDP	Gross domestic product
GHG	Greenhouse gas
HDV	Heavy duty vehicles
ICEV	Internal combustion engine vehicle
ICT	Information and Communication Technology
JASM	Joint Activity Scenarios and Modelling
LCA	Life cycle assessment
LCOE	Levelized Cost of Electricity oder Energy
MUKEN	Model regulations of the cantons in the energy sector
NET	Negative emissions technologies
NG	Natural Gas
PV	Photovoltaic
SCCERs	Swiss Competence Centers of Energy Research
SDGs	Sustainable Development Goals
SECO	State Secretariat for Economic Affairs
SFOE	Swiss Federal Office of Energy
SIA	Swiss society of engineers and architects
SMRs	Small modular reactors
SNB	Swiss National Bank
SNG	Synthetic natural gas
SNSF	Swiss National Science Foundation
TRL	Technologies with low readiness level
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

Who are we?

The **Swiss Academies of Arts and Sciences (a+)** are an association of the Swiss Academy of Sciences (SCNAT), the Swiss Academy of Humanities and Social Sciences (SAHS), the Swiss Academy of Medical Sciences (SAMS), the Swiss Academy of Engineering Sciences (SATW) and the Swiss Young Academy (SYA). They further comprise the two centres of excellence TA-SWISS (Foundation for Technology Assessment) and Science et Cité, as well as other scientific networks. The Swiss Academies of Arts and Sciences network the sciences regionally, nationally and internationally. They represent scientific communities on a disciplinary and interdisciplinary basis and independently of institutions and subjects. Their network is geared to the long term and committed to scientific excellence. They advise politics and society on knowledge-based and socially-relevant issues.

The **Extended Energy Commission of the Swiss Academies of Arts and Sciences** promotes and coordinates the discussion and exchange of knowledge on the topics of energy and the sustainable use of resources within the research community and maintains a dialogue with politics and society. It seeks cooperation with Swiss universities and universities of applied sciences and maintains a network of the Swiss research community on the topic of energy.