Perspectives of Power-to-X technologies in Switzerland

A White Paper

Report

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July 2019

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Synthesis

The Swiss energy system is facing substantial transformation and associated challenges: While nuclear power plants will be gradually phased out, power generation from photovoltaics and wind is supposed to (partially) fill the resulting gap. At the same time, the energy system is expected to reduce its carbon-dioxide (CO_2) emissions in order to meet climate goals in line with the Paris Agreement of limiting the global temperature increase to well below 2 °C compared to pre-industrial level. For Switzerland, this means specifically to replace fossil fuels in the mobility sector as well as for heating.

An electricity system largely based on intermittent renewables needs temporal flexibility options buffering generation and demand. One of those flexibility options is "Power-to-X" (P2X): This term describes the electro-chemical conversion of electricity into gaseous or liquid energy carriers or industrial feedstocks. This White Paper therefore covers P2X electrochemical processes, but not the use of electricity for direct heat generation (power-to-heat). The conversion process starts with electrolysis of water (Figure 1.1). The hydrogen generated from electrolysis can either be directly used as fuel, or – in combination with CO_2 from different sources – it can be further converted into synthetic fuels, such as methane or liquid hydrocarbons. Hydrogen and synthetic fuels can directly replace fossil fuels for heating, mobility or electricity generation and can thereby reduce CO_2 emissions. However, one needs to consider the entire P2X conversion chain to assess how much CO_2 is effectively reduced. In particular, the level of achievable CO_2 emissions reduction mainly depends on the CO_2 emissions associated with the electricity used for electrolysis. Promising P2X options in the Swiss context are the use of hydrogen in fuel cell vehicles and the generation of synthetic methane replacing natural gas as heating and transport fuel. In the mobility sector, synthetic fuels can become important in particular for long-distance, heavy-duty transport where direct electrification with battery technologies faces severe limitations. Both hydrogen and SNG can also be converted back into electricity.

Hydrogen, methane and liquid hydrocarbons can – as opposed to electricity – easily be stored over long time periods complementing other short-term energy storage options for an advanced integration of photovoltaics and wind energy. Provided that these long term storage options are available for P2X products, the option of seasonally matching electricity production and energy demand represents an important benefit of P2X; it can also provide services for electricity grid stabilisation. As such, the value of P2X technologies unfolds in the combination of its multiple benefits that relate to increased temporal flexibility provided to the electricity system, the production of potentially clean fuels for energy end-users, and the reduction of CO_2 emissions through the use of CO_2 for the production of synthetic fuels replacing fossil fuels. However, each of the conversion steps involved in P2X technology comes along with energy losses.

Since energy losses are associated with costs and also due to the fact that some of the processes involved in P2X are still in the development phase, costs of P2X products are currently high. A key factor for the competitiveness of P2X refers to the provision of electricity at lowest possible costs. As a technology that enables the interconnection of different energy supply and consumption sectors (sector coupling technology), it is important for a successful market integration of P2X technology to be able to generate revenues in different markets. Under suitable boundary conditions, economic competitiveness could be achieved in the future. Such a positive development depends on a number of key factors:

- Reaching technology development goals and reducing hardware costs,
- A broad rollout of fuel cell or synthetic methane vehicles together with the required fuel distribution infrastructure,
- A regulatory framework that treats electricity storage technologies and thus P2X equally (especially with regard to grid charges) and monetarises the environmental benefits of P2X products (e.g. by taxing CO_2 emissions).,
- The identification of P2X market opportunities in different sectors and the use of optimal sites for P2X units with access to low-cost renewable electricity and CO_2 sources.

Based on the existing knowledge, a few recommendations supporting the implementation of P2X in Switzerland targeting policy makers, research and other stakeholders seem appropriate:

- Ambitious goals for domestic reduction of CO_2 emissions are required
- Current ambiguities in the regulation framework should be eliminated acknowledging the benefits of P2X in the electricity system as producer and consumer of electricity,
- Upscaling of pilot P2X plants should be supported in order to reach commercial unit sizes,
- Innovation policy should strengthen the domestic market for P2X products and

support learning-by using P2X technologies in comprehensive project setups covering complete P2X value chains,
- Clear rules for accounting for potential environmental benefits of P2X fuels should be established and these benefits need to be monetized,
- The role of P2X and the optimal use of P2X to achieve long-term energy and climate goals should be deepened in holistic studies (e.g. scenario analyses of the Swiss Energy Strategy 2050), with particular attention to system integration and local aspects (consumption structures, availability of resources and infrastructure).

1 Preface and introduction

This White Paper emanates from the corresponding project of the Joint Activity of five Swiss Competence Centers for Energy Research (SCCER) funded by the Swiss Innovation Agency Innosuisse and the the Swiss Federal Office of Energy. The objective of this White Paper is to collect the major existing knowledge on P2X technologies and to provide a synthesis of existing literature and research findings as basis for the evaluation of these technologies in the Swiss context and their potential role on the Swiss energy market. This White Paper concerns P2X related to electro-chemical conversion and does not address electro-thermal convertion systems such as electric heating and warm water systems. With the aim to derive a technical, economic and environmental assessment of P2X technologies with their systemic interdependencies, the gas and electricity markets as well as the mobility sector are specifically investigated including the corresponding regulatory and innovation policy aspects (Figure 1.1). Complementary to this White Paper, a comprehensive background report with detailed information on the various technological aspects of P2X as well as the corresponding implications for markets, legal aspects and policies is available (for instance, under http://www.sccer-hae.ch/). The background report also contains references to all literature sources used, whereas this White Paper is limited to a few selected literature sources.

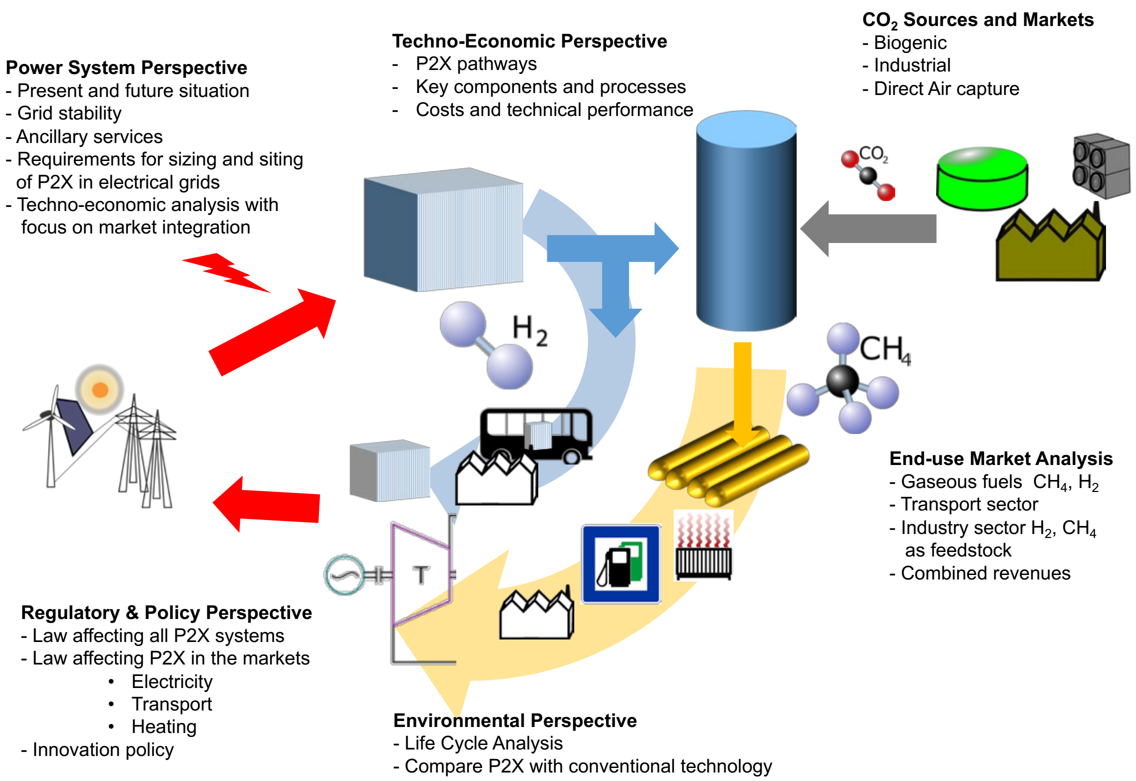


Figure 1.1: Schematic representation of the scope of this White Paper.

2 What is Power-to-X?

The "X" in P2X represents products such as hydrogen, methane or methanol.

2.1 Basic principle

The basic principle of P2X systems entails in a first step the electrolysis of water: using electricity as process input, water is split into hydrogen and oxygen. Depending on the end-use application, hydrogen can be used directly or it can be used to produce other energy carriers. The synthesis of other energy carriers requires further process steps, which produce gaseous or liquid hydrocarbons such as methane, methanol other liquid fuels, or ammonia (Table 2.1). In case of production of hydrocarbons, this second step needs a source of carbon, which can be a syngas from biogenic feedstock, CO_2 extracted from the atmosphere, or CO_2 captured at stationary emission sources, e.g. fossil power or cement plants. In a third and last step, the final products may need to be upgraded and conditioned for further usage.

1. First step: Electrolysis of water:
   $2\,H_2O \rightarrow 2\,H_2 + O_2$
2. Second step (optionally, depending on target product; one of the following processes):
   - Methanation of CO_2 and hydrogen:
     $CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O$ or
     Methanisation of CO and hydrogen:
     $CO + 3\,H_2 \leftrightarrow CH_4 + H_2O$
   - Methanol synthesis:
     $CO_2 + 3\,H_2 \leftrightarrow CH_3OH + H_2O$
   - Synthesis of liquid fuels, Fischer-Tropsch process:
     $CO_2 + H_2 \rightarrow CO + H_2O$;
     $CO + H_2 \rightarrow C_xH_yOH + H_2O$
   - Ammonia synthesis:
     $N_2 + 3H_2 \leftrightarrow 2NH_3$
3. Product upgrading/conversion and conditioning for further usage (depending on the pathway):
   - Separation/cleaning and further processing of gaseous and liquid products
   - Compression
   - Pre-cooling

2.2 Electrolysis

Each P2X conversion pathway is characterized by a specific combination of technologies which depends on the required inputs and the outputs (Figure 2.1); electrolysers are a core component of all P2X systems. There are three main types of electrolysers:

1. alkaline electrolysers
2. polymer electrolyte membrane (PEM) electrolysers
3. solid oxide electrolysis cells (SOEC) electrolysers

While alkaline electrolysis is the incumbent water electrolysis technology and widely used for large-scale industrial applications, PEM electrolysers are typically built for small-scale applications, but have a comparably higher power density and cell efficiency at the expense of higher costs. SOEC, which operate at high temperature levels, are on an early development stage with the potential advantages of high electrical efficiency, low material cost and the option to operate in reverse mode as a fuel cell or in co-electrolysis mode producing syngas from water steam and CO_2. Even though electrolysis is an endothermic reaction, usually heat transmission losses occur resulting in waste heat that might be used in other applica-

Table 2.1: Technology overview of P2X systems including main technologies and their major in-/outputs.

P2X pathway	Conversion step	Carbon atoms	Inputs	Technology	Outputs
Hydrogen (H_2)	1(+3)	0	Electricity, water, heat (in case of SOEC)	Electrolyser, hydrogen storage	Hydrogen, oxygen, heat
Synthetic methane (CH_4)	1+2+3	1	Electricity, water, CO_2	Electrolyser, methanation reactor	Methane, oxygen, heat
Synthetic methanol (CH_3OH)	1+2+3	1	Electricity, water, CO_2	Electrolyser, methanol synthesis reactor	Methanol, oxygen, heat
Synthetic liquids (C_xH_yOH)	1+2+3	variable	Electricity, water, (heat), CO_2	Electrolyser, Fischer-Tropsch reactor	Liquid hydrocarbon fuels, oxygen, heat
Ammonia (NH_3)	1+2+3	0	Electricity, water, nitrogen (N_2)	Electrolyser, Ammonia synthesis reactor	Ammonia, oxygen, heat

Electrolysis is the key process common to all P2X systems.

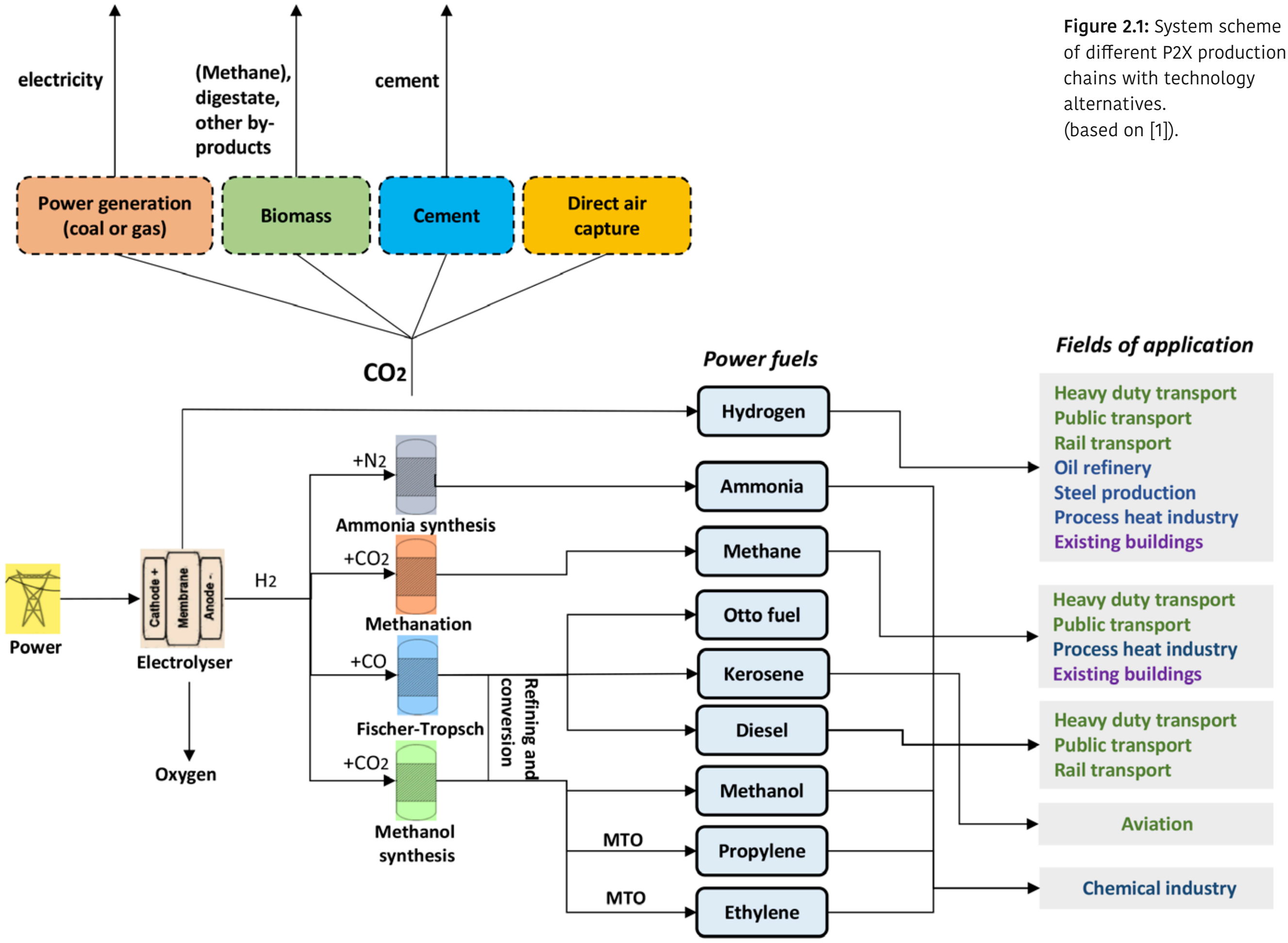


Figure 2.1: System scheme of different P2X production chains with technology alternatives.
(based on [1]).

tions. The process efficiencies, i.e. the energy content of the hydrogen based on the upper calorific value (HHV) in relation to the effective energy input, of advanced future systems are in a range of 62–81 % for alkaline and up to 89 % for PEM electrolysers and even higher for SOEC electrolysers. Beyond the three main types of electrolysis there are other electrolysis processes being investigated, such as plasma electrolysis, which is also in an early research stage.

2.3 Synthesis of methane, other hydrocarbons or ammonia

For the production of synthetic gaseous or liquid hydrocarbons in subsequent process steps after electrolysis, different additional reactor systems are required, such as a methanation reactor (catalytic reactor or biological reactor), the catalytic Fischer-Tropsch reactor, or the methanol synthesis reactor, which can also be used in combination with a further process to produce oxymethylene ether (OME). In these reactors, CO_2 is a feedstock input in addition to hydrogen. The CO_2 can originate from various sources: CO_2 can be captured from biogenic or synthetic gas streams, from flue gas from combustion of fossil or biogenic fuels, or from the atmosphere. Throughout the complete P2X chains, each process step is associated with energy losses: typical efficiencies for the production of electrici-

P2X can generate clean fuels substituting petrol, diesel and natural gas.

ty-based synthetic fuels range are in the order of 20 % (OME) to about 40 % (methane) [2]. Depending on the thermodynamics of the processes, improved efficiencies can be achieved if waste heat (e. g. from the methanation reactor) is used for heating purposes of other processes within the P2X system. Also the efficient integration of carbon sources leads to efficiency gains, as demonstrated by direct methanation of biogas in a P2X plant with an overall efficiency of almost 60 % [3].

2.4 Stage of development

The various technologies involved in P2X systems are currently at different technology readiness levels ranging from level 5 ("technology validated in relevant environment") up to level 9 ("completed and qualified systems"), which is second highest level just before "prove of the system in an operational environment". Electrolyser technologies, which are common to any route, are already mature, in particular alkaline technology. Methanation reactors have also progressed recently to the commercial level following some successful demonstration projects, e. g., a 6.3 MWel Power-to-Methane plant in Werlte (Germany) using catalytic technology for methanation [4] and the 1 MWel plant from the BiOCAT project in Copenhagen [5]. Fischer-Tropsch and methanol reactors have already been widely applied in the chemical industry in much larger scale, but their implementation in P2X systems is still in development.

2.5 Infrastructure

In addition to the energy conversion equipment, infrastructure is needed to bring P2X products to end-users. Storage systems allowing for temporal flexibility of production and consumption of P2X products need to be part of this infrastructure. For some of the P2X products existing distribution infrastructure systems can be used, e.g. the natural gas grid or the infrastructure for liquid fuels. The current bottleneck in Switzerland is the missing infrastructure for hydrogen distribution and supply. However, it is also possible to transport small quantities of hydrogen in the natural gas network. However, long-distance transport and storage of hydrogen has been proven, mainly related to industrial application, such as the Rhine-Ruhr-pipeline in Germany with a length of 240 km.

3 Why Power-to-X in Switzerland?

Rational behind P2X: The transformation of the energy system in response to future energy and climate challenges.

3.1 Greenhouse gas emissions and climate change

Mitigating climate change requires a substantial reduction of greenhouse gas (GHG) emissions across all sectors of the economy. This will have significant implications for the energy landscape as well as other emissions sources. Switzerland has committed to reducing its annual direct emissions of GHG by 50 % by 2030 compared to 1990. A major share of this reduction shall be achieved domestically while some emissions can be based on measures abroad through the use of international credits [6]. The Swiss government has also formulated the long-term ambition to reduce GHG emissions in 2050 by 70–85 % compared to 1990 levels (including measures abroad), and to achieve climate neutrality after 2050 [7]. Today, domestic GHG emissions in Switzerland originate by about 60 % from energy conversion in the transport and building sectors, and by 40 % from other sources including industry. Currently, mobility is the sector with largest CO_2 emissions (Figure 1). Swiss electricity production is almost CO_2-free – electricity is mainly generated from hydropower (60 %), nuclear (32 %) and new renewable energy (6 %) [8]. Future pathways for the development of the Swiss energy sector are framed by the Energy Strategy 2050, which aims at discontinuing energy supply from nuclear power plants in Switzerland, and promoting renewable energy and energy efficiency [5].

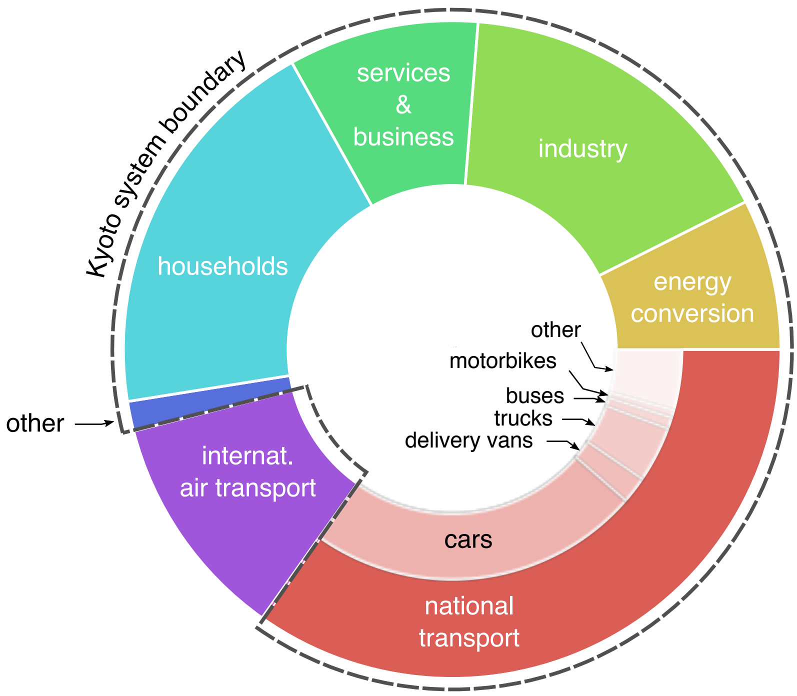


Figure 3.1: CO_2 emissions in Switzerland in 2015 split into different sectors and the Kyoto system boundary [9].

3.2 Increasing renewable power generation

The transformation of the Swiss energy system towards climate neutrality calls for the deployment of new low-carbon energy solutions. At the same time, the current high level of reliability must be maintained. One option to reduce GHG emissions is an increased electrification of energy services based on low-carbon electricity generation technologies. With growing shares of intermittent renewables in the electricity mix, such as wind and solar power, the challenges of temporal and spatial balancing of supply and demand is expected to increase in future. Temporal balancing arises due to the inevitable mismatch between renewable electricity production and demand as a consequence of day/night cycles, weather effects and seasonal differences, while spatial balancing is resulting from differences between the locations of electricity production and consumption.

3.3 Need for flexibility options

A future Swiss energy supply substantially relying on large shares of intermittent electricity generation will need sufficient flexibility options. These must allow for shifting energy between day and night as well as from summer to winter: roof-top PV installations, which exhibit the largest potential for new renewable electricity generation in

Power genertion from intermittent renewable sources calls for more.

Switzerland by far, show distinct seasonal peaks in summer and daily peaks at noon. In the case of simultaneously low power consumption, such generation peaks pose a challenge for the power grid, and these peaks – if not to be curtailed – must either be stored and re-used as electricity at times without sufficient generation, or transformed into other energy carriers such as gases and liquids, which can be used as e.g. transport or heating fuels. In addition to the flexible power plants operated in Switzerland already today, i.e. reservoir hydro plants and pumped storage hydro plants, increasing flexibility by installing further flexible power plants, storages and international electricity trade becomes inevitable at very high shares of wind and solar PV in order to operate the electricity system cost-efficiently and to ensure the system's secure operation [10]–[12]. P2X technologies represent one option to increase flexibility. P2X technologies not only offer the possibility of enhanced sector coupling between the power sector and energy demand sectors, but also to provide short and long-term supply and demand balancing.

4 Flexibility as an important element in climate change mitigation

P2X can provide temporal and geographical flexibility in the energy system while enhancing the portfolio of clean fuels.

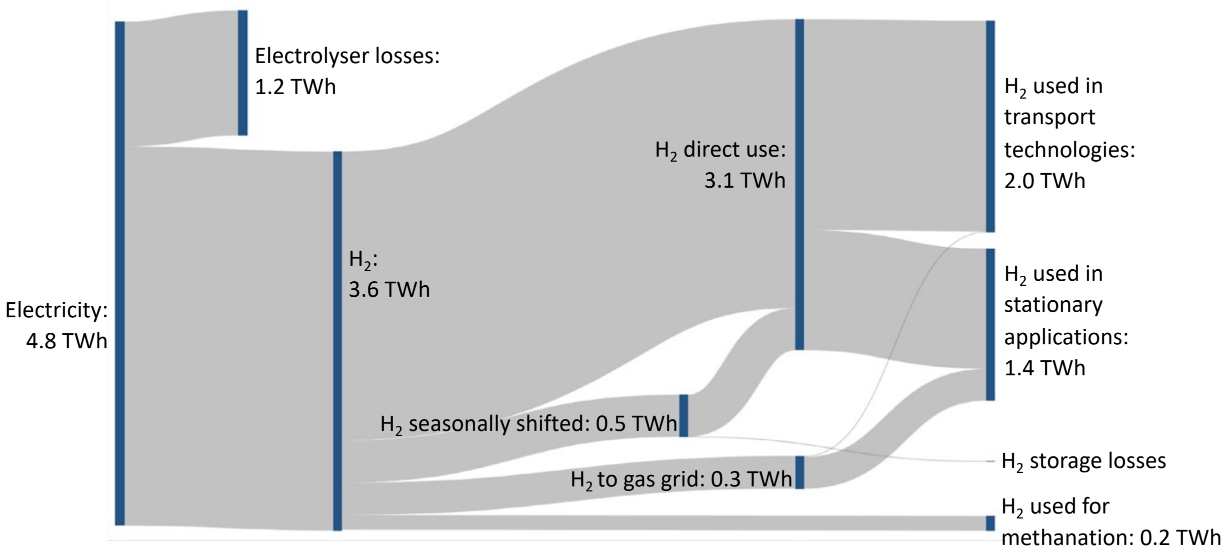
4.1 Three core benefits of P2X

P2X systems can be designed to increase the flexibility of the energy system and to mitigate GHG emissions at the same time. The following three main purposes can be identified:

1. Energy supply and demand balancing over a long time horizon (e.g. seasonal) through storage of hydrogen or synthesis products and possible re-electrification of those products
2. Short-term balancing flexibility in the power system through load management enabled by smartly controlled electricity consumption of electrolysers
3. Supply of low-emission synthetic energy sources based on electricity using CO_2 from the atmosphere, stationary sources, biogas plants and industrial processes as a substitute for fossil fuels and combustibles as well as a raw material for industrial processes.

Flexibility to the power system can be provided by electrolysers, if operated in a system-supportive way- in particular, when abundant renewable electricity is available and production exceeds demand ("excess electricity"). Hydrogen produced by electrolysers or energy carriers produced in subsequent steps can be stored over different time scales, which is of value for seasonal balancing of energy supply and demand. This can help to cover demand during times when electricity supply is limited (e.g., in winter, when PV generation is low). Low-carbon fuels from P2X can substitute fossil fuels in multiple demand sectors and thereby reduce GHG emissions. Hydrogen, methane and liquid synthetic fuels can be used for various purposes: as fuels in engines, fuel cells and turbines, for heat and electricity production, as well as transport fuels, but also as feedstock in chemical and industrial processes. Some of these P2X products, such as synthetic methane, can be direct substitutes for fossil energy carriers used today, because they do not require changes in end-use technologies at the consumer side. Methanol as well as other liquid synthetic fuels can be upgraded to petrol, diesel and kerosene. However, direct use of hydrogen would not only require a new distribution infrastructure or further development of the existing gas grid, but also new end-use technologies, such as fuel cells that enable more efficient use of energy than many current technologies.

Figure 4.1: Combination of different hydrogen pathways attributable to P2X technology as part of one possible cost-optimal configuration of the Swiss energy system in 2050 under stringent climate mitigation policy [13]. The diagram shows the electricity used for electrolysis and the quantities of energy produced in P2X technology in the form of hydrogen and synthetic methane, as well as the use and distribution of P2X products. "H_2 direct use" refers to consumption of hydrogen in end-use sectors without being transported through the natural gas grid.



Compared to other new renewable energy sources, particular high potential for electricity from solar PV in Switzerland making P2X a key element in a sustainable energy system.

4.2 P2X as an important element in future energy scenarios

To which extent P2X products and the corresponding technologies can provide these multiple benefits to the energy system in a cost-efficient and climate friendly way depends on various key factors, including the overall system efficiency, and the environmental and economic performance compared to alternative energy technologies and to other climate change mitigation options. Depending on the market conditions, P2X technologies can contribute to a cost-optimal energy supply in Switzerland in the long-run.

Figure 4.1 illustrates benefits of P2X and one possible configuration of P2X in the Swiss energy system subject to scenario-specific assumptions on future developments.

Serving demand sectors (in particular the mobility sector) with low-carbon fuels based on electricity complements several other climate change mitigation measures and technologies in order to meet ambitious climate goals. Model-based calculations indicate an electricity consumption by P2X technologies in 2050 equivalent to about one third of the electricity generated from wind and PV in this year. With about half of the consumption during the three summer months, P2X technologies absorb excess electricity and convert it into clean fuels, which are partially seasonally stored to relieve the pressure on the electricity system in winter.

5 Costs of Power-to-X

Today, P2X is expensive but research and innovation is expected to reduce costs in future.

5.1 Levelized costs of P2X products today

The current levelized costs of producing hydrogen and synthetic fuels based on literature data (details provided in the supplementary report) as used in this study show substantial variations for the different P2X conversion pathways (Figure 5.1):

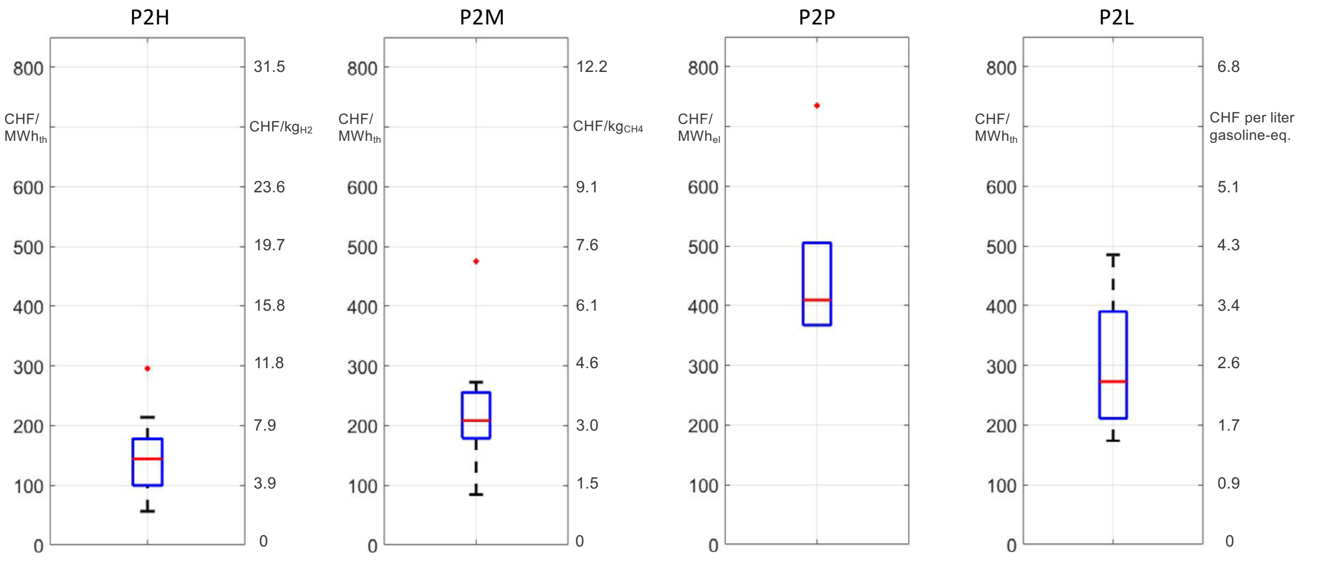
- 100–180 CHF/MWh$_{th}$ for hydrogen production (HHV based) (Power-to-Hydrogen: P2H)
- 170–250 CHF/MWh$_{th}$ for methane production (Power-to-Methane: P2M)
- 210–390 CHF/MWh$_{th}$ for synthetic liquid fuel production (Power-to-Liquids: P2L)
- 370–500 CHF/MWh$_{el}$ for electricity production (Power-to-Power: P2P)

The spread in costs is related to a number of factors, including uncertainties on the system designs as well as plant size and equipment needs, which is attributable to different levels of technology readiness. Also, costs provided in this white paper differ as a result of the assumptions made in the various underlying studies. Main determinants for the variations are the following cost factors:

- electricity price (for electrolysis),
- operation profile of the electrolysis,
- type of electrolyser,
- system efficiency.

As such, the bandwidths of production costs illustrate the cost implications of a range of specific system parameters and market conditions of P2X technology and underpins its manifold technology design and market configurations. As a consequence of site-specific characteristics (e.g. low-carbon electricity supply, CO_2 source, hydrogen demand, gas grid capacity) equipment needs and scale effects impact the investment needs associated to P2X. Literature indicates scale effects of a reduction of the specific investment costs by half when scaling up from kW to MW size levels [14], which is typical for large-scale industrial applications in the chemical and energy sector.

Figure 5.1: Distribution of the levelized cost for the various P2X routes based on current cost and performance data (representative for the year 2015; data sources are provided in the supplementary report). The boxplots include the median (middle quartile inside the box), 25th and 75th percentiles. The whiskers extend to the most extreme data points not considering outliers, and the outliers are plotted individually using the '•' symbol. For routes producing gas, data are based on the HHV; for the P2L route, the unit "CHF per liter gasoline eq." represents an energy-related cost matrix with limited comparability to retail fuel prices, which entail a significant tax component.

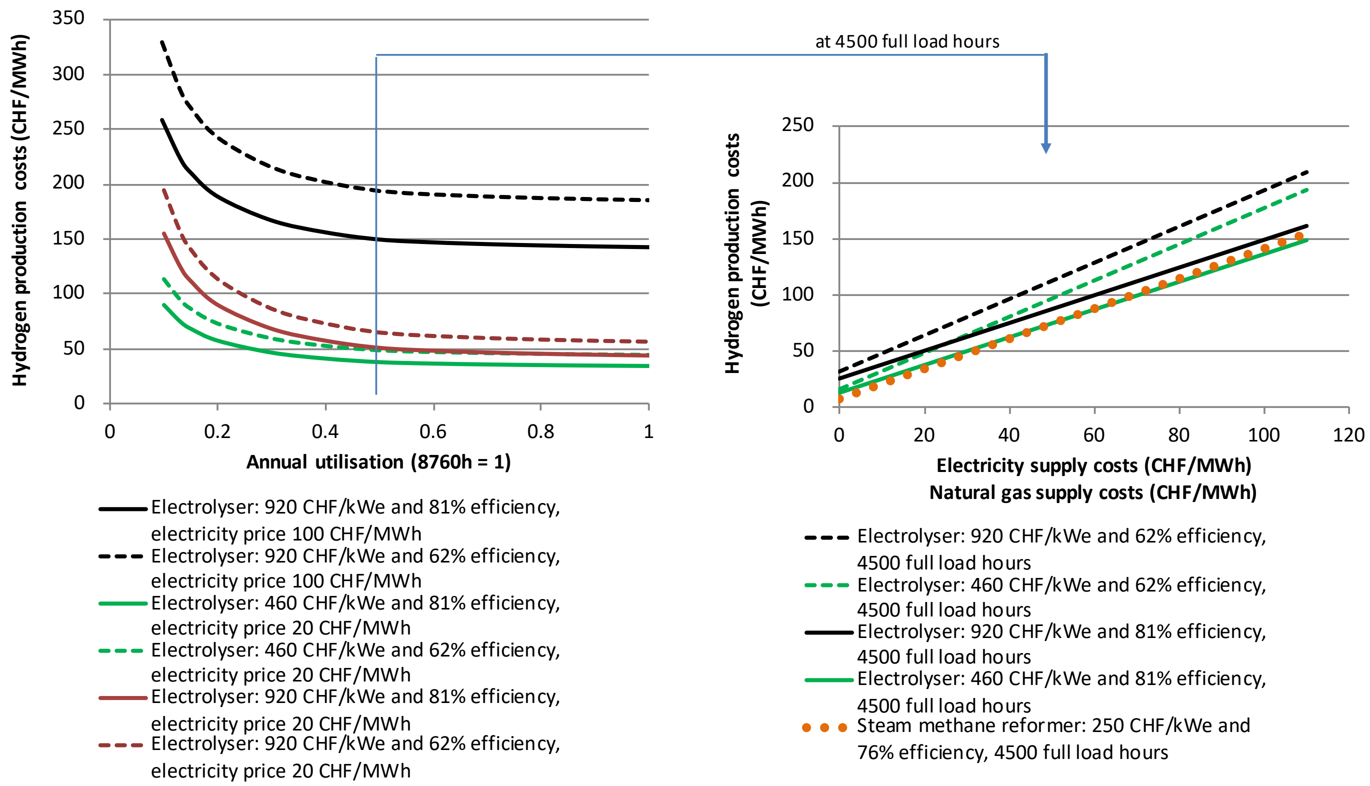


Key for cheap hydrogen: low-cost electricty and a few thousand hours of annual production.

5.2 Power-to-Hydrogen

With the electrolyser being the core component of P2X systems, hydrogen production costs substantially depend on the expenditures for electricity. For current P2H technology, the average across the studies depicts hydrogen production costs of 144 CHF/MWh$_{th}$. Depending on costs of electricity supply, the share of electricity in total hydrogen production cost for electrolysis can be 50 % and higher. When comparing the hydrogen production costs for electrolysis with alternative production processes, it becomes evident that producing hydrogen with P2H systems is currently more expensive than production based on the widely applied natural gas steam reforming process (around 60 CHF/MWh$_{th}$ of hydrogen at a gas price level of 40 CHF/MWh). Several comparative studies highlight this difference in production costs with a factor of two to five [15][16]. Electricity-based hydrogen production could become competitive, if natural gas supply costs substantially increase, e.g. as consequence of increasing world market prices for natural gas and/or environmental legislation, and if electricity supply costs for electrolysis are low [17]. As it can be seen in Figure 5.2, which depicts the generation costs for hydrogen as function of the fuel input costs in the right panel, very low hydrogen production costs for electrolysis can only be achieved at low electricity costs. If electricity is available at zero or at very low

Figure 5.2: Hydrogen production costs for different electrolyser configurations (regarding investment costs, efficiency) as function of the annual electrolyser capacity utilization (left panel) and as function of the costs for electricity supply (right panel). For comparison the right panel includes hydrogen production costs for steam methane reforming, which are depicted relative the costs for natural gas supply. For all hydrogen production technologies maximum 90000 total operation hours or 20 years lifetime and a discount rate of 5% is assumed.



Costs to provide CO_2 as input to methanation represent show high variability and depend on the carbon source.

Low-cost synthetic methane requires large methanation plants.

price (e.g. at times of low demand and high generation), hydrogen production costs would be mainly determined by the costs for equipment and operation and maintenance (O&M). According to the literature, low capital costs for alkaline electrolysers of 460 CHF/kW_{el} (green lines in Figure 5.2) might be achieved in 2030, which would translate into a production cost level of less than 40 CHF per MWh_{th} of hydrogen given high efficiency and very low electricity price levels (<20 CHF/MWh). Under less optimistic assumptions for the capital costs of the electrolyser (920 CHF/kW_{el} for an alkaline electrolyser in 2030), hydrogen production costs are above 40 CHF/MWh_{th} at an electricity price of 20 CHF/MWh_{el} and could increase to a level of more than 150 CHF/MWh_{th} at high electricity prices (black lines). Compared to alkaline electrolysers, today's specific investment costs of PEM electrolysers are roughly twice as high; however, research and development and scale effects in production might bring down costs close to those of alkaline technology. Under optimistic assumptions regarding the development of investments costs and comparably higher efficiencies, PEM electrolysers might be able to produce hydrogen at slightly lower costs than alkaline electrolysers in future. In addition, PEM electrolysers promise improved operating behaviour at partial and overload loads as well as reduced space requirements compared with alkaline electrolysers.

With increasing electricity supply costs, the efficiency of the electrolyser becomes more important for the system's profitability. However, potential efficiency increases are limited and may not be able to fully compensate high electricity prices. The annual utilization of the electrolyser has a smaller impact on the production costs, as long as operated at higher utilization rates. In the cases presented in the left panel of Figure 5.2, hardly any significant cost impact resulting from changes in the annual capacity utilization of the plant can be observed above 4500 full load hours per year (annual utilization factor around 0.5 in graph). This implies that there are not necessarily negative hydrogen production cost implications if P2X plants are not operated during seasons when electricity demand is high and renewable resource availability comparably low, as it is the case during the winter time. Very low utilization rates, however, have a significant impact on the amortization of the investments and hence on the costs of hydrogen production. For electrolysers operating about 900 full load hours per year, which is roughly equivalent to the annual full load hours of PV in central Europe, only the capital-related hydrogen production costs are in a range of 50–100 CHF/MWh_{th} (for investment costs of 460–920 CHF/kW_{el} and a discount rate of 5% and 20 years lifetime). From this, it can be deduced for a cost-effective production of hydrogen that either a significant reduction in the investment costs of the electrolyser is required if electricity can only be obtained at low cost for a few hours per year, or that P2X system operators can ensure cost-effective electricity over a longer period of time – i.e. also use sources of electricity that go beyond the exclusive use of surplus electricity from solar PV.

5.3 Power-to-Methane

Synthetic methane production requires additional process steps after electrolysis resulting in additional costs: investment costs for the methanation reactor, costs associated with an additional efficiency drop and costs for CO_2 supply. These additional costs increase the current average levelized production cost by about 70 CHF/MWh_{th} to 170–250 CHF/MWh_{th} for the P2M pathway. While future expected technology learning rates for methanation reactors seem to be lower than for electrolysers, unit sizes and up-scaling seem to have a substantial impact on costs. Depending on unit sizes, specific investment costs for current methanation reactors are in a range of 1150–460 CHF/kW_{th} for sizes of 1–10 MW_{th} (catalytic methanation), respectively. These capital costs translate into additional methane production costs on top of the hydrogen costs of about 20–40 CHF/MWh. Literature suggests that future investment costs could halve by 2030 resulting from technology improvements and scale-up effects. Another cost component for methane production are the costs associated with supply of CO_2. The specific energy and costs per unit captured CO_2 typically decrease with increasing CO_2 concentration. Very low costs can be achieved, if energetic synergies of biogas upgrading plants and P2M plants can be used, for instance when heat as by-product can be used efficiently in the P2M system.

The highest cost reported in the literature used in this study refer to direct CO_2 capture from the air (250 CHF per ton of CO_2 [18]), which results in additional costs of 50 CHF/MWh_{th}. However, since direct air capture technology is in an early commercial development stage, there exist substantial uncertainties related to the costs for direct air capture technology – capture costs of 600 CHF per ton of CO_2 [19] could imply substantially higher additional costs for methane production of up to 120 CHF/MWh_{th}. It is

Re-electrification of hydrogen leading to very high electricity supply costs.

expected that the costs of capture from other CO_2 sources, such as fossils power plants and cement plants, are lower since the CO_2 concentration of these flue gas streams is higher than the CO_2 concentration in the atmosphere [20].

5.4 Power-to-X-to-Power

When hydrogen or methane generated in P2H and P2M systems are converted back into electricity (P2P), levelized costs of energy conversion increase substantially. The costs of the P2P pathway depend on the conversion processes used to produce the synthetic gas (i.e. P2H or P2M), the type of re-electrification (e.g., fuel cell or gas turbine) and the hydrogen or SNG storage equipment, if needed. Here we focus on both P2P routes providing mid-term (on an hourly level) and seasonal storage. Currently, electricity can be produced in a gas turbine combined cycle plant with methane produced via P2M at total levelized generation costs of about 300 CHF/MWh$_{el}$; generation costs increase to 470 CHF/MWh$_{el}$ for a system of 1 MW$_{el}$ using P2H, hydrogen storage and a commercial-scale fuel cell. In this calculation, however, no revenues from the inherent co-production of heat are considered. If heat is used (e.g. for heating of buildings or in industrial processes) and revenues (or credits) can be accounted for, lower P2P costs can be calculated.
Only limited learning can be expected in the future for the re-electrification via traditional gas-based technologies (gas turbine or internal combustion engine). This implies that cost declines for the P2P route relate rather to the cost developments of electrolysers and methanation units. For fuel cell systems, future technology outlooks reveal high technology learning rates with reductions in specific investment costs by a factor of 2–6 until 2030. Combining the high fuel cell technology learning with the possible technology developments for electrolysers, total costs of hydrogen based P2P electricity generation could be reduced by two thirds until 2030 resulting in 150 CHF/MWh$_{el}$.

5.5 Power-to-Liquids

Current costs related to synthetic liquid fuel production in P2L plants show the highest range with 210–390 CHF/MWh$_{th}$. Similar to the methanation process, the costs for the production of synthetic liquid fuels substantially depend on the plant size. Ethanol plants can be built up to scales of multiple hundred megawatts, as practiced in Asian and the US. This leads to substantial costs reductions compared to small-scale plants. However, it also requires a corresponding infrastructure to supply and process inputs and outputs. The specific investment costs of a methanol synthesis reactor ranges from 120–310 CHF/kW$_{th}$; Fischer-Tropsch reactors cost about 80–300 CHF/kW$_{th}$. Already today, these reactor technologies are well established on global markets which makes cost reductions in the future unlikely. Therefore, future cost declines for P2L technologies will mainly be attributable to reductions of electrolyser costs and scale-effects when increasing plant sizes and production volumes.

6 Climate change mitigation related benefits

Climate benefits to be achieved only with low-carbon electricity.

6.1 Life Cycle Assessment (LCA) considerations

With electricity as major input, impacts of P2X processes on climate change – i.e. their GHG emissions – mainly depend on the carbon intensity of the electricity used for electrolysis [21]: LCA results show that using renewable electricity such as wind power or photovoltaics results in substantially lower life-cycle GHG emissions than conventional hydrogen production via steam methane reforming of natural gas, the major production route today. Also using current average Swiss electricity from the grid (including imports) is advantageous in terms of GHG emissions. Compared to steam methane reforming of natural gas, the threshold for the GHG-intensity of electricity used for electrolysis is around 210 g CO_{2eq}/kWh, which is roughly 50 % lower than the life-cycle GHG emissions of a natural gas combined cycle power plant or the current electricity mix in Europe.

For generation of synthetic gaseous fuels from H_2 and CO_2, the carbon intensity of electricity used for electrolysis, the carbon source as such and the carbon emissions associated with heat and electricity supply for CO_2 capture are the decisive factors regarding overall GHG emissions. Only electricity with a carbon intensity as low as hydro or wind power allows for a substantial reduction of life cycle GHG emissions compared to the use of natural gas (or other fossil fuels) as vehicle fuel. Due to the energy losses along P2X chains, direct use of electricity in BEV is the preferred option in terms of life-cycle GHG emissions, as soon as electricity supply is associated with higher GHG emissions than electricity from hydro or wind power plants (Figure 6.1). Among the P2X fuels, the direct use of hydrogen leads to lower climate impacts than the use of synthetic hydrocarbons. In case of hydrocarbons, the origin of CO_2 is a decisive factor: While using synthetic fuels with CO_2 captured from the combustion of fossil fuels or the use of mineral sources always represents an addition of CO_2 to the natural carbon cycle, capturing CO_2 from the atmosphere or biogenic sources in principle allows for the synthesis of carbon neutral energy carriers [22]. In general, process integration with use of "waste heat" from conversion processes improves the environmental footprint of P2X.

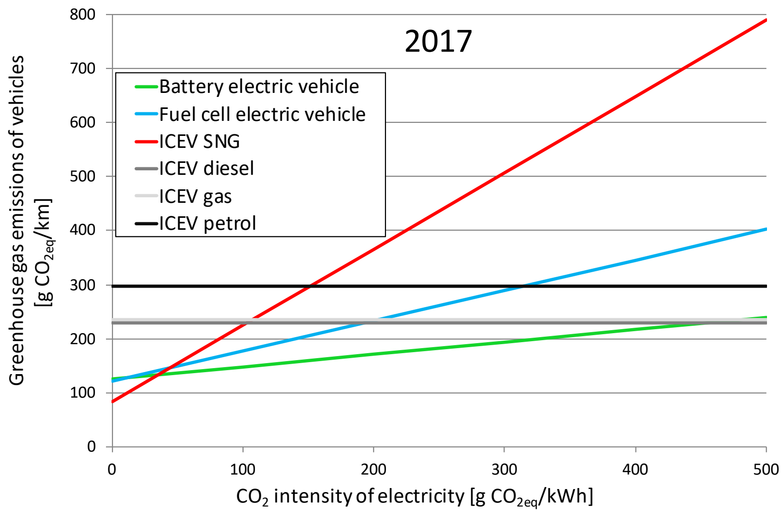


Figure 6.1: Life-cycle GHG emissions per kilometer for different current passenger vehicles and fuels as a function of the GHG emission content ("CO_2 intensity") of electricity used for battery charging, hydrogen or SNG generation, respectively [23]. Here, CO_2 for SNG production is captured from the atmosphere and represents no additional addition to the carbon cycle when SNG is combusted. ICEV: Internal combustion engine vehicle. CO_2 intensities of specific electricity sources in Switzerland for comparison: hydropower ca. 10 g CO_{2eq}/kWh, wind power 10–30 g CO_{2eq}/kWh, PV 50–100 g CO_{2eq}/kWh, Swiss mix 100–150 g CO_{2eq}/kWh, natural gas combined cycle 400–500 g CO_{2eq}/kWh [24].

6.2 CO_2 sources

For the production of synthetic methane and liquid synthetic fuels, a carbon source is required which can be based on biogenic, mineral or fossil feedstock; also the atmosphere can act as CO_2 source. Such CO_2 sources need to be available in sufficient

Location of P2X production matters: direct access to renewable power and sufficient amounts of CO_2 are required.

quantities at competitive costs. Capturing CO_2 needs energy and infrastructure, unless biogas is directly used as feedstock for direct CO_2 methanation. Ultimately, when the synthetic gaseous or liquid fuel produced from CO_2 and hydrogen is used for energy conversion (e.g. in a car with combustion engine or in a CHP), CO_2 will be generated again as combustion product. As such, P2X technologies are able to shift emissions in time, but they do not represent a net carbon removal from the carbon cycle.

One possible source of CO_2 is biogas produced from biogenic substrates (sewage sludge, green wastes, agricultural residues and manure) by means of anaerobic digestion. Depending on the substrate and the process, the CO_2 content of the biogas can reach up to 45 %. If the CO_2 is captured from the biogas, methane remains a major product which can be fed as biomethane into the gas grid or directly used on-site. Today's existing biogas production in Switzerland (around 150 biogas plants [25]) represents a CO_2 supply potential of about 0.14 Mt CO_2 per year.

While the feedstock potential from sewage is already used largely today, anaerobic digestion of agricultural crop by-products, green wastes and especially manure has the potential to strongly increase the amount of available biomethane and biogenic CO_2. Further potential biogenic CO_2 sources refer to the conversion of wood residues through indirect wood gasification and methanation of the producer gas, followed by CO_2 removal. Using one quarter of the unused wood within the corresponding gasification plant would double the flow of biogenic CO_2 available from existing biogas plants.

Other potential sources of CO_2 are large stationary combustion units and industrial plants, such as waste incineration plants (29 in Switzerland) or cement plants (5 in Switzerland); however, location of the plants matters [26]. Using these sources implies to separate CO_2 from a gas stream, which contains nitrogen and unburned oxygen, as well as sulfur oxides, nitric oxides and many other impurities. A typical CO_2 concentration in the flue gas of these point sources is below 20 %. Today's waste incineration plants are responsible for roughly 60 % (4.2 $MtCO_2$) of the CO_2 rich flue gases in Switzerland and the five cements plants for 38 % (2.7 $MtCO_2$). All the biomass-based plants represent minor share. Although, from a technical point of view, these sources could provide substantial amounts of CO_2, their vicinity to large-scale production sites of renewable generated electricity could be problematic. If the CO_2 source is close to the P2X plant and to the electricity production source, transport infrastructure, and hence costs, can be reduced.

Direct air capture allows to use CO_2 contained in the ambient air, i.e. already being part of the natural carbon cycle. However, the low CO_2 concentration in the air below 0.1 Vol.-% makes direct air capture more energy intensive and expensive compared to many other CO_2 capture options. With pilot plants at several sites, direct air capture technology is being developed and tested in Switzerland today.

7 Power-to-X and the Swiss electricity market

P2X – a competitive seasonal electricity storage option.

7.1 P2X as service provider

P2X technologies can support the power grid in two ways:

1. to balance supply and demand and to manage the excess of electricity generated from non-dispatchable fluctuating renewable electricity sources
2. to provide ancillary services to stabilise the grid frequency

Which services P2X is actually able to provide depends on the system design. If no re-electrification technology is installed, electrolysers can be operated as flexible electricity consumers. For such an operation, hydrogen storage is required, since hydrogen demand is less flexible. Equipped with a hydrogen storage and a re-electrification unit, more system services can be offered. In particular, positive and negative balancing power simultaneously. Yet another aspect can be considered: if installed at properly selected locations in the grid, P2X plants would also have the potential to relieve the grid infrastructure from line and transformer overloads by absorbing locally the generated power and eventually also to control the voltage if it exceeds the given limits. In practice, it will be rather difficult to install P2X plants exactly at locations of the Swiss electricity grid where needed for these purposes. To what extent P2X can provide these system services in a cost-efficient way depends on the market conditions and characteristics of alternative technologies. These alternatives include flexible electricity supply via imports and exports, flexible power plants, alternative storage options and demand side management [27].

7.2 P2X as electricity storage option

In order to balance electricity supply and demand on a short time scale (day/night), pump storages, Li-Ion batteries, and potentially compressed air energy storages (CAES) are able to provide this service at lower costs than P2X systems with re-electrification. Assuming 365 storage cycles per year, the levelized cost of energy storage of a pump storage is about 50–70 % lower than the costs of P2P systems (at 370–500 CHF/MWh$_e$ as shown in Figure 5.1), while the corresponding costs of battery systems are about 20–30 % lower. Taking into consideration the rapidly developing battery market, this cost difference of batteries compared to pump storage power plants can be expected to become (much) smaller in future. When comparing storage systems, important parameters are the number of cycles, the storage efficiency, the power-to-energy ratio and the composition of the costs. Compared to Li-Ion battery systems, P2X systems have higher storage losses as well as higher costs for the conversion equipment, which results in a comparably high share of capital for the energy charging unit as well as higher operation costs if used for daily balancing purposes. Conversely, if P2X systems are used for seasonal storage with one cycle per year, they are able to convert and store energy at lower costs compared pump storages and Li-Ion batteries. This results from the low costs related to the storage part of P2X systems (e.g. in hydrogen vessels or underground) in comparison to a hydro dam or the batteries.

Technically, P2X technologies with re-electrification can provide seasonal flexibility to balance electricity supply and demand. However, this would require substantial investments and dedicated market mechanisms. P2X technologies connected to large storages for methane or hydrogen with the option to re-electrify these energy carriers offer a unique option for the electricity system addressing large variations of seasonal production and consumption patterns. Currently, there is no storage option within Switzerland that is able to absorb large quantities of electricity (e.g. from solar PV) in summer and to store the energy for producing electricity again in winter when demand usually is high and electricity production from PV is low.

Alternatively to shifting electricity from one season into another using P2P, other flexibility measures could be deployed. One option is to use the flexibility the international trade of electricity offers by exporting electricity during the summer and importing electricity during winter. This scheme is already practiced in Switzerland today as the consequence of the seasonal availability of hydropower. Applying this scheme in the future imposes the risk that similar production patterns across Europe lead to the situation that Switzerland exports electricity at times when market prices are low while imports are required during times of high electricity prices. However, comparing the levelized cost of electricity storage of the entire P2P pathway (370–500 CHF/MWh$_{el}$) with the current expenditures for electricity trade (corresponding to specific average costs of 40 CHF/MWh$_{el}$ as average in 2016), trade represents a less expensive option to provide seasonal flexibility. This statement is supported by the price developments on the spot market, where, for instance, more than 95 % of the trade volume in Germany was traded at prices below 50 €/MWh in 2016 [28]. The corresponding differences in

P2X units can be pooled to provide electricity system services.

the average monthly spot market prices did not exceed 16 €/MWh. This comparison of electricity prices and P2P storage costs shows that electricity price spreads between months or seasons would need to be much higher as observed in the recent past until P2P becomes a cost-efficient monthly or seasonal flexibility option. Model-based long-term analyses for the year 2030 indicate increasing prices for electricity on European wholesale markets, if natural gas prices and prices for CO_2 emissions certificates increase [29]. However, the market price levels would be still below optimistic assumptions for the electricity production costs for the P2P pathway. It can be expected that rising electricity price spreads applicable to the market participants would also trigger the deployment of further supply and demand flexibility options, such as flexible power plants, digitalized demand side response and energy saving measures. An example for the supply side would be power plants with combined heat and power production operated during the intermediate seasons and the winter time when the heating demand is high and electricity production from solar PV is low. On the demand side, for instance, higher prices during the winter season could trigger investment shifts from heat pumps with lower efficiencies to heat pump systems with high energy performance. Longer periods of low prices during the summer would provide incentive for broader deployment of electricity-based applications during this time which would also include electricity-based hydrogen production. Model-based scenario analysis shows multiple flexibility options being available to ease long-term supply and demand variations in the future Swiss energy system, of which P2X systems with seasonal storage and re-electrification represent a solution with comparably high costs [13].

7.3 Grid stabilization via P2X

From a technical point of view, P2X systems can contribute to stabilize the grid and offer such services on the ancillary services markets, possibly as part of a virtual power plant. The existing electric power system has been built on power plants in which electricity is generated centralized using large conventional synchronous generators. Their control loops and inertia resulting from the rotating masses stabilize the frequency of the electrical power system. With increased deployment of new renewable energy, i.e. wind and solar PV, and the phase out of nuclear power generation, the conventional power generation is gradually replaced by an increasing amount of rather small power plants using renewable energy sources. These power plants are decentralized and connected to the grid at lower voltage levels through power electric devices without any mechanical inertia, which would directly contribute to the short-term stability of the power system. Gas turbine technologies fueled with hydrogen or methane produced in P2X technologies could provide this benefit at reduced climate impact compared to the use of natural gas. On top of the inherent stability provided by rotating masses, a three stage ancillary services mechanism referred to as primary, secondary and tertiary control reserves exists in order to ensure a stable operation of the today's electrical power system. From the technical point of view, P2X systems can participate in all three markets. Beyond the proof of sufficiently flexible operation, direct participation on the control reserve markets requires the ability to offer a minimum bid of 1 MW or 5 MW, depending on the type of control reserve. Since today's electrolysers are typically smaller, this would require P2X technologies to be part of a cluster of smaller plants. Participating in the market through clustering averages the earnings at the level of 60 % of the market price. However, through pools not only the minimum bid size of 5 MW can be overcome, but also the control reserve can be offered asymmetrically, i.e. only into one direction when providers offer a change of set-point of either only the consumption (–) or the generation (+) by the committed amount of reserved power. Moreover, through a pool the service provider can bid only for a few days or hours instead of a whole week; thus, its flexibility is higher through the pool. Based on the data provided by Swissgrid for 2017, an overview of all three stages of frequency control for Switzerland is provided in Table 7.1. The total capacity for providing ancillary services was small compared to the installed generation capacity of the entire electricity system: a primary control reserve of about ±70 MW, and a secondary and tertiary reserve in the range of ±400 MW. The control reserve markets are competitive with large hydro power plants dominating these markets in Switzerland. Since 2015, the markets are also open for small hydro power plants, biomass, wind and solar PV power plants, which lead to an increase in the number of participants.

Among the upcoming electricity-based storage systems, and based on typical and expected technology characteristics, batteries seem to be appropriate as balancing systems on the market for primary and secondary control reserves, while P2X is rather considered as a balancing option in the

Provision of system services can generate some additional revenues for plant operators but competition on Swiss market to increase in future.

Ancillary Service Control reserves	Weekly average in 2017 [CHF/MW]	Size of reserve [MW]	Min bid size [MW]	Max bid size [MW]	Estimated market size [Mio CHF/Year]
Primary reserves	2466	±68	1	25	10
Secondary reserves	5535	±400	5	50	120
Tertiary reserves (–)	680	–300	5	100	10
Tertiary reserves (+)	450	+450	5	100	10

Table 7.1: Ancillary services, control reserves in Switzerland 2017 [30] (Swissgrid, "Ausschreibungen Regelleistung 2017"). Providers of secondary and tertiary control reserves are paid also for the provided energy according to the energy market price increased by 20%.

secondary control reserve market. Battery storage systems are now entering the primary control market (e.g., EKZ installations in Dietikon and Volketswil with capacities of up to 1 MW and 18 MW, respectively) and new technical approaches (often referred to as "virtual power plants") are already available on the market. These new market participants increasingly provide primary and secondary control reserves through coordinated and aggregated management of flexible loads (such as heat pumps) and smaller battery energy storage systems for households.

Even though P2X systems are able to provide electricity grid services, current economic conditions on these markets alone are insufficient to provide incentives for P2X technology investment and operation. The prices on the ancillary services market have shown a declining trend over the past years. Conversely to the spot market for electricity, which follows a market clearing rule with one uniform market price for the trading period, remuneration on the ancillary services market applies the "pay-as-bid" scheme where each successful bid is remunerated as offered on the market. In 2017, system services were remunerated with on average 2470 CHF/MW per week on the primary reserve market and 5540 CHF/MW per week on the secondary reserve market. This corresponds to potential revenues on today's ancillary services markets in the range of 10 Mio. CHF/year for primary reserve and 120 Mio. CHF/year for secondary reserve. These average weekly revenues compare to total weekly costs of electrolysers of about 10000 CHF/MWh_{el} (with investment costs of 920 CHF/kW_e, a 3% share of fixed operating and maintenance costs and an interest rate of 5% as well as electricity procurement costs of 40 CHF per MWh, 4500 hours of use per year and an electrolysis efficiency of 62%) of which the capital-related expenditures represent about 1420 CHF/MW_{el}. For a P2X plant with a fuel cell re-electrification unit, the capital-related expenditures even exceed 20000 CHF/MWh_{el} per week. This comparison indicates that operation of P2X technology on ancillary services markets can provide some additional revenues, but these markets cannot cover the full costs. Whether P2X technologies can compete on these markets depends on other market participants. Swissgrid aims at enhancing the market for control reserves and to further promote "virtual power plants" to participate on these markets. This is expected to unlock additional flexibility potentials available on the supply and demand sides, which would lead to a further increase of competition.

The future demand for control reserve capacity is unknown. However, model-based calculations indicate an increasing need in future. According to [13] up to 50% more secondary positive control reserve compared to today will be needed in 2050 due to very high shares of solar PV and wind in the Swiss electricity system, while the peak of the required positive reserve capacity shifts from winter to summer. A large share of the additional reserve capacity could be provided by hydro power plants complemented by other flexible generation and battery systems.

Synthetic methane is 2–3 times more expensive than natural gas today, but close to sales prices for biomethane.

Synthetic methane can easily be stored over longer periods.

8 Power-to-X and the Swiss gas market

Integrating P2X technologies into the gas market has two main advantages:

1. Direct substitution of fossil energy carriers using existing infrastructure
2. Access to large scale storages in the European gas network, e.g. the underground gas storage in the French Jura

The Swiss natural gas market hosts energy consumers responsible for 11.5% of the Swiss gross energy consumption in 2016. Nowadays natural gas is mainly used in households, the industry and in services for heating purposes and thus underlies seasonal fluctuations with the highest consumption during winter. The natural gas transport infrastructure, a pipeline network, has been built to supply the midland, the east, the west and central Switzerland. Currently, Switzerland has access to a total storage capacity of about 1600 GWh, equivalent to less than one month of average annual natural gas consumption. 5% of this storage capacity relates to the national gas grid and its ability to absorb higher quantities of natural gas through pressure increase or stored in small scale vessels. 95% refer to the storage site in the France which is currently dedicated to ensure supply security in Switzerland.

8.1 Sythetic methane

The gas market might play an important role in the transformation of the Swiss energy system: compared to other fossil energy carriers, environmental impacts of natural gas are low; and, natural gas can be gradually replaced by biomethane and synthetic methane using the existing infrastructure. Beyond new gas supply technologies, the gas market might face other changes in future: demand for methane will likely decrease as a result of increases in energy efficiency in the building sector; and, large gas power plants might enter the market as consequence of the phase-out of nuclear power.

The Swiss gas industry supports Swiss biomethane and P2X technologies. The gas association VSG aims at an annual biomethane production of 4400 GWh until 2030 by better exploiting the existing potential, by using P2X technologies and by imports under an international register.

Comparing the production costs of synthetic methane with the current average consumer prices for natural gas reveals a difference of about 100–180 CHF/MWh of methane, equivalent to a CO_2 tax level of about 500–900 CHF per ton of CO_2. The current price for natural gas is low with an average across all customers of about 70 CHF/MWh (2018) including the CO_2 tax of 17.7 CHF/MWh. This price is excluding value added tax (VAT) and grid supply costs of around 10 CHF/MWh. The gas market offers gas tariffs for 100% biomethane of around 150 CHF/MWh – mostly private customers are willing to pay this premium. Biomethane prices do not need to include the CO_2 tax, but private customers have to pay for grid supply fee and VAT. Thus, the price difference between biomethane and SNG is much smaller than the price difference between natural gas and SNG.

8.2 Hydrogen

Besides SNG, hydrogen might enter the gas market, either integrated into the natural gas network or with a separate distribution infrastructure. Today, the Swiss hydrogen market is very small compared to the Swiss natural gas market with around 1% of its size. Hydrogen is used for small-scale industrial applications, e.g. to prevent oxidation in manufacturing processes. If large quantities of hydrogen are needed for industrial processes, mainly in the chemical sector, production of hydrogen usually takes place on-site. This implies that hydrogen is often not a good trade on a market. Hydrogen for mobility is currently negligible. Due to the small hydrogen market, no distribution grid for hydrogen exists. However, hydrogen can be can be injected in the existing gas grid to a maximum of 2% of the transported volume of natural gas. There are discussions about increasing the maximum volumetric injection share up to around 10%, but further investigation (preferably in a European context) is necessary in order to better understand the implications of higher hydrogen shares for the operation of the grid and for the applications at the end-users.

The Swiss hydrogen market is a competitive, unregulated market with substantial price variabilities. Consumer prices are not publically available. Current common prices derived from industrial companies indicate prices for hydrogen production and transport to the customer of around 1 CHF/Nm^3 and around 10 CHF/kg (equivalent to 250 CHF/MWh$_{th}$) for mobility applications. In contrast to international literature, Swiss hydrogen producers claim that their prices for hydrogen production and its transport are the same for steam methane reforming of natural gas and electrolysis. Main reason is that transport of hydrogen with trailers contributes most to final consumer prices and therefore, the production route (electrolysis or steam methane reforming) does not play such an important role. Beside the refinery in Cressier and the chemical plant

Today, the hydrogen market in Switzerland is very small with price varabilites and no centralized distribution infrastructure.

in Visp, there are no big chemical industries in Switzerland that produce hydrogen as cheap "by-product". For decentralized hydrogen demand, Swiss hydrogen producers expect that the future hydrogen demand can be covered by electrolysis fed by renewable electricity, which would require a continuous low-cost electricity supply.

Future prospects for hydrogen applications depend on the ambitions to reduce CO_2 emissions in the energy end-use sectors and the competitiveness of hydrogen applications to alternative options. According to model-based analyses, the direct use of hydrogen to satisfy energy demand can grow towards 2050 to about 3 TWh/a (2 % of final consumption), if stringent climate policies will be in place.

9 Power-to-X and the transport sector

9.1 Aviation

Synthetic electricity-based fuels represent one of the few CO_2 emission reduction options for aviation, which is entirely based on fossil fuels and exhibits large growth rates today. Replacing liquid fuels and current airplane technology with electric propulsion systems is difficult because of the high fuel energy density required.

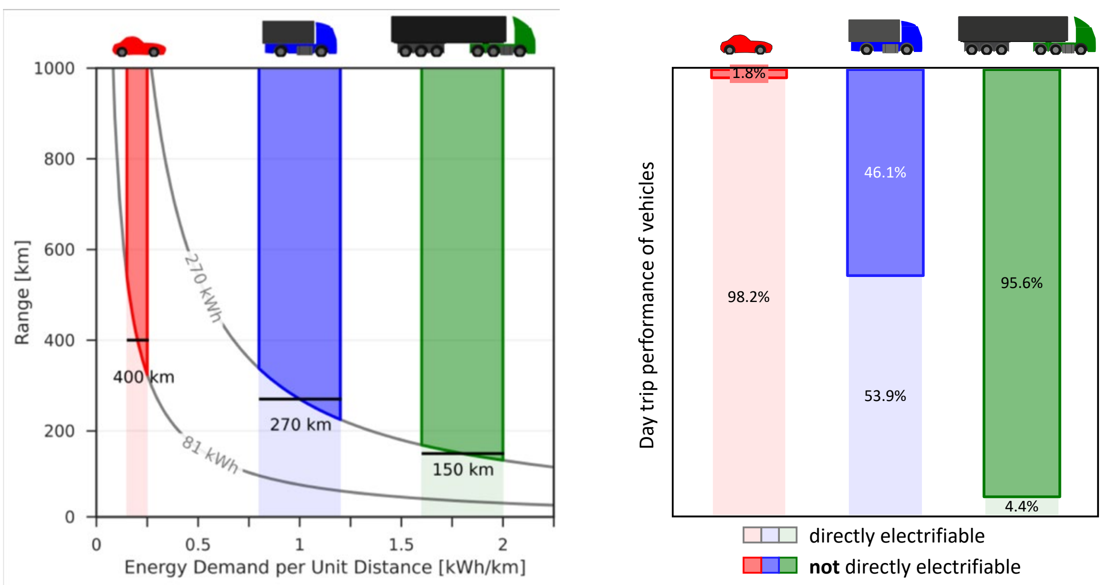
Currently, there is no legal obligation to account GHG emissions from international aviation and reduce these emissions. However, in 2016, 191 member states of the International Civil Aviation Organization (ICAO), including Switzerland, agreed on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [31]. It aims at freezing CO_2 emissions at 2020 levels and at carbon-neutral growth from 2021 on. Synthetic aviation fuels might play a major role in achieving these goals. Since regulations are not yet finalized and since production technologies for liquid synthetic fuels like e-kerosene are not yet available at large scale, the following will focus on road transport.

9.2 Road transport

Synthetic P2X fuels can reduce the carbon footprint of road transport, which is currently responsible for almost 40% of the Swiss domestic CO_2 emissions. Passenger cars contribute around two thirds of these emissions. A substantial and quick reduction of mobility related GHG emissions requires drastic changes of vehicle technologies and fuels. Evaluating the potential of synthetic fuels needs to distinguish between new and existing vehicles – both need to be addressed.

While new vehicles can be electrified directly via electric drive trains (BEV or FCEV), the existing fleet can be electrified indirectly

Figure 9.1: Direct vs. indirect electrification of cars and trucks. Left panel [33]: Trade-off between specific energy demand and range for cars (red), rigid trucks (18 t, blue) and articulated trucks (40 t, green). The hyperbolic curves indicate the amount of energy that is stored in a vehicle. The displayed two curves show specific battery capacities corresponding to currently available vehicles. Their intersection with the typical specific energy demand of each vehicle type results in the maximum distance that can be driven without recharging. Hence, the area below the three curves in the plot indicates the application space for BEV (direct electrification). Right panel (adopted from [33]): Share of observed day trip performance that can directly be electrified (as share of total vehicle kilometers) given the maximum range identified in the left panel. Calculations based on [32].



Long-distance, heavy-duty vehicles as first P2X targets in mobility.

Driving patterns determine preferred fuels.

with synthetic fuels based on renewable electricity. Common lifetimes of passenger vehicles (10–20 years) set a temporal limit for the substitution of the existing fleet with new technologies – conventional drivetrains will still hold large vehicle shares in the mid-term future and also existing infrastructures and their transformation need to be taken into account.

Technology shifts in the mobility sector are partially determined by driving patterns of consumers [32]. Compared to the average (short daily travel distances), few high-mileage vehicles contribute disproportionately to the total mileage of the Swiss vehicle fleet. The shares of short- vs. long-distance drivers correlate with the shares of directly and indirectly electrifiable vehicles depicted in the right panel of Figure 9.1. Currently, not all new vehicle technologies can satisfy all drive patterns. Battery electric vehicles (BEV) are limited in terms of range – current passenger vehicles have ranges in the order of 200–400 km, small trucks around 250 km (left panel of Figure 9.1); battery electric heavy-duty trucks are hardly available yet. Figure 9.1 shows that the indirect electrification of the truck fleet in particular offers great application potential for synthetic fuels, as the range of applications for battery electric vehicles is limited here. Relying on existing vehicle technology allows for benefits of scale, and hence, economic advantages.

Considering the entire energy conversion chain (well-to-wheel), vehicles operated with P2X fuels need roughly 2–4 times more electricity than BEV. However, P2X technologies allow both geographical and temporal (both short- and long-term) decoupling of fuel production and use, which can be an important asset in a future energy system

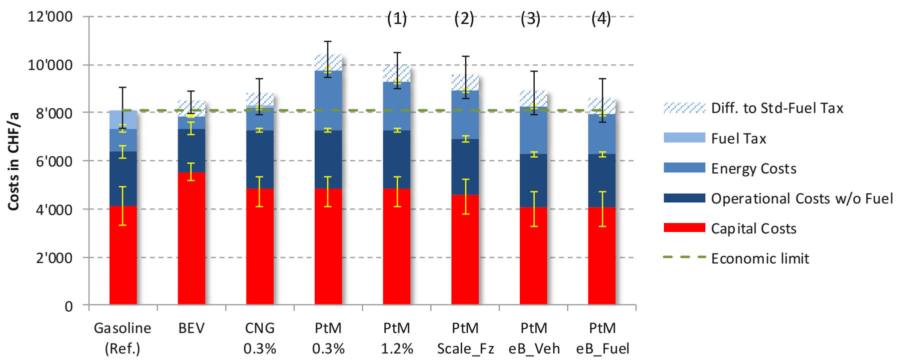


Figure 9.2: Total cost of ownership (TCO) calculation for a gasoline vehicle as reference, a BEV, and vehicles using CNG or SNG (P2M), both with a basic market penetration of 0.3%. P2M vehicle costs are also calculated considering the following cost reduction effects: (1) increased market penetration of CNG vehicles from 0.3% to 1.2%; (2) reduced purchase price due to increased sales volumes; (3) considering environmental benefit of the vehicle; (4) considering environmental benefit of the synthetic fuel.

with high shares of intermittent renewable power generation. An optimal combination of the high efficiency potential of BEV and flexibility potential offered by P2X fuels might lead to a more substantial CO_2 reduction than BEV alone. Direct and indirect electrification (via BEV and P2X fuels) are therefore complementary

The total cost of ownership (TCO) of passenger cars show rather small shares of energy costs (fuel/ electricity) compared to other cost components (Figure 9.2). This has positive implications for the deployment of synthetic fuels. Without taxes, synthetic fuels are currently 2–3 times more expensive than fossil fuels (at the filling station). Fuel distribution and fueling infrastructure costs for SNG and hydrogen strongly depend on the degree of utilization – the more SNG vehicles and FCEV in operation, the lower the costs per fueled energy unit. This opposite to BEV: the more BEV charged from the grid, the higher the expenses for power lines and charging stations.

Figure 9.2 shows the impact of increased sales and a potential monetization of CO_2 emission reduction for compact SNG cars compared to current gasoline cars or BEV in terms of annual costs. While the total cost of ownership are substantially higher for SNG (P2M) cars today, increasing market shares (from 0.3 % to 1.2 %) and monetizing CO_2 reductions according the CO_2 regulations for the new passenger car fleet would result in very similar annual costs for both gasoline and SNG vehicles.

Essentially, P2X fuels can become competitive under certain conditions:

1. A high degree of maturity of P2X technologies.
   This maturity is given today for hydrogen and methane production in mid-size

While gaseous fuels (P2M) require an area-wide construction of gas filling stations, synthetic liquid fuels (P2L) can be integrated directly into the existing infrastructure.

P2X plants. Synthetic liquid fuel production is not yet on the same level, but is supposed to achieve it soon.

2. A broad rollout is needed for an economic implementation of a P2X fuel. While this would be easy for synthetic liquid fuels relying on the existing vehicles, logistics and filling stations, it is more challenging for SNG. Market shares for newly sold SNG vehicles would have to be substantially increased to at least 24%. Only such market shares allow for amortization of high fueling station investment costs.
3. A beneficial regulation framework. Within the draft CO_2 regulations for passenger cars and light duty trucks in Switzerland, CO_2 reduction due to synthetic fuels is taken into account and the environmental benefits may be monetized (see (4) in Figure 9.2).

The entry point for hydrogen might be heavy-duty trucks, given the exempt of electric powertrains from the heavy good vehicle tax (LSVA). This represents an important benefit, since 50% of TCO of heavy-duty trucks are statutory levies (LSVA and fuel tax). Due to the exemption of statutory levies for electric powertrains, hydrogen driven fuel cell trucks may have similar TCO as diesel trucks already today, even if the truck purchase price is three times higher (Figure 9.3). Hydrogen fuel cell passenger vehicles, however, do not profit from such boundary conditions: due to the high purchase price, the capital costs rise substantially and are not compensated for by low operational costs.

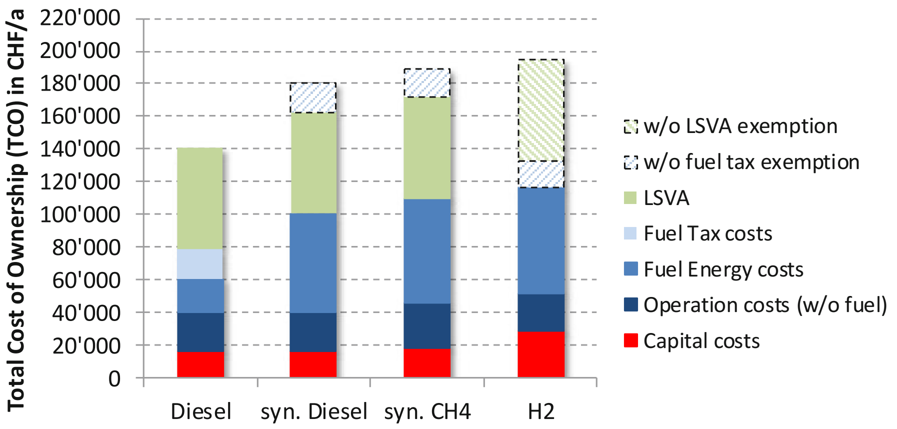


Figure 9.3: TCO calculation for a 28t truck using diesel, synthetic diesel or methane, or hydrogen with a fuel cell (H2).

10 Power-to-X in industry

Swiss refinery is largest hydrogen consumer, further small-scale consumers in chemical industry.

10.1 The role of hydrogen

Hydrogen is a major energy carrier and feedstock for production of base chemicals, synthetic fuels and lubricants. Hydrogen can also be used as reduction gas or inert gas, for instance in the iron ore industry as well as for flat glass production. In some industrial production processes, hydrogen is a by-product and either sold or used elsewhere, which is the case for hydrocarbon cracking in refineries, for the Chlorine-alkali electrolysis and for the production of acetylene. In large production clusters of the chemical industry (e.g. in Leuna/Bitterfeld and in the area of Hamburg in Germany) hydrogen networks connect producers and consumers. Large production facilities and integrated networks for chemical products allow for supplying hydrogen at comparatively low costs. In such networks, P2X technology can be integrated as complementary hydrogen supply technology. Often, industrial processes run continuously and require reliable input of feedstock such as hydrogen. Therefore, P2X technologies with intermittent renewable electricity supply need to be designed with sufficient production capacities integrated hydrogen storage to prevent feedstock supply interruption. The competitiveness of hydrogen from P2X technologies, however, depends substantially on the existence of stringent climate policy, given the current low hydrogen supply costs resulting from production from fossil fuels.

10.2 Swiss industry

In Switzerland, the industry sector accounted for 18 % of the final energy demand in 2015, with natural gas and electricity accounting for more than 60 % of the total industrial energy demand. Almost half of the final energy demand was used for the generation of process heat. With more than 20 % share of the industry's final energy consumption, the chemical industry represents one of the sectors with the highest consumption. Conversely to other countries, where mass-production of basic chemicals represents a significant share of the chemical industry, the Swiss chemical sector is very versatile. It produces more than 30'000 products and rather targets production of specialized products, e.g. pharmaceutical products, vitamins, fine chemicals, and substances for diagnostics and plant protection. Hydrogen consumption in Switzerland in 2018 amounted to about 13'000 tons. The refinery in Cressier represents the largest single consumer with about 85% of the total consumption [34]. Other small-scale consumers belong to the watch industry, chemical and pharma industry, and synthetic stone production. About 90 % of the hydrogen is produced from fossil fuels. Hydrogen for the refinery is produced on-site from naphta and methane, hydrogen for the LONZA chemical plant in Visp from liquefied petroleum gas. A small fraction is produced from electricity either via chlor-alkali electrolysis or water electrolysis. Since the closure of the fertilizer production in Visp in early 2018, which was besides the refinery a major consumer of hydrogen, there is a significant overcapacity in hydrogen production in Switzerland with about 21'500 t/a.

11 Integration of Power-to-X in multiple markets

Revenues from selling products and services on different markets would increase profitability of P2X.

Combining different applications and thus the potential of serving different markets is a key advantage of P2X technologies. The different pathways of P2X allow for a number of distinct applications, serving the different markets described. Accordingly, business cases of P2X can potentially build on multiple revenue streams. From an economic point of view, the multi-market/application nature of P2X has two main advantages:

1. It provides the option to expand an investment in the future by adding further process steps
2. The availability of several distinct markets allows for operational flexibility

Several applications can also be combined with the provision of ancillary services for power grids. The possibility to serve different markets not only potentially increases revenues, but also potentially affects the overall market risk exposure and hence the cost of capital of investment projects. The extent, to which the multi-market flexibility creates a valuable real option (either in extension investment or in production flexibility) and accordingly improves the risk profile of investment projects, depends on the correlation of prices that can be achieved on the different markets. Due to the low correlations of prices for natural gas (methane), electricity and capacity reserves, the combination of these strands can lead to lower overall risks. The "real option" of extending for instance an electrolysis plant with a methanation process could therefore become relevant in the future.

The key limitation for the combination of applications is the location of the P2X plant, which determines the access to (low-cost) electricity, the gas network, a potential heat network, as well as a CO_2 source. Given the magnitude of investment costs for utility-scale P2X units, their location should be chosen with the optionality for later extension in mind.

12 Power-to-X and innovation policy

Research and innovation should focus on optimal integration of P2X in the energy system.

Stable innovation conditions needed to facilitate learning-by-using on domestic markets.

12.1 Strengthening the domestic market

While currently P2X technologies still comes at high costs, there are several implications for policy makers who aim to enable or induce learning-by-doing, -using, and -interacting and thereby drive P2X down along its cost learning curve. Political decision-makers can take measures to promote P2X technologies via the incentive of learning processes. As most sub-systems can be regarded design-intensive technologies, learning-by-using and interaction of technology integrators with technology users seem to be the most relevant learning processes. To this end, a home market is conducive, characterized by stable demand [35]. Accordingly, policies strengthening the domestic market represent more effective innovation policies than mere technology subsidies. Due to the relatively low manufacturing complexity of the components, large and increasing market scale for the production of P2X components is not required, which could be regarded unrealistic anyway in the case of Switzerland.
Due to the low complexity of pure Power-to-Hydrogen-to-Power technology setups, substantial learning-by-using, -doing- or -interacting effects cannot be expected. This is different for methanation, Fischer Tropsch and methanol setups. Expert interviews point out that economies of scale are particularly relevant in case of the latter two sub-systems. Hence, for setups including either or both of these processes, large plants would be required. Given Switzerland's market size, this seems overly ambitious. Consequently, R&D support to enable learning-by-searching in P2X setups using Fischer-Tropsch and/or methanol reaction seems to be a more realistic option in Switzerland. In addition, research and technology demonstration collaborations with countries that have larger potential market sizes can be an option. Policy supporting methanation setups, where economies of scale are not as important as for e.g., Fischer-Tropsch, seems more appropriate for Switzerland from an innovation policy point of view.

12.2 Interaction between producers and users

Supporting P2X plants in different use environments (using different CO_2 and power sources) could result in higher learning-by-using than simply supporting one standardized setting. In order to increase the user-producer interaction, networks of local users, producers and regulators should be formed around these projects. To this end, one option would be to make grants only available to consortia that include users and producers. Furthermore, performance incentives should be considered, e.g., by providing grants for innovative product features. At the same time, policy support should be adjusted periodically to account for technological learning and the resulting cost reductions. To enable cost-based adjustments, policy support should be tied to reporting of cost and performance data (at least to the policy maker). Finally, in order to reduce the cost of deployment policies for such P2X setups, de-risking tools, which reduce the financing cost of P2X projects, could be used (e.g., through SFOE's Technology Fund).

13 Legal aspects related to Power-to-X

Swiss law treats P2X differently than pump storage with negative implications on costs.

13.1 General regulations

General legal regulations that apply to all P2X plants concern planning and approval procedures, environmental law, safety regulations and the status of P2X as final consumer. Regarding structural planning, P2X plants are probably not required to be included in the structure plan, since unit sizes and impacts on landscape are relatively small. Safety regulations need to be considered, if hydrogen and methane are produced.

13.2 Status of P2X systems as final consumers and power plants

There is ambiguity in the law, whether P2X must be regarded as "final consumer" – if regarded as "final consumer", P2X plants would have to pay electricity grid fees. An attempt to explicitly classify all storage systems except for pumped hydro systems as final consumers in a revised Electricity Supply Ordinance was withdrawn after significant criticism during the consultation.
Regulation related to P2X systems that feed electricity back into the grid would allow defining P2X technology as power plants, which would allow for particular conditions for the location and for electricity grid access. Legal uncertainty exists regarding the treatment of the power output of P2X directly connected to renewable power supply: Ideally, the law would support the definition of the electricity output as renewable, if corresponding sources of origin for the electricity used in electrolysis can be verified. Such a provision, however, is missing in the law so far.

13.3 P2X as grid investment

If the feed-in of electricity from renewable sources necessitates investments into P2X technologies at the distribution grid level, such costs could be reimbursed under the Electricity Supply Ordinance. In this case, ElCom would have to approve the costs and Swissgrid would have to reimburse the distribution grid operator. While investments in future infrastructure are often subject to regulatory scrutiny, recent legislation has introduced the option to reimburse costs of certain innovative grid measures.

13.4 Unbundling rules

Determined by the unbundling rules, Swiss law distinguishes responsibilities of electricity producers, transmission system operators and distributors of electricity, which might prohibit certain electricity market actors to operate P2X systems. According to the unbundling law, electricity producing companies are allowed to operate storages, and hence P2X technology. For companies operating a distribution grid, Swiss law calls for the unbundling of the financial reporting only. Consequently, such operators would likely be able to operate P2X units, as long as these activities are separated from the grid operation in the financial reporting and, inter alia, no cross-subsidisation takes place. Conversely, Swissgrid, the transmission system operator, is not allowed to participate in the production of electricity.

13.5 Gas market regulations

Biogas and synthetic methane are already partially included in the Swiss gas market regulations and directives. The gas grid access of P2X-facilities can be ensured through the Pipeline Act or the Cartel Act. However, P2X operators likely cannot rely on the "Verbändevereinbarung zum Netzzugang beim Erdgas", since this document is geared towards large consumers of gas, not producers that want to feed the gas into the grid.

13.6 Regulations regarding the transport sector

Law affecting the transport sector may lead to incentives for importers of fossil fuels to invest in P2X in order to compensate for a share of the carbon emissions resulting from the fuels imported. This might create an additional revenue stream for P2X. Related to the treatment of hydrogen and methane produced from biogenic sources, uncertainty exists regarding the calculation of the carbon intensity of gas fueled vehicles based on the biogenous share of the gas mixture. The law on the mineral oil tax is explicit about the treatment of biogenic fuels. When used as fuel, hydrogen, synthetic methane, methanol and other synthetic fuels from P2X are exempt from the Mineral Oil Tax if the energy used originates from renewable sources and certain environmental criteria are met.

13.7 Regulations regarding the heating sector

The CO_2 tax legislation therefore offers advantages for the use of P2X products in the heating sector. Regulations are mainly stipulated by the Cantonal Model Laws on Energy (MuKEn 2014), which are not directly applicable, but which the cantons may implement. Currently, however, renewable gases from P2X are not accepted as part of the standard solutions under the MuKEn.

Applying equal electricity grid fees across different storage technologies is key for the competitiveness of P2X.

Due to the fact that the CO_2 tax only applies to fossil energy carriers, the carbon tax legislation may offer advantages for the use of P2X products for heating, since synthetic energy carriers do not fall under this provision. This would create an incentive to use biogenic synthetic fuels over fossil fuels. Also, hydrogen and synthetic methane used as a combustible do not fall under the mineral oil tax.

13.8 Regulative impact on business models

The legal framework has several implications for P2X business models – in particular regarding the currently debated question, whether grid fees have to be paid. If this were the case (as it was envisaged in the consultation draft of the revised Electricity Supply Ordinance), this would:

- lower the overall profitability of any P2X installation that stores electricity from the public grid
- set incentives to no longer use the public grid, but store electricity directly from renewable electricity production instead

The latter incentive may have further implications. Industrial carbon sources are often not situated close to (decentralized) renewable electricity generation. Since a potential duty to pay grid fees would incentivize the installation of P2X plants close to renewable electricity sources, this would limit the opportunities to use industrial large-scale carbon sources. However, grid fees for electricity consumption of P2X may set incentives for the use of other CO_2 sources for the production of synthetic gases or fuels, such as direct air capture, probably associated with higher CO_2 costs, if local cheap electricity is not available. Clearly, the legislative framework can impose substantial implications for the deployment of new technologies, and needs to be designed to support those options that contribute effectively to the super-ordinated goals.

14 Acknowledgements

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15 Abbreviations

Battery Electric Vehicles (BEV)
Capital costs (CAPEX)
Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)
Compressed Air Energy Storages (CAES)
Compressed Natural Gas (CNG)
Electric Vehicle (EV)
Emission Trading Scheme of the European Union (EU ETS)
Fuel Cell Electric Vehicle (FCEV)
Greenhouse Gas (GHG)
Heavy goods vehicle tax (LSVA)
Higher Heating Value (HHV)
International Civil Aviation Organization (ICAO)
Internal Combustion Engine Vehicle (ICEV)
Life Cycle Assessment (LCA)
Lower Heating Value (LHV)
Megawatt-electric (MWe)
Methanol-to-Olefin (MTO)
Natural Gas (NG)
Operation and Maintenance (O&M)
Oxymethylene Ether (OME)
Operational costs (OPEX)
PhotoVoltaic (PV)
Power-to-Hydrogen: P2H
Power-to-Liquids: P2L
Power-to-Methane: P2M
Power-to-Power: P2P
Power-to-X: P2X
Polymer Electrolyte Membrane (PEM)
Research and Development (R&D)
Solid Oxide Electrolysis Cells (SOEC)
Swiss Federal Office of Energy (SFOE)
Synthetic Natural Gas (SNG)
Total Cost of Ownership (TCO)
Value Added Tax (VAT)
Well-to-Wheel (WTW)

16 Glossary

- *Alkaline electrolysis:* uses an alkaline solution, e. g. sodium hydroxide or potassium hydroxide, as an electrolyte and is the most mature technology commercially available for hydrogen production with efficiencies in the range of 50–70 %
- *Ammonia synthesis:* hydrogen is catalytically reacted with nitrogen (derived from process air) to form anhydrous liquid ammonia: $N_2 + 3H_2 \leftrightarrow 2NH_3$
- *Anaerobic digestion:* chemical processes in which organic matter is broken down by microorganisms in the absence of oxygen [1]
- *Ancillary services:* markets for grid balancing (frequency regulation)
- *Biogas upgrading:* refines raw biogas into clean biomethane (removal of impurities) which can be then injected in the natural gas grid [2]
- *Biogenic CO_2 sources:* supply of CO_2 based on conversion of wood residues through indirect wood gasification and methanation of the produced gas, followed by CO_2 removal
- *Biogenic substrates:* sewage sludge, green wastes, agricultural residues and manure
- *Biological reactor:* uses methanogenic microorganisms under anaerobic conditions
- *Chlorine-alkali electrolysis:* chemical process for the electrolysis of sodium chloride producing chlorine and sodium hydroxide
- *CHP:* a device that uses a heat engine or a power source to produce electricity and useful heat
- *CO_2 emissions certificates:* quantity of CO_2 emissions being part of a trading scheme
- *Co-electrolysis mode:* producing synthetic gas from water steam and carbon dioxide
- *Compressed Air Energy Storages (CAES):* electricity storage technology useing electricity to compress air that is stored in underground formations (salt or rock caverns or abandoned mines) or in tanks (P2G in Switzerland); expansion of compressed air generates electricity
- *Decentralised generation:* electricity produced in decentralized renewable power plants such as solar PV and wind
- *Digitalised demand:* smart meters, energy management systems, automated demand response or microgrids [3]
- *Direct air capture:* carbon capture method that separates CO_2 from air
- *Electricity production costs:* an economic indicator of the total costs of building, operating and decommissioning a power plant over its lifetime per unit of energy production
- *Electrolysis:* electro-chemical process that converts electricity and water into a gaseous form of energy (hydrogen and oxygen)
- *Emission Trading Scheme of the European Union (EU ETS):* a market where emission allowances and emission reduction certificates are traded thereby allowing for CO_2 emissions reduction at the least cost
- *Endothermic reaction:* chemical process absorbing energy in the form of heat
- *Energy saving measures:* measures aiming at reducing energy consumption (thermal insulation, LED lighting…)
- *ENTSO-E:* 43 electricity transmission system operators from 36 countries across Europe
- *Fischer-Tropsch:* processes converting gases containing hydrogen and carbon monoxide to hydrocarbon products: $CO_2 + H_2 \rightarrow CO + H_2O$; $CO + H_2 \rightarrow C_xH_yOH + H_2O$
- *Flexible power plants:* dispatchable electricity such as flexible gas power plants
- *Higher Heating Value:* accounts for the latent heat of water vaporization in the reaction products
- *Hydrocarbon cracking:* hydrocarbons are splitted into smaller molecules by breaking carbon bonds depending on the temperature and presence of catalysts
- *Levelised cost:* an economic indicator of total cost to build and operate a power plant over its lifetime per unit of energy output
- *Life Cycle Assessment (LCA):* provides insights on the environmental performance of products and services, taking into account production, use, and disposal/recycling of products, supply chains and related infrastructure
- *Lower Heating Value:* assumes that the latent heat of water vaporization in the reaction products is not recovered [4]
- *Methanation:* hydrogen and carbon dioxide are combined through a chemical or a biological catalytic reaction
- *Methanol synthesis:* hydrogenation of carbon monoxide or of carbon dioxide: $CO_2 + 3\ H_2 \leftrightarrow CH_3OH + H_2O$
- *Polymer Electrolyte Membrane (PEM):* uses proton transfer polymer membranes as electrolyte and separation material between the different sections of the electrolysis cell
- *Power-to-X (P2X):* Power-to-Hydrogen, Power-to-Liquids, Power-to-Methane, Power-to-Power: a class of innovative technologies that use an electro-chemical process to convert electricity into a gaseous or liquid energy carrier or chemical product
- *Primary control reserve:* Maintenance and use of power plant capacity to ensure the mains frequency from 50 Hz to ±200 mHz.
- *Pump storage:* uses surplus power to pump water from a lower reservoir to be stored in an upper reservoir

- *Reverse mode:* operation as a fuel cell as opposed to electrolysis mode
- *Secondary control reserve:* balances electricity supply and demand; operates for up to 15 minutes
- *Solid oxide electrolysis cells (SOEC):* Technology in which water electrolysis is carried out with a solid oxide or ceramic electrolyte.
- *Steam methane reforming:* chemical process in which methane from natural gas is heated with steam to produce carbon monoxide and hydrogen [5]
- *Synthetic liquid fuel:* fuels resulting from the conversion of hydrogen into liquid hydrocarbons
- *Synthetic Natural Gas (SNG):* synthetic gas (substitute for natural gas) produced from coal or electrolysis for instance
- *System services:* Service to ensure the operation of the electricity network (frequency regulation)
- *Total Cost of Ownership (TCO):* purchase price of an asset plus the costs of operation [6]
- *Virtual power plant:* a control system consisting of distributed energy resources (renewable energy such as solar, wind) and flexible power consumers [7]
- *Well-to-Wheel (WTW):* includes resource extraction, fuel production, delivery of the fuel to vehicle and end use of fuel in vehicle operations [8]

1 https://www.britannica.com/science/anaerobic-digestion

2 https://www.infothek-biomasse.ch

3 https://www.weforum.org/agenda/2016/03/perspective-distributed-digital-and-demand-side-energy-technology-implications-for-energy-security/

4 https://h2tools.org/hyarc/calculator-tools/lower-and-higher-heating-values-fuels

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