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Abstract

This deliverable describes the model-based analysis of deep decarbonisation pathways for Switzerland and the role that the H2-CCS have in achieving ambitious climate targets. The Swiss TIMES energy systems model (STEM) was expanded to include the technologies of particular interest in ELEGANCY and applied for a multi-scenario analysis. The analysis considers two core scenarios, a *Baseline* scenario reflecting current trends and a *Net-Zero* scenario aiming at net-zero CO_2 emissions in the Swiss energy system by 2050. A set of technological and policy variants was also assessed to identify a) major drivers that influence the uptake of hydrogen, as well as b) the sectors in the Swiss energy systems in which hydrogen plays the most important role. The key findings of the analysis with STEM are summarised below:

- About 8.6 $MtCO_2$/yr of CO_2 needs to be captured in 2050 to achieve net-zero emissions in the energy system alone (i.e. excluding agriculture, forestry and international aviation). The sources of captured CO_2 are mainly the municipal solid waste (MSW) plants, the industry with CO_2 emissions captured from combustion and process-related emissions, as well as the production of hydrogen and bio-liquids. Direct air capture is deployed as a backstop option at comparatively low levels in 2050.
- So-called "Negative Emission Technologies" (NET) are needed to achieve net-zero emissions in 2050. The amount of negative emissions accumulates to almost half of the total captured CO_2 emissions in 2050. An early embedding of carbon dioxide removal approaches needs to be implemented in Swiss climate policy to provide long-term signals to investors and stakeholders. Key among them is adequate CO_2 pricing, coordination of policies across sectors, as well as crediting the negative emission technologies as compensation measures to advance scaling to a marketable size.
- CO_2 storage in Switzerland is a challenge, and a connection with European networks is a key requirement for the successful development of the CO_2 capture technology in Switzerland. Not having the option of capturing and storing CO_2 within and out of

Switzerland would have significant implications on the achievement of ambitious Swiss climate goals and the associated costs. Access to transport and storage infrastructure across the EU and Norway would need international agreements and participation in projects of common interest dealing with cross border CO_2 transport and storage infrastructure.

- Low-carbon hydrogen (based on renewable primary energy and/or generated with CCS) is an energy carrier of growing importance in a climate-neutral and low air pollution Swiss economy in 2050. A strong climate policy accelerates its deployment. However, the future success and timing of the hydrogen economy are highly dependent on technological developments and targeted measures. The industry sector can be the first mover for hydrogen applications until 2030, but transport scales up hydrogen uptake in the post-2040 period in Switzerland. Automotive applications constitute a key segment for the future of fuel cells, lead to improvements that can spill over to other applications, and carry forward infrastructure development. Hydrogen in buildings faces high upfront costs and strong competition with existing infrastructures. District heating micro grids based on fuel cell CHP can be an option to provide hydrogen-based heat in buildings and industrial complexes.
- In a long-term perspective hydrogen supply progressively shifts from natural gas based steam methane reforming (SMR/ATR), which is deployed first, to renewable hydrogen (electrolysis, biogenic SMR/ATR and wood gasification with CO_2 capture). SMR/ATR units need to be equipped with CO_2 capture and storage by 2050 and natural gas as feedstock needs to be partly replaced by biomethane, especially when substantial amounts of negative emissions are needed. For the scaling-up of the hydrogen production from solid biomass, there are challenges related to the availability of biomass and the competition for this resource with other sectors in the energy system seeking for carbon-neutral energy sources.
- The mid-term horizon until 2030/40 is crucial for the wider deployment of hydrogen in the long term. As investment cycles in the clean energy sector run for about 25 years, and the time needed for new energy technologies to penetrate existing markets is long, boosting demand and supply of hydrogen requires various forms of support to help stimulating commercial demand for cleaner hydrogen.
- During the transition phase of the hydrogen infrastructure development, policy support should not lead to stranded assets. To foster innovation and confidence of investors, policy needs to provide stable long-term signals (such as rigid climate goals) creating demand for hydrogen while mitigating the investment risks. The creation of hydrogen demand can be facilitated by stringent emission and efficiency standards for vehicles and buildings, or market-based mechanisms such as taxation of fossil fuels. Industrial clusters may offer good opportunities for the deployment of low-carbon hydrogen and could be stimulated by a reinforcement of the emission trading scheme and carbon intensity reduction goals.

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1 ENERGY MODEL ANALYSIS OF THE ROLE OF H2-CCS SYSTEMS IN SWISS ENERGY SUPPLY AND MOBILITY

The analysis using the Swiss TIMES Energy Systems Model mainly focuses on the prospects of a hydrogen economy in Switzerland. Developments of the rest of the energy system are only discussed in connection to their impact on the evolution of hydrogen supply and demand system.

1.1 Drivers to the Swiss energy system development

This section discusses the assumptions that influence the development of Swiss energy demand. The main economic and demographic assumptions are based on the Swiss Federal Statistical Office (BFS) and the Swiss State Secretariat for Economic Affairs (SECO). They have been further processed in the context of the SCCER Joint Activity Scenarios and Modelling (Marcucci et al., 2020), which are the ones used in the current analysis.

As shown in Table 1.1, the population in Switzerland increases by 2.1 million in 2050 from 2015 levels based on the expected robust economic situation in the country, the demand for labour, and current family and immigration policies in place. The growth in employment and labour productivity increases the Gross Domestic Product (GDP) by 1.3% p.a., between 2015 and 2050. The services and commercial sectors (and in particular the insurance, financing and trade sectors) drive the economic growth, as these sectors combined produce more than two-thirds of the Swiss GDP. In industry, the chemicals and pharmaceuticals sectors have the highest contribution to the sectoral gross value-added and see their share increasing from 22% in 2015 to 41% in 2050. The large share of services and non-energy intensive industries in the Swiss GDP indicates that the Swiss economy is progressively changing its structure as sectors with higher value-added develop more rapidly than sectors that are heavily intensive concerning energy and materials. This trend lowers the energy intensity of the Swiss economy in the forthcoming years, and it accelerates the decoupling between energy consumption and economic activity.

The tendency of smaller household sizes observed in recent years also continues until 2050. While population grows by 0.6% p.a. between 2015 and 2050, the number of households increases by 0.7% over the same period. The overall housing demand and energy reference area in the residential buildings grows about 0.8% p.a. from 2015 to 2050. The passenger mobility demand displays saturation effects with respect to the growing incomes, while the freight transport demand continues to decouple from economic activity due to improved logistics. Both the passenger and freight demands are drawn from the ARE scenarios (Mathys & Justen, 2016).

Table 1.1: Key economic and demographic indicators of Switzerland 2015 – 2050.

	2015	2020	2030	2040	2050	CAGR 2015-2050
Population (millions)	8.3	8.7	9.4	10.0	10.4	0.6%
Number of households (million)	3.6	3.8	4.2	4.5	4.7	0.7%
GDP in market prices (BCHF2010)	661	725	820	922	1023	1.3%
Gross Value Added (Index 2015=100)	100	106	121	135	149	1.2%
Industry	100	105	121	134	148	1.1%
Services & Commercial Sectors	100	106	121	136	150	1.2%
Energy Reference Area in residential (Mm2)	475	507	561	601	632	0.8%
Passenger transport demand (Bpkm)	122	132	138	143	146	0.5%
Freight transport demand (Btkm)	28	30	33	37	39	1.0%

Source: SCCER Joint Activity Scenarios and Modelling

Next to the domestic drivers, the international context is also a key influential factor for the future development of the Swiss energy system as it affects the prices of imported energy carriers at the Swiss border. Following the assumptions of SCCER Joint Activity Scenarios and Modelling (Marcucci et al., 2020), two distinct price trajectories are assumed (Table 1.2). The first trajectory corresponds to a worldwide continuation of existing trends and policies (*Reference*), and it is used in the current analysis for scenarios that do not implement the climate goals of the Paris Agreement. The second trajectory corresponds to a normative scenario with a global effort to limit the increase in the average surface temperature below 2°C by the end of the century compared to pre-industrial levels (*Climate trajectory*), and it is used in the analysis for the scenarios achieving net-zero emissions by 2050.

Table 1.2: Import prices at the Swiss border, excluding taxes and transmission tariffs.

Reference (CHF2010/GJ)	**2020**	**2030**	**2040**	**2050**
Crude oil	8.8	18.5	20.7	22.8
Natural gas	3.1	9.3	10.4	11.0
Biodiesel	42.7	49.7	52.4	55.0
Ethanol	30.4	39.4	41.9	44.3
Biogas	17.0	19.1	22.3	24.4
Electricity*	16.7	21.2	20.3	18.0
Hydrogen	26.9	40.1	42.7	44.7
Climate (CHF2010/GJ)				
Crude oil	8.8	11.0	10.7	10.3
Natural gas	3.1	7.4	6.9	6.5
Biodiesel	42.7	56.4	65.7	70.8
Ethanol	30.4	48.2	59.2	64.1
Biogas	17.0	20.6	24.2	27.4
Electricity*	16.7	27.7	27.7	28.9
Hydrogen	26.9	41.6	44.4	52.1

** Electricity prices are averaged across the neighbouring countries and across the hours of a year*
Source: SCCER Joint Activity Scenarios and Modelling

1.2 Technological prospects for hydrogen supply and demand to 2050

The aim of this section is not to provide an in-depth technical analysis, but to point out the main developments regarding costs and efficiencies of hydrogen production and demand technologies, which are assumed in the analysis up to the year 2050. Table 1.3 shows the improvement over time regarding investment costs and efficiencies used in the analysis, assuming a “baseline” technology learning[1].

The improvement in cost and efficiency of electrolysis is attributable to innovation and economies of scale in the manufacturing process. In contrast, the production of hydrogen from natural gas reforming, which is the incumbent hydrogen production technology, displays limited potential for cost reductions. Although worldwide there are demonstrations of biomass gasification, the technology is still immature and cost reductions uncertain. Besides, the complex processing of biomass renders it a more expensive option than electrolysis. The main benefit of biomass gasification is its contribution to achieving negative emissions when it is combined with CCS. Its major disadvantage is the difficulty of a large-scale rollout due to the limited biomass availability. Regarding the demand technologies that use hydrogen, fuel cells have seen considerable cost reductions in the last decade, but costs remain high, and manufacturing volumes are still low. According to (IEA, 2019), future costs reductions can be induced via research and economies of scale. Spill-overs between stationary and mobile applications of fuel cells can also accelerate their technical and economic improvement. The main challenge lies on simultaneously improving the fuel cell performance and its durability, while at the same time keeping the stack costs low.

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[1] In the variants that are assessed in this study, we also explore increased learning rates.

Table 1.3: Technical and economic prospects of key hydrogen production and demand technologies.

Hydrogen production technologies	Capital cost CHF/kW_{H2}		Fix O&M cost CHF/kW_{H2}*a		Efficiency %	
	Current	2050	Current	2050	Current	2050
Electrolysis (PEM)	1400	600	21	9	64%	71%
Gas SMR	910	910	43	43	76%	76%
Gas SMR with CO2 capture	1680	1280	50	38	69%	69%
Wood gasification	3500	1900	350	190	61%	61%
Wood gasification with CO2 capture	4800	2300	480	230	55%	55%

Source: IEA, 2019: The Future of Hydrogen & Own assumptions

Hydrogen Fuel Cell CHP	Capital cost CHF/kW_e		Fix O&M cost CHF/kW_e*a		Electrical Efficiency %		Total Efficiency %	
	Current	2050	Current	2050	Current	2050	Current	2050
CHP Fuel Cell in industry	3800	2800	93	38	44%	62%	80%	90%
CHP Fuel Cell in industry w reformer	4000	3000	100	45	42%	60%	80%	90%
CHP Fuel Cell in services	9800	2800	93	38	53%	67%	80%	90%
CHP Fuel Cell in services w reformer	10000	3000	100	45	51%	65%	80%	90%
CHP Fuel Cell in residential w reformer	16000	4000	300	200	36%	45%	88%	90%

Source: Bauer et al, 2019

Hydrogen vehicles	Capital cost CHF/veh		Fix O&M cost CHF/veh*a		Efficiency km/MJ	
	Current	2050	Current	2050	Current	2050
Mid size passenger car	77300	49500	1000	900	0.787	1.145
Van & light duty vehicle <3.5 t	84200	54100	7500	6000	0.449	0.605
Mid size bus	518700	173100	86700	21500	0.137	0.219
Truck >3.5 t	493600	168000	45000	45000	0.174	0.219

Source: SCCER Mobility

1.2.1 Modelling the hydrogen infrastructure development

1.2.1.1 New infrastructure, dedicated to hydrogen distribution

Regarding the infrastructure for hydrogen distribution and storage, the main source of cost data is also (IEA, 2019). The concept of "local hydrogen clusters" (EC, 2020) is used as a stylised representation of infrastructure development. In the current analysis, a "local hydrogen cluster" refers to a situation at the initial stages of a take-off of a hydrogen economy falling well short of maturity of such economy. At this stage, the economic performance of the network could play a crucial role in determining the extent of penetration of hydrogen as an energy carrier. The "local hydrogen cluster" relies on local production of hydrogen and local demand, which is transported over short distances.

As shown in Figure 1.1, we assume that a "local hydrogen cluster" refers to an area of 25x25km with a mix of urban and rural settlements. The average population density is about 450 inhabitants per square km, similar to the density seen at the Swiss Plateau[2]. It can be argued that it corresponds to an average (or "reference") geographical area of Switzerland somewhere in the region stretching from Lake Geneva in the southwest of Switzerland to Lake Constance in the northeast. It includes a hydrogen production facility (marked with an A in Figure 1.1) that is also serving for storage and balancing. It also includes a "turnpike" pipeline (marked with B in the figure), which is used to connect similar areas. A pipeline distributes hydrogen to the industrial zone (E), while the urban area (D) is connected with a pipeline backbone ring (shown as a circle around the urban area in the figure) [3]. The rural area is served by trucks (C). The mix of transport and distribution options for hydrogen are based on the analogue of gas and oil distribution infrastructure seen today. The sizing of the infrastructure is based on the assumptions shown in the table next to Figure 1.1. It

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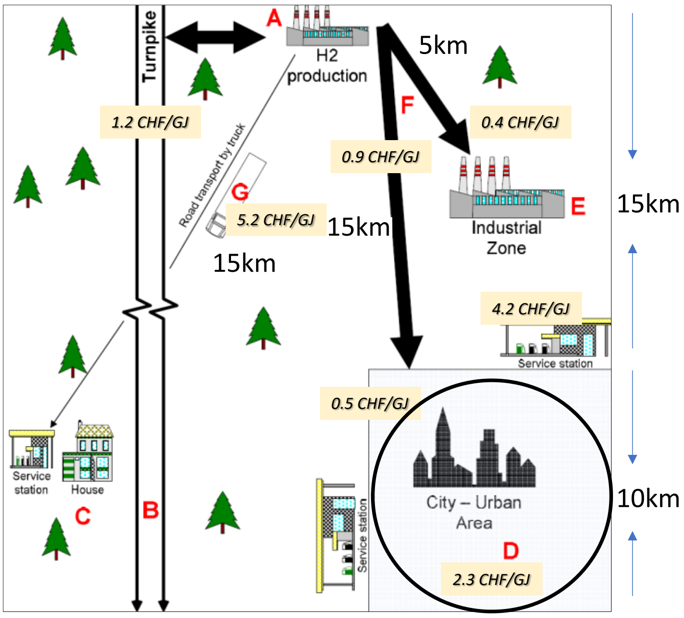
[2] https://www.eda.admin.ch/aboutswitzerland/en/home/umwelt/geografie/mittelland.html

[3] Like natural gas, hydrogen can also be liquefied before it is transported to increase its density. However, liquefaction of hydrogen is energy intensive and consumes 25-35% of the initial hydrogen quantity (IEA, 2019). Therefore, this option is not assessed in the analysis. In addition, alternative options converting hydrogen to ammonia or LOHCs (liquid organic hydrogen carrier) is also not considered because they often cannot be used as a final product and a further processing step is needed to extract hydrogen from them.

turns out that the cost of hydrogen distribution to buildings is on average 5 CHF/GJ, in industry 2.4 CHF/GJ and transport 3.8 CHF/GJ (8.2 CHF/GJ when also including fuelling station costs) in 2050[4]. On average, the hydrogen distribution costs are about 35-75% higher than the natural gas distribution costs.



Reference Area Characteristics	
Switzerland density /km2	218
Swiss Plateau density /km2	450
Total Area km2	625
Urban Area km2	100
Urban Area Density /km2	2000
Total Population	281250
Urban Population	200000
Rural Population	81250
Number of cars	149063
Number of households	127841
Urbanisation rate	71%
Reference Area Hydrogen Consumption	
H2 consumption in industry (TJ)	285
H2 consumption in buildings (TJ)	1'273
of which urban	905
of which rural	368
H2 consumption in cars (TJ)	738
of which urban	*525*
of which rural	*213*
Total H2 needs (TJ)	3'569
Size of H2 production facility (MW)	340
H2 Production facility output (TJ)	3'569
Operating hours of the H2 production facility (h)	3000

Figure 1.1: The reference area of a local hydrogen cluster for hydrogen distribution and storage. The figure also shows the main demographic characteristics of the specified reference area and the estimated hydrogen consumption in the different sectors. It also shows the distribution costs of hydrogen for the different hydrogen delivery means in 2050.

1.2.1.2 Using existing natural gas infrastructure for hydrogen distribution

We also consider blending hydrogen to natural gas grids at a limited percentage: from 2% today up to 4% in 2050 on a volumetric basis. However, the blending is a less efficient way to distribute hydrogen because it diminishes the value of hydrogen, as well as it can also change the quality of natural gas and affect the design of gas infrastructure, and end-user applications.

Repurposing of existing natural gas pipelines to distribute hydrogen is also an option in the analysis. Still, it requires that current network operators to be allowed to operate and finance hydrogen pipelines, as well as that the technical suitability of the existing gas infrastructure has been assessed and that the necessary regulatory frameworks are already in place. The main challenge in using existing gas pipelines for hydrogen distribution is that three times more volume is needed to supply the same amount of energy as natural gas. Thus, it is considered as a transition option (EC, 2020).

1.3 The Swiss TIMES Energy Systems Model – STEM

The Swiss TIMES Energy Systems Model - STEM (Kannan & Turton, 2014) is based on the TIMES modelling framework (Loulou et al., 2016) of the International Energy Agency – Energy Technology Systems Analysis Program (ETSAP). STEM is a bottom-up cost optimisation

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[4] Or, in terms of CHF/kg H_2, these figures correspond to 0.6 CHF/kg for buildings, 0.3 CHF/kg to industry and 0.5 CHF/kg for the transport sector 1.0 CHF/kg when also including fuel station costs), in line with the estimates reported in (IEA, 2019)

framework suitable to assess the long-term transformation of the Swiss energy system. The model combines a long time horizon (2010 – 2050) with 288 intra-annual operating hours (four seasons and three typical days per season with 24h resolution) in order to better capture the variability of energy supply and demand. An overview of the structure of STEM is given in Figure 1.2.

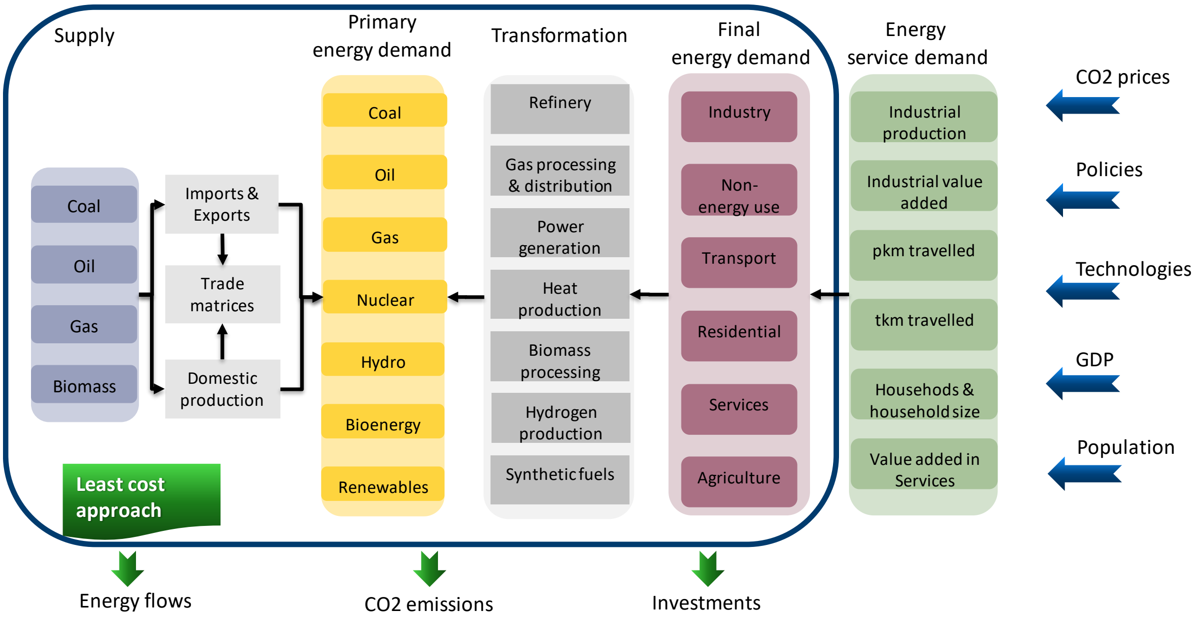

Figure 1.2: Simplified overview of the Swiss TIMES Energy Systems Model.

STEM has a complete representation of the Swiss energy system from resource supply to energy end uses. The main energy demand sectors in the STEM model are industrial, residential, commercial and transport. The transformation sector includes the conversion of fuels, and power and district heat generation. The model includes options for producing synthetic fuels and hydrogen, and it has an explicit representation of storage, transport and distribution required for the secondary energy carriers. STEM simultaneously optimises investment and operating decisions to meet the future energy demand, by implementing a linear approximation of the unit commitment problem and by accounting for the stochastic nature of renewable supply and consumption of energy (Panos et al., 2019).

In the context of the Swiss case study for the ELEGANCY project, STEM is used for a long-term scenario analysis focusing on the role of hydrogen for decarbonising the Swiss transport sector and the other sectors of the Swiss energy system.

1.4 Definition of the long-term scenarios and variants

Two core scenarios are assessed, mainly differentiated by the level of the climate change mitigation effort. Both scenarios share the same economic, demographic and technology performance assumptions stated in the previous sections:

- The *Baseline* scenario assumes a continuation of already implemented policies and measures, without enforcing specific long-term targets regarding renewable penetration, climate change mitigation and energy efficiency improvement. However, the already decided phase-out of existing nuclear power plants (BFE, 2017) is implemented in the *Baseline scenario* by assuming a maximum of 60 years lifetime for the current reactors.
- The *Net-Zero* scenario aims at achieving the target of net-zero CO_2 emissions in 2050, in a context of phasing-out existing nuclear power plants. The current Swiss climate policy

considers the emissions reduction target in 2050 as indicative, and it includes emissions from the energy system, agriculture, wastes and LULUCF[5] (Swiss Federal Office for the Environment, 2020). In the current analysis, we focus on achieving net-zero emissions in the energy system with only domestic measures. Hence, an amount of at least 5 Mt CO_2eq in 2050 that corresponds to non-CO_2 related greenhouse gases emitted from the non-energy sectors according to (Swiss Federal Office for the Environment, 2020) is assumed to be offset via carbon dioxide removal technologies deployed outside the Swiss territory[6].

The *Net-Zero* scenario also implements emissions standards for buildings and vehicles, and it also assumes the strengthening of the Swiss and EU emission trading schemes (Table 1.4). These measures are at the moment under discussion in the Swiss Parliament (FOEN, 2019). Beyond 2030, the targets for the transport sector are based on scenario projections from the European Commission (E3mlab & IIASA, 2017; EC, 2018), while for buildings on extrapolation of the MINERGIE standards (Sidler & Humm, 2019)

Table 1.4: Sectoral decarbonisation measures assumed in the Net-Zero scenario. The targets "linear factor of ETS" refers to the annual change over the corresponding period. The emissions standards in buildings and vehicles refer to the end year of the corresponding period

	2020-2030	**2030-2040**	**2040-2050**
Linear factor of the Swiss ETS (% p.a.)	-2.2	-2.6	-2.8
Emissions standards in buildings (kgCO2/sqm)			
Residential existing buildings	12	4	0
Residential new buildings	4	0	0
Commercial buildings (average)	12	4	0
Emissions standards in transport (% grCO_2/km from 2020 ; average of new registrations)			
Private cars (target in 2020: 95 grCO_2/km)	-38	-60	-83
Buses	-30	-40	-50
Light duty vehicles	-31	-34	-37
Trucks	-30	-40	-50

Because of the uncertainty in the domestic CO_2 sequestration potential and the development of cross border CO_2 transport infrastructure, we assume that: a) the CCS technologies are deployed in Switzerland from 2035/2040 onwards; b) the domestic CO_2 sequestration potential is limited at around 50 Mt CO_2 (Diamond et al., 2019). Regarding the access to cross-border CO_2 transport infrastructure, we follow an egalitarian approach based on the per capita captured CO_2 across the EU in 2050 (EC, 2018). By applying the average per capita CO_2 captured to the Swiss population, we set the potential to export CO_2 from Switzerland to about 15 Mt/yr in 2050.

We also examine variants of the *Net Zero* scenario aiming at exploring the drivers for accelerating the penetration of hydrogen as an energy carrier, while at the same time achieving net zero CO_2 emissions by 2050 in the Swiss energy system. The variants, which are briefly described below and summarised in Table 1.5, look in particular at the role of technical improvement in infrastructure and demand technologies, as well as of targeted policies that bring forward in time the introduction of hydrogen in the Swiss energy mix:

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[5] Land use, land-use change, and forestry.

[6] STEM in an energy systems model. Including emissions from the non-energy sectors in the assessment requires interfaces with models for agriculture and forestry, which is not in the scope of the ELEGANCY project.

- The *demand-pull* variant considers a breakthrough in fuel cells. Given the importance of the automotive industry[7], technological leadership in fuel cell technologies is considered to be a key part of industrial competitiveness by the governments of developed economies. Governments and industries dedicate massive R&D funding to breakthroughs in areas that are known inhibitors of high-volume production of fuel cell vehicles. As a result, the wholesale costs of the fuel cell stack significantly reduces. Focused research is also directed to high-efficiency, low-emission decentralised power generation using stationary fuel cell combined-heat-and-power plants.
- The *supply-push* storyline considers a breakthrough in hydrogen production. In this storyline, the political framework sets out clear support for the hydrogen economy at an early stage. An example of this is the recently announced EU hydrogen strategy (EC, 2020). Issues such as safety regulations, infrastructure development and policy support are agreed upon the developed economies and provide a stable environment for long-term investments.
- The *subsidy of hydrogen infrastructure* variant assumes that growing private incomes lead to a public willingness to act against increasing air pollution and particulate matter. A market-based approach is additionally implemented to the emission standards for vehicles, in which the tax for fossil fuels in road transport is doubled for all fuels except the “emission-free” fuels such as hydrogen and electricity. Half of the revenues are then assumed to be used to further finance hydrogen distribution and storage projects for accelerating hydrogen uptake and bringing hydrogen demand technologies forward in time.
- The *combined-policy* storyline represents a very optimistic scenario framework in terms of developments in favour of hydrogen. It is a combination of the developments of the *demand-pull* storyline, the *supply-push* storyline and the *subsidy of hydrogen infrastructure* storylines.

Table 1.5: Overview of the assessed scenarios and variants.

Core scenarios

Code in charts	**Scenario**	**Remark**
Baseline	Baseline	Business as usual scenario
Net-Zero	Net-Zero	Net zero CO2 emissions in the energy system (incl. Industrial processes) by 2050

Variants of the Net-Zero Scenario

Code in charts	**Variant**	**Remark**
R&D in FC	Demand-pull	Costs of fuel cells cars reduce by 10% in 2050; Cost of fuel cell CHP reduce by 20% in 2050
R&D in H2 supply	Demand-push	Costs of renewable hydrogen production reduce by 50% in 2050; Costs of distribution infrastructure reduce by 10% in 2050
Tax Recycle	Subsidy of infrastructure	Increase the current fossil fuel tax by +22.3 CHF/GJ (doubling the existing tax) from 2030 onwards and use half of the revenues to finance H2 distribution infrastructure
R&D in FC + R&D in H2 Supply + Tax Recycle	Combined policy	All the above policies implemented together

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[7] The leading fuel cell vehicles manufacturers today are Toyota and Hyundai, with very ambitious plans of selling about 30000 fuel cells cars annually by 2020 (IEA, 2019). In addition, Japan implements currently an ambitious program for accelerating hydrogen in the mobility sectors (IEA, 2019).

1.5 Results from the core *Net-Zero* scenario

In this section, the model-based analysis of hydrogen economy prospects is presented. The results focus on the role of hydrogen in decarbonising the Swiss energy system. Implications on the rest of the energy system regarding the transition to deep decarbonisation are briefly mentioned and in relation to the penetration of hydrogen.

1.5.1 CO_2 emissions

The CO_2 emissions from fuel combustion and industrial processes, excluding international aviation, peak in both *Baseline* and *Net-Zero* scenarios in 2010. Achieving net-zero emissions in 2050 requires additional reductions in the cumulative CO_2 emissions budget over the period from 2015 to 2050 of about 480 Mt CO_2 in the *Net-Zero* scenario relative to *Baseline*. The residential, service and transport sectors are almost fully decarbonised, and the sources of the remaining emissions in the energy system are the industrial sectors. Negative emission technologies based on bioenergy with carbon capture and storage (BECCS) are deployed in the energy conversion sectors for the production of electricity, hydrogen and biogenic gases and liquids (Figure 1.3). Direct Air Capture with carbon capture and storage (DACCS) is deployed as a backstop technology, after the deployment of BECCS. Its contribution to negative emissions is expected to increase in the years after 2050, as BECCS cannot be scaled up by only using domestic resources to maintain the overall CO_2 budget within the limit needed for achieving the Paris Agreement goals.

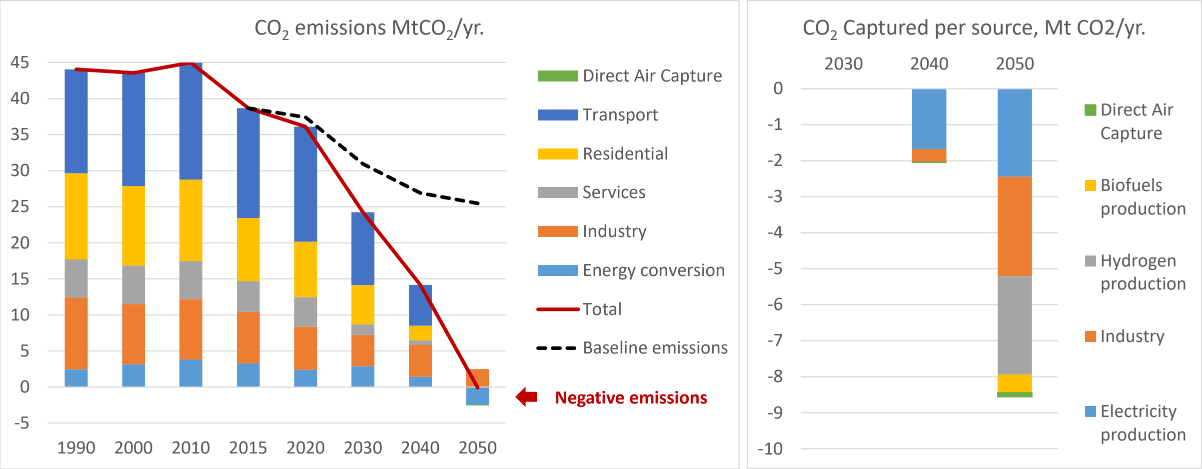

Figure 1.3: Left: CO_2 emissions from fuel combustion (excluding international aviation) and industrial processes in the Net-Zero scenario; about 2.6 Mt CO_2/yr are net negative emissions in 2050 offsetting emissions mainly from the industry; the dotted line represents the emissions in the Baseline scenario. Right: CO_2 captured from different sources towards the net-zero target in 2050.

The total CO_2 emissions captured are about 8.6 Mt CO_2/yr in 2050, of which 3.9 Mt CO_2/yr are considered as negative emissions, i.e. are captured by BECCS and DACCS. BECCS for hydrogen production accounts for about half of the negative emissions. The rest are mainly captured in waste incineration plants with CCS, and they refer to the renewable part of the waste (50% of the total waste used in the incineration). BECCS for biofuel production (syngas) and DACCS capture 0.6 Mt/yr.

Because of the assumed limited domestic sequestration potential, more than three-quarters of the captured CO_2 needs to be transported out of Switzerland. The utilisation of captured CO_2 for the production of synthetic fuels emerges in 2040. Around 0.2 Mt CO_2/yr is used in 2040 and 2050 to produce about 1 TWh of synthetic liquid and gaseous fuels to be used in the heating sector, road transport and domestic aviation[8].

1.5.2 Overview of the energy system transition

Electrification and energy efficiency play an essential role in a future decarbonised Swiss energy system. Until 2030, there is a very small increase in electricity generation due to efficiency measures in the demand sectors. In the last two decades of the projection, the new electricity uses in the *Net-Zero* scenario in mobility, heating and electrolysis, result in additional electricity production of about 10 TWh/yr, compared to *Baseline* in 2050 (Figure 1.4). The electricity sector is transformed towards decentralised generation, where consumers maximise self-consumption. Solar photovoltaics have the lions' share in the additional electricity supply, as electricity generation costs from solar declines over time, while the potential is, comparatively to other non-hydro renewable sources, high. The total generation from variable renewable energy sources in the *Net-Zero* scenario is close to 30 TWh/yr in 2050 (or, more than one-third of the total electricity supply).

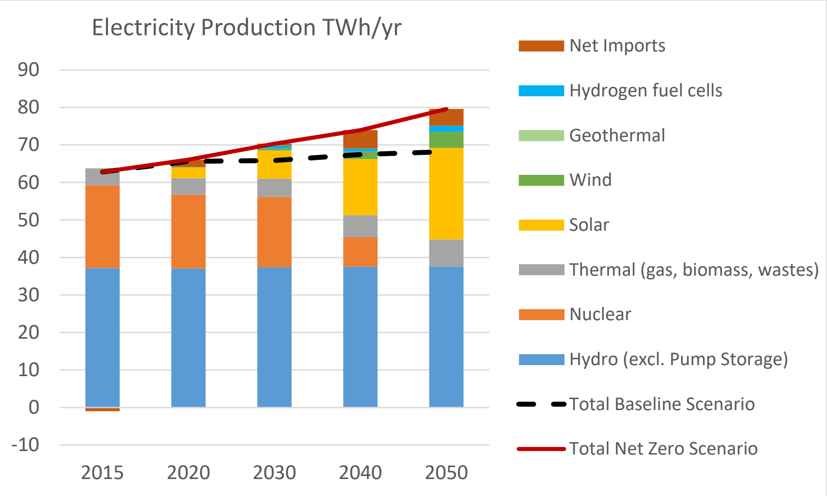

Figure 1.4: Electricity generation by source in the Net-Zero scenario. Dotted lines represent the total electricity generation in the Net-Zero scenario (red) and the Baseline scenario (black).

The total final energy consumption (excluding international aviation) strongly declines in the *Net-Zero* scenario from today's levels, due to increased electrification and deployment of efficiency measures (Figure 1.5). The fuel mix shows a progressive decrease in oil and gas. The residential heating shifts away from fossil towards heat pumps and renewables (wood and solar thermal). District heating and heat from distributed CHPs slightly expand, mainly in the last two decades. Almost all of the remaining natural gas in the energy mix of 2050 is consumed in the industrial sectors for processes that require gas combustion, the electrification of which is extremely difficult or even not possible. The transport sector shifts away from fossil oil products by 2050. It is fully decarbonised via electrification, hydrogen and imported bio-liquids or e-fuels from Power-to-Liquid applications.

Biogenic gases (biogas, syngas and biomethane) also play an important role in the Swiss energy mix towards decarbonisation. About 7 TWh of biogas and syngas is domestically produced in 2050, with half of it being upgraded to biomethane.

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[8] Synthetic fuels for international aviation are not considered in the analysis.

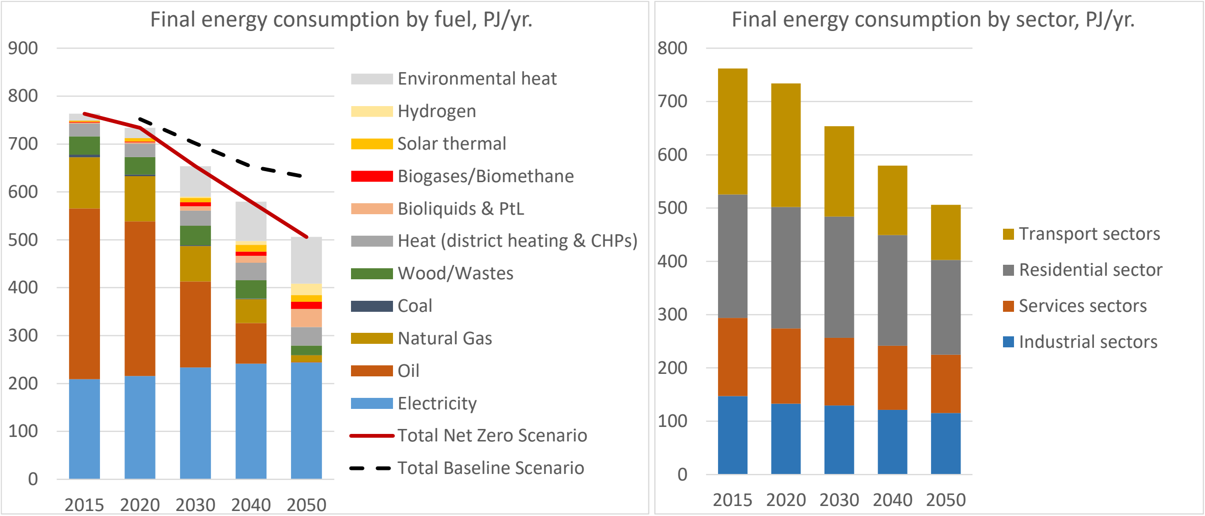

Figure 1.5: Final consumption by fuel (left) and by sector (right), excluding fuels for international aviation. Fuel consumed for on-site CHP plants is not reported in the figure, to avoid double-counting with the electricity and heat. The figure reports both marketed (i.e. district heating) and non-marketed (i.e. consumed on-site) heat.

1.5.3 Hydrogen demand

This section focuses on the use of hydrogen as an energy carrier in the Swiss energy system, with a particular emphasis on the decarbonisation of the transport sector. It also discusses the emerging cost-effective production pathways and provides insights regarding the overall infrastructure needs.

1.5.3.1 Overview of the hydrogen penetration in the Swiss energy system

In 2018, the hydrogen consumption in Switzerland amounted to 0.11 PJ (or 431 GWh). Refineries consume 85% of it, and the rest is used in the watch industry (high-quality glass production), chemical and pharma industry (plastics, fragrances, vitamins, etc.), in synthetic stone production (also for jewellery markets), and metal processing industry (Lehner et al., 2018). However, in refineries, integrated processes cover most of the hydrogen demand. This means that refineries do not generate external demand for hydrogen. By excluding them, the demand for hydrogen in Switzerland today is less than 0.02 PJ (65 GWh).

By 2030, in the *Net-Zero* scenario, hydrogen use for the supply of low, medium and high-temperature heat emerges in the Swiss industry (Figure 1.6). Its uptake is facilitated by the increasing carbon prices and the reinforcement of the emission trading scheme. Because of the technical challenges related to the direct combustion of hydrogen (high combustion velocity, low radiation heat transfer, corrosion and brittleness in boilers), the major application in hydrogen for process heat is in fuel cells. Molten carbonate fuel cells and solid oxide fuel cells can supply heat that reaches a temperature of 1000°C (Bauer et al., 2017).

While the industry is a first mover in the use of hydrogen as an energy carrier in the Swiss energy system, the scaling up of the domestic consumption is mainly sought on the transport sector (Figure 1.6). If the cost of fuel cell stacks will be reduced to the levels foreseen by the manufacturing industry, then fuel cell vehicles can become competitive to battery-electric ones in the private transport, and to the internal combustion and hybrid engines in the freight transport. The enforcement of vehicle emissions standards can accelerate the penetration of hydrogen in all transport modes, and, in particular, in those that are hard to electrify via battery-electric vehicles, such as the freight and long-distance transport.

District heating from stationary fuel cells also emerges beyond 2040. The concept builds on micro-grids that can provide electricity and heat to building blocks and communities[9]. Fuel cells can be scaled-up to serve large residential, office and industrial building complexes, benefitting from the advantage of high electrical efficiencies. Their application in district heating lifts to some extent barriers in their penetration to single houses or buildings, which are related to high upfront costs and complexity of the integration of fuel cell CHPs compared to alternative heating options.

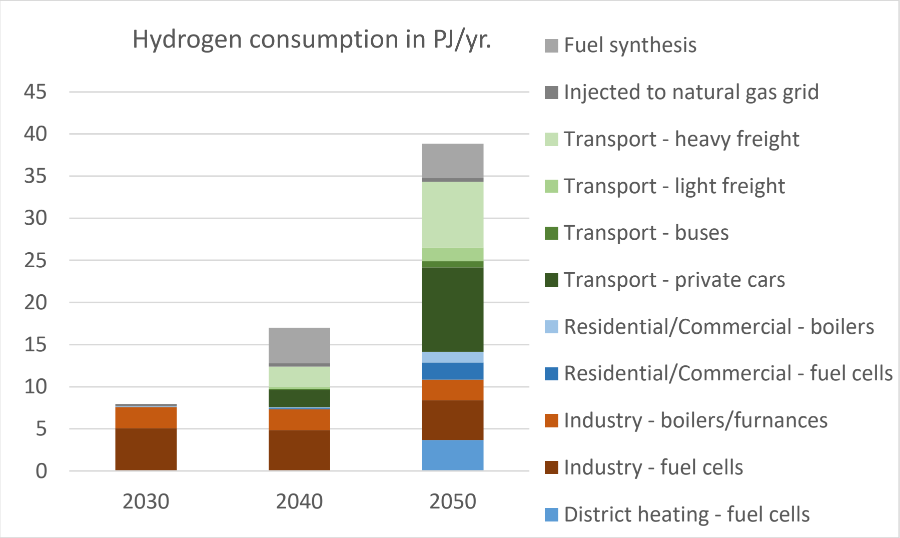

Figure 1.6: Hydrogen consumption, decomposed to the different uses of hydrogen, in the Net-Zero scenario.

On top of the direct use of hydrogen in industrial, commercial, district heating and mobile applications, hydrogen is also used for the production of synthetic methane and synthetic oil products. The domestic synthetic fuel production using hydrogen peaks around 2040, by when about 1 TWh of synthetic fuels are produced and consumed in heating sectors, road transport and domestic aviation. The hydrogen that is used in fuel synthesis is produced by electrolysis in 2040, and also from BECCS in 2050. The source of carbon is captured CO_2 from the production of electricity, hydrogen, as well as industrial processes and direct air capture. It should be noted that the analysis excludes the possibility to use synthetic fuels in international aviation, which is a sector with potential for scaling-up their consumption (McKinsey, 2020).

When considering the total energy demand, the direct consumption of hydrogen accounts for about 8% of the total final energy consumption in 2050. When the electricity and heat produced from hydrogen fuel cells are also accounted, then the share of hydrogen in total final energy consumption increases to 10%. The relatively small share of hydrogen should be seen in the context of the higher efficiency that fuel cells achieve in meeting the electricity, heat and mobility demands compared to boilers and conventional cars.

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[9] See for example the FC-District Project https://cordis.europa.eu/project/id/260105/reporting , the LEMENE Project http://www.lempaalanenergia.fi/content/en/1/20126/LEMENE.html and the ELECTROU project https://www.fch.europa.eu/project/mw-fuel-cell-micro-grid-and-district-heating-king’s-cross

Box 1. Increasing the utilisation of CO_2 and hydrogen for synthetic fuels

A variant of the *Net-Zero* scenario has been also assessed aiming at exploring the conditions under which an increased penetration of domestically produced synthetic fuels in 2040 and beyond is achieved. The synthetic fuels in the analysis are consumed in the heating sectors, road transport (and domestic aviation) as international aviation is excluded. The production of synthetic fuels increases as consequence of higher demand for synfuels as decarbonisation option, if:

a. The expected reduction in hydrogen fuel cell stack costs is not achieved,
b. The electrification of the road transport is delayed,
c. The emission reduction targets are in the range from more than 70% compared to 1990 (see Box 3).

When the first two conditions are met, then the amount of synthetic fuels produced in 2040 can be twice the amount seen in the *Net-Zero* scenario. However, maintaining these levels of production also in 2050 and at the same time aiming at net-zero emissions, requires an accelerated deployment of DACCS to achieve negative emissions, due to the limited domestic potential of biomass in BECCS. The analysis therefore suggests that the synthetic fuels in road transport is a transition option, until alternative drivetrains will be mature or stringent climate targets are in place.

1.5.3.2 Prospects of hydrogen for decarbonising the Swiss transport sector

Figure 1.7 shows the composition of the transport sector per major technology in the *Net-Zero* scenario in 2050.

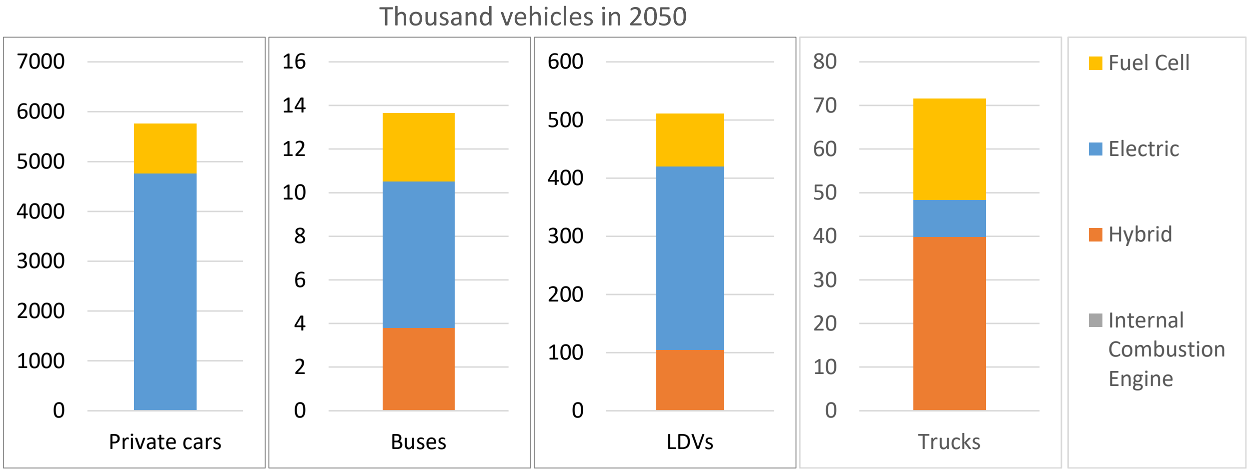


Figure 1.7: Composition of vehicle fleet (in thousand vehicles) in the Net-Zero scenario in 2050 by drivetrain. The electric vehicles include battery-electric and plug-in hybrids. LDV = Light-duty vehicles. Hybrids exclude plug-in vehicles. Buses also include coaches in the figure.

Private cars sector

In the private cars sector, car ownership increases from 540 cars per thousand capita in 2015 to 553 in 2030 and then remains at this level until 2050. These saturation effects imply a deceleration in the growth in vehicle stock until a stagnation is reached after 2030. The combination of decelerating stock growth and present vehicle scrapping rates would normally result in virtually stable new registrations around present levels. However, it is assumed that as per capita incomes increase, the average life of vehicles declines, and, as a result, scrapping accelerates leading to market expansion. Hence, the growth in private cars is about 28% from 2015 to 2050 or 1.3 million cars. This growth dynamic is an important factor for vehicle stock renovation and the potential for the introduction of new technologies, especially in the later years.

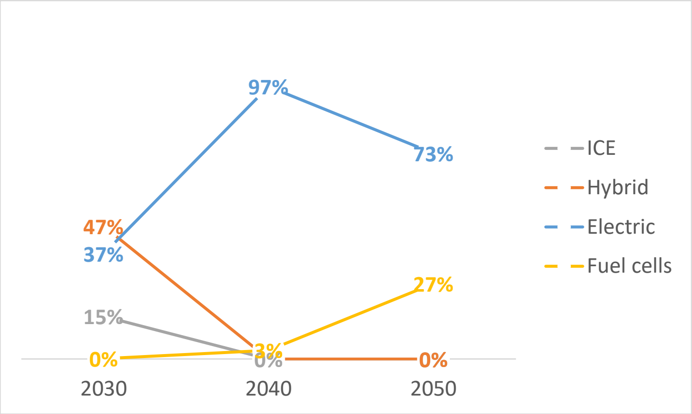


Figure 1.8: New registrations (percentage of total) of the different technologies in private cars in the Net-Zero scenario. ICE=internal combustion engines. The electric vehicles in the chart include battery-electric vehicles and plug-in hybrids. The new registrations in the Net-Zero scenario relate only to technologies suitable to meet the vehicle emissions standards.

Figure 1.8 shows the registrations of new private cars in the *Net-Zero* scenario. The period from now until 2050 is divided into three principal stages: a) the period until 2030 is characterised by transition with many options competing; b) the period 2030-2040 which sees a rapid introduction of electric vehicles; and c) the period 2040-2050 in which fuel cell cars emerge and gain share in the market, while electric vehicles continue to grow. The last two decades of the projection period are characterised by a rapid transformation of the private cars sector, mainly driven by the take-off of electric cars, including fuel-cell electric vehicles.

Public road transport and trucks

Successful demonstrations of fuel cell busses have been already performed in Switzerland (Postauto, 2017), and new models of busses and trucks have been recently produced and purchased worldwide (IEA, 2019). In the *Net*-Zero scenario, by 2050 the share of vehicles fuelled by hydrogen is higher in the public and freight road transport than in private cars. This result implies that heavy trucks and intercity buses seem to be promising and competitive applications for fuel cell electric powertrains.

The results for heavy trucks (Figure 1.9) show that, as in the case of private cars, the developments in the period from 2020 to 2050 can be divided into three main segments. Until 2030, the stringent emission standards in heavy-duty vehicles result in a strong hybridisation. In the period from 2030 to 2040, hybrid engines still have the lion's share in the new sales, but electric and fuel cell electric powertrains combined already start to account for one-third in the new registrations. In the post-2040 period, fuel cell trucks become a competitive option to hybrids, as the costs of fuel cell stacks are reduced, and there is a limited potential for increased electrification of the sector to meet the need for lower emissions in the sector. As a result, the share of fuel cell trucks in new registrations doubles in 2050 from 2040 and reaches 35%.

The segment of light-duty vehicles and vans is also characterised with a strong hybridisation until 2030, in order to meet the post-2020 emissions standards of new vehicles. The sector displays better electrification prospects than the heavy-duty trucks, due to the lower payloads and shorter haul trips. Hence, in 2050, battery-electric and plugin-electric light-duty vehicles dominate the stock. The penetration of fuel cell drivetrains in light-duty vehicles lags about a decade compared to the heavy-duty trucks.

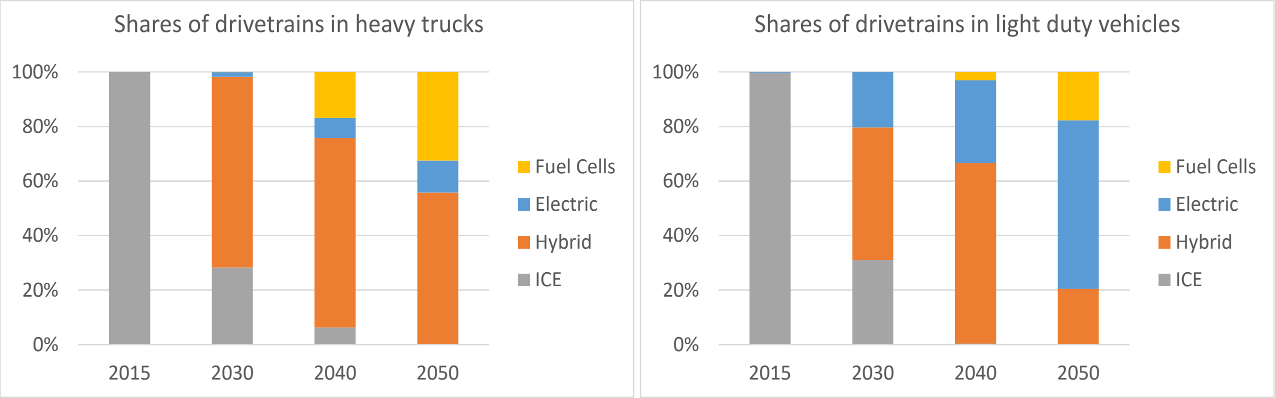


Figure 1.9: Share of drivetrains in freight transport in the Net-Zero scenario, based on the number of vehicles. Electric includes both battery-electric and plug-in hybrids. ICE=internal combustion engine.

Regarding the public road transport, i.e. urban buses and coaches, internal combustion engines dominate the mix until 2040 (Figure 1.10). This is attributable to the assumed emissions standards and fuel efficiency of buses (as of today, the European Commission has not set targets for buses yet, in contrast to trucks and light-duty vehicles where post-2020 targets have been already defined). The electrification of the public road transport accelerates after 2030 due to the improvements in batteries (costs and density). Fuel cells mainly enter the long-distance intercity public transport and to a lesser extent in urban city transport. It should be noted that the overall impact of buses and coaches regarding the penetration of hydrogen is small, as the sector accounts only for 20% of the total demand for public transport in Switzerland; the rest 80% is met via electrified rail transport.

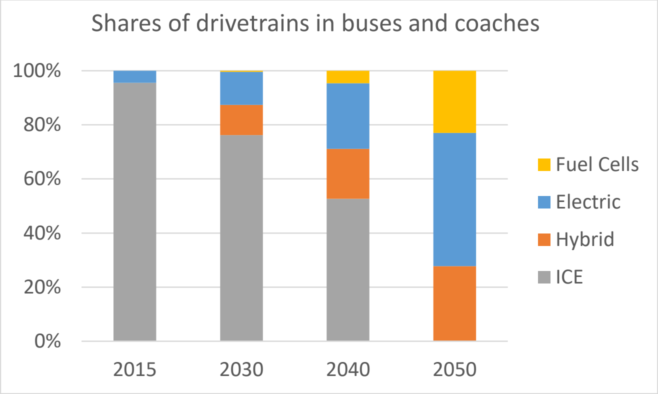


Figure 1.10: Share of drivetrains in buses and coaches in the Net-Zero scenario, based on the number of vehicles. Electric includes both battery-electric and plug-in hybrids. ICE=Internal Combustion Engine.

1.5.4 Hydrogen production

Hydrogen appears in the Swiss energy system by the time when carbon prices are high, and large emissions reductions are needed to achieve carbon neutrality by 2050. Pure fossil fuel options and options without CO_2 capture are not economically attractive for hydrogen production in the *Net-Zero* scenario in the long-term. In this context, fossil-based technologies to produce hydrogen without CCS can only be considered as transition options until CCS matures or the costs of electrolysis declines.

As shown in Figure 1.11, the demand for hydrogen in 2030 is mostly met via SMR/ATR (which is also the main hydrogen production option today - worldwide and in Switzerland), and then in

2040 also by electrolysis. In 2050, when deep reductions in CO_2 emissions are needed, producing fossil-based hydrogen without CCS is not an economically viable option. SMR/ATR loses shares in favour of electrolysis and wood gasification with CCS. Any SMR/ATR plants that remain in operation need to be equipped with CCS, and if possible, to use biogenic gas as a feedstock. However, biomethane is limited, and there is strong competition for the resource in other sectors where gas cannot be easily replaced (e.g. industrial processes). In the current analysis, less than 5% of the hydrogen produced with SMR/ATR in 2050 is based on biomethane. Figure 1.11 also implies that a large-scale penetration of SMR/ATR relies on the future availability of CCS. Otherwise, stranded assets can be generated in the long-run.

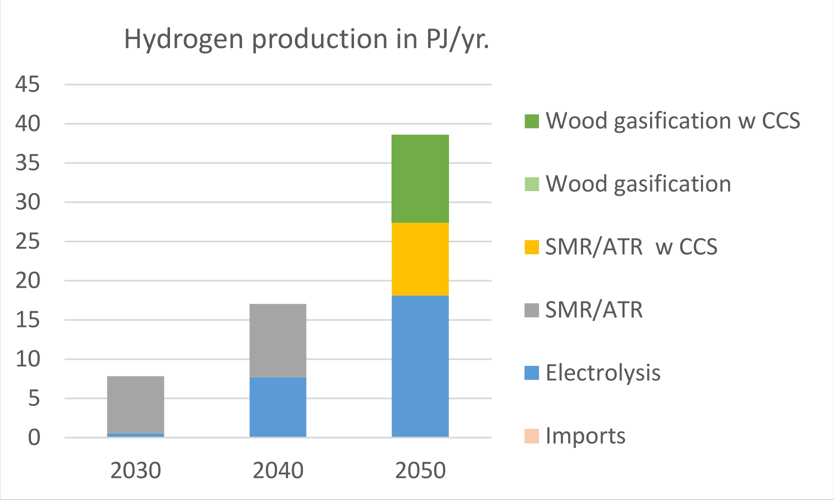


Figure 1.11: Domestic hydrogen production by technology in the Net-Zero scenario.

Electrolysis has a dual role in the Swiss energy system. It provides a scalable low-carbon option for hydrogen production and at the same time helps in the daily and seasonal balance of the electricity system. It can convert excess renewable electricity to hydrogen, which then can be stored at daily, weekly and seasonal timescales (see also next section). It should be noted that the major source of electricity in electrolysers is hydropower (mainly run-of-river), as the bulk of the electricity produced in solar photovoltaics is mainly consumed and balanced locally. Electricity from solar is used in electrolysis only when other demand-side and flexibility options are not available or cannot be deployed on a large scale. Electrolysis using electricity from distributed solar photovoltaics mainly occurs in summer weekends and, to a lesser extent compared to weekends, in summer working days, see also (Panos et al., 2019). This outcome also implies that electrolysers face grid connection costs as well as water taxes in the post-2030 period, by the time when they are already an economically viable option for hydrogen production.

One of the most promising options for producing hydrogen when carbon prices are high is through biomass gasification with CCS. However, the technology is currently rather immature, which is a barrier of its early penetration. Consequently, this option enters into the Swiss energy system only by the end of the projection horizon if the technology has reached commercialisation level. Another major barrier that hinders its scalability is the availability of wood and the competition for the resource from other sectors in the energy system.

1.5.5 Role of hydrogen in balancing the energy system – P2X

The transformation of the Swiss electricity sector towards solar PV in Switzerland accentuates the need for balancing the system at different timescales: daily, weekly and seasonal. In this regard, hydrogen produced from renewable electricity can provide increased flexibility to the energy system in order to integrate high shares of variable renewable energy. As shown in Figure 1.12, about one-fifth of the produced hydrogen from electricity in the *Net-Zero* scenario is stored and seasonally shifted from summer to winter in order to balance the system. The required hydrogen storage capacity is about 320 GWh or 1.5 GW. The main storage option assumed in the analysis is hydrogen tanks, the storage cost of which ranges from 12 to 24 CHF/kWh.

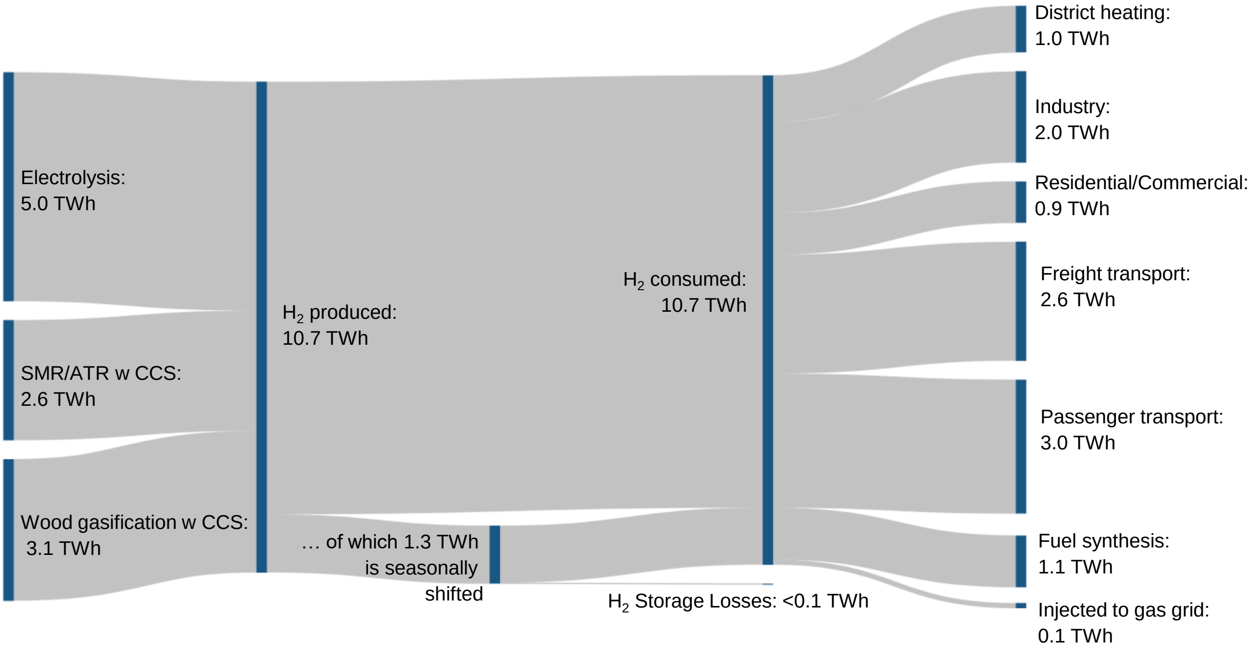


Figure 1.12: Production and demand for hydrogen and its role in the seasonal balancing and sector coupling in the Swiss energy system in the Net-Zero scenario in 2050.

Hydrogen can also be used as a backup and provide buffering functions, enhancing the security of supply in the long term. According to (EC, 2020), energy buffering that is realised through renewable and low-carbon hydrogen is a function very much beyond renewable electricity storage. Hydrogen buffering interlinks different end-use sectors (for instance industry and transport), and energy markets, and it could allow to re-price energy in specific hydrogen markets. As shown in Figure 1.12, in a hydrogen buffer system, the excess renewable energy is stored in the form of hydrogen, and then fuel cells (mobile or stationary) are used to produce electrical power. This, on the one hand, decouples demand loads from the variability of resources, but on the other hand, it also couples different sectoral demands.

1.5.6 Investments in hydrogen production and infrastructure

Figure 1.13 shows the cumulative undiscounted investment expenditures in hydrogen production, distribution and demand technologies from 2030 to 2050. The cumulative capital outlays in hydrogen production amount to 3.5 billion CHF_{2010}. Electrolysers account for about half of the investment expenditures. SMR/ATR with CCS and biomass gasification with CCS absorb about a quarter of the capital outlays in hydrogen supply each.

The cumulative investment in hydrogen distribution and storage is 3.5 times higher than the investment in hydrogen production. Pipelines have the highest share with more than 50%, while fuel service stations account for 25%. Another 20% is directed to storage of hydrogen and the rest to hydrogen trucks. In terms of sectors, the delivery of hydrogen in the mobility sectors dominates the costs, as it accounts for more than 90% of the total outlays in hydrogen distribution infrastructure.

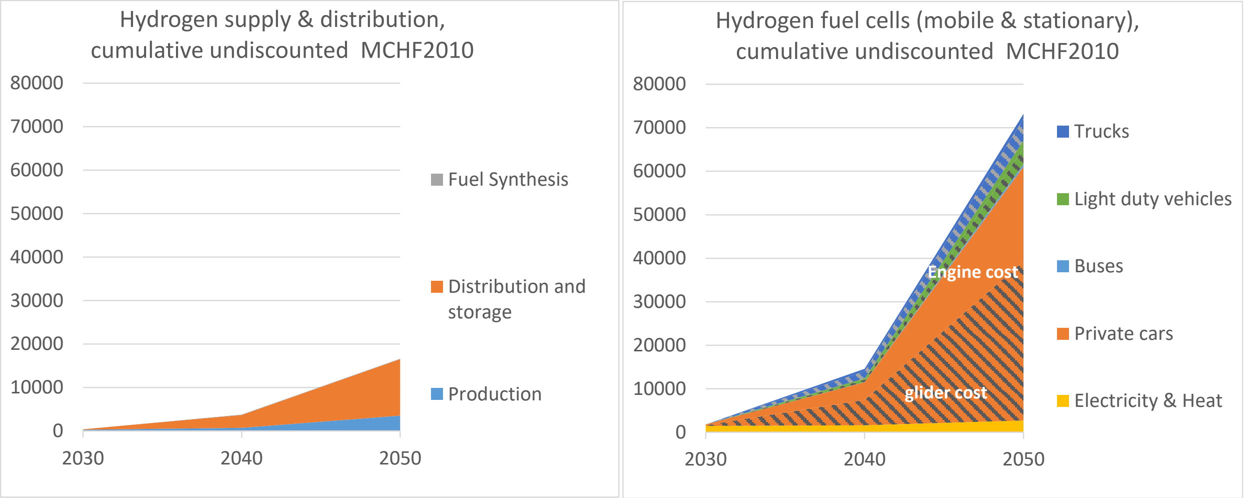


Figure 1.13: Cumulative and undiscounted lumpy investment in hydrogen supply and storage infrastructure (left) compared to the investment expenditures directed to hydrogen demand technologies (right) in the Net-Zero scenario. The shaded parts in the right-hand side figure correspond to glider costs, while the solid coloured parts to the cost of the engine and storage.

The lion's share in the expenditures in hydrogen technologies is on the demand side. The fuel cell cars alone take about four times more capital than the hydrogen supply and distribution infrastructure. However, the purchase costs of the vehicles also include the cost of the glider. By excluding the glider costs, then the cumulative undiscounted investment expenditures in fuel cell drivetrains are about 20% higher than the investment expenditures in hydrogen supply and distribution infrastructure (20 vs 17 billion CHF in 2050). The investment in stationary fuel cell applications constitutes only 4% of the total expenditures in hydrogen demand technologies despite of their much larger contribution in the overall hydrogen consumption. When excluding glider costs from the investment in transport, stationary fuel cells have a share of 12% in the total investment in fuel cell stacks. These results indicate the importance of the mobility sector in the investment in hydrogen technologies.

Using existing natural gas infrastructure, via either blending or repurposing, it mostly appears as a transition option. The upper limit in blending is about 2% in Switzerland today in terms of volume, or 0.3% in terms of mass. By 2050, roughly 1% of the total hydrogen delivered amount is blended with the natural gas grids. Blending faces challenges related to the lower energy density of natural gas, the risk of increasing the spreading of flames, and can alter the quality of natural gas. Therefore, it cannot be considered as a long-term and large-scale option.

Repurposing existing natural gas pipelines for 100% hydrogen distribution is likely to be technically feasible, but this will be a large undertaking due to the need to convert the majority of end-use equipment. The feasibility of using existing high-pressure transmission networks completely for hydrogen distribution is less clear than the low-pressure networks, not only because of logistical reasons for keeping gas transmission networks in operation but also because of technical issues arising from the high pressures. Since the natural gas is supplied by complex networks with many interconnections linked to a central transmission system, it would be hard to isolate parts of the networks for repurposing. Moreover, repurposing does not eliminate the need to have hydrogen on tap and ready to feed into converted networks, which in the end hydrogen production and distribution infrastructure needs to be developed prior to the conversion process of the natural gas grid. In the analysis with STEM, the repurposing of the gas infrastructure occurs mainly as a transition option, by converting the easier parts of the network first, until the full deployment of hydrogen-specific infrastructure (Figure 1.14). However, it should be noted that the findings of the analysis are subject to further investigation regarding the technical possibilities in converting existing gas networks to pure hydrogen networks in Switzerland, which was out of scope in the context of the ELEGANCY project.

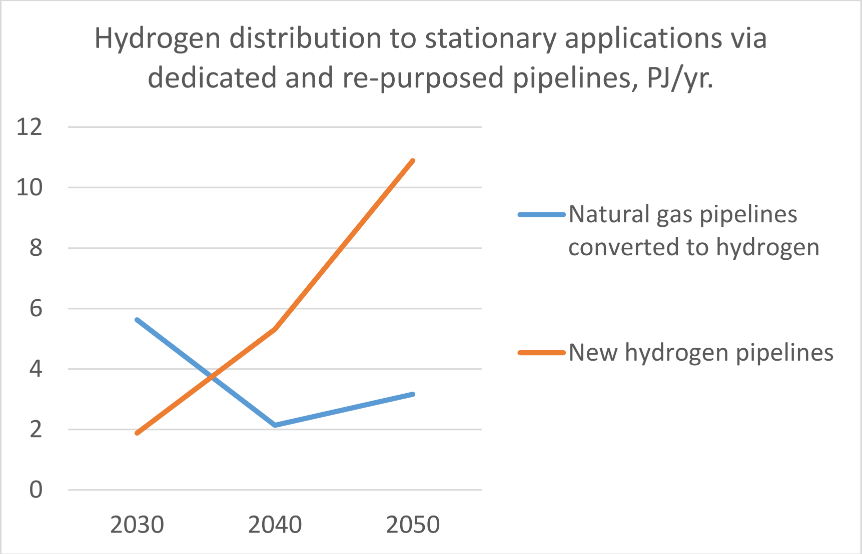


Figure 1.14: Delivered hydrogen to stationary applications via new hydrogen pipelines and via natural gas pipelines repurposed to 100% distribution of hydrogen. The slight increase in the repurposed natural gas pipelines observed in the last decade is due to the introduction of new hydrogen uses in residential/commercial sectors as well as in district heating applications. However, additional analysis is needed regarding the feasibility of converting natural gas pipelines in Switzerland.

1.6 Assessment of the drivers leading to increased hydrogen penetration – key insights from the variants of the Net-Zero scenario

The analysis of the *Net-Zero* scenario identified the main drivers influencing the uptake of hydrogen in the Swiss energy system. Climate policy, emissions standards, the development of the infrastructure, and mainly the development of the demand are among them. In this section, sensitivity analysis for each one of these drivers is performed to provide additional insights into their potential to increase the penetration of hydrogen.

1.6.1 Impact on the mobility sector

Figure 1.15 summarises the composition of the vehicle stock in the different variants that deal with technology improvement and targeted policies (on top of the climate policy). The R&D infusions to reduce the costs and improve the efficiency of fuel cell stacks have a larger impact on the penetration of hydrogen-fuelled vehicles than the cost reductions in the infrastructure, especially concerning heavy trucks. In contrast, R&D expenditures only in hydrogen supply and distribution infrastructure do not significantly increase the penetration of hydrogen in the mobility sectors, compared to the *Net-Zero* scenario. Targeted additional policies, such as taxation of fossil fuels, when combined with R&D in hydrogen supply and distribution infrastructure result in a substantial increase in the uptake of hydrogen in transport. The combined case, in which all measures are in place, is the most optimistic case for hydrogen and achieves the highest penetration of hydrogen in mobility in all sectors. The above indicates that: a) the fuel cell stack cost is a decisive factor for the uptake of hydrogen in transport; b) the costs reductions in hydrogen supply and infrastructure seem to benefit more the stationary than the mobile application of fuel cells.

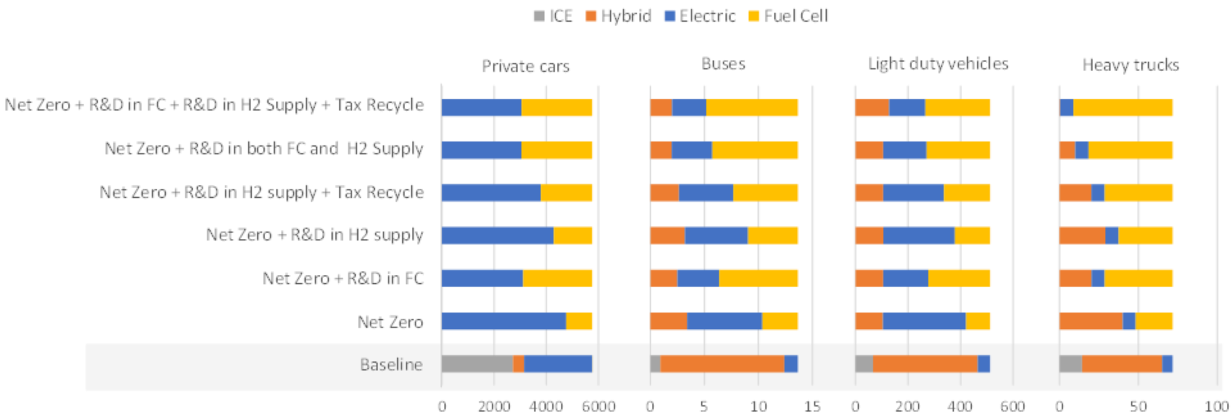


Figure 1.15: Penetration of hydrogen in transport in the different variants of the Net-Zero scenario in 2050.

1.6.2 Impact on the timing regarding the introduction of hydrogen in the energy mix

The increased taxation in fossil-based road transport brings the overall penetration of hydrogen forward in time. Figure 1.16 shows the trajectory in the hydrogen production in the *Net-Zero* scenario and its variants. The introduction of hydrogen in the Swiss energy mix is about 30% higher in 2040 when there is an additional tax in fossil-based road transport, compared to the cases when only R&D expenditures in fuel cells are in place. Viewed another way, the assessed targeted policy support on the hydrogen supply and distribution infrastructure accelerates the introduction of hydrogen in the energy mix by 5 to 10 years.

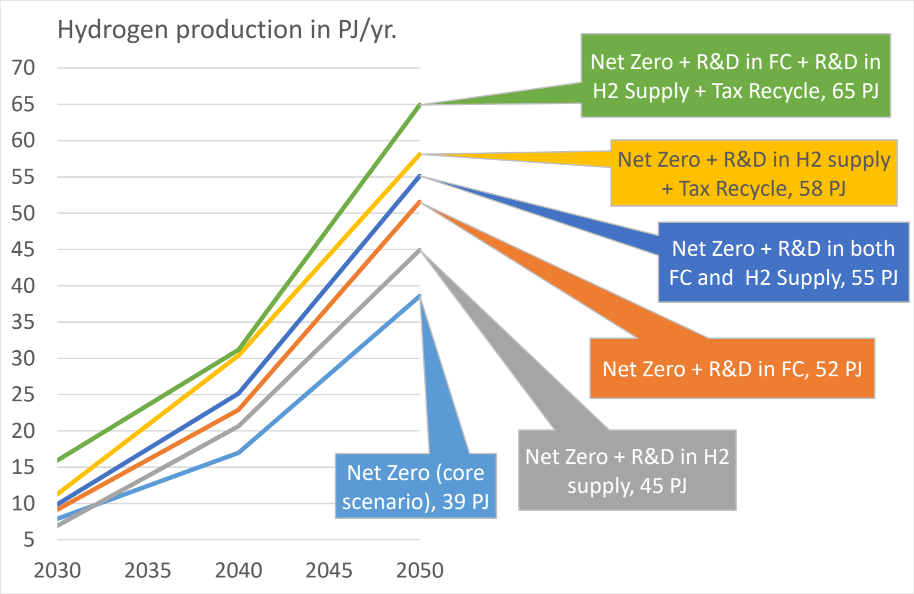


Figure 1.16: Trajectories of hydrogen production in Switzerland under different technology developments and targeted policies. The timing of the introduction of hydrogen in the Swiss energy mix is important regarding the uptake of hydrogen in 2050. The next two decades are critical regarding the development of the hydrogen economy, as a delay in the infrastructure could lead to a significantly lower uptake of hydrogen in 2050.

The timing in the introduction of hydrogen is important towards the realisation of a hydrogen economy. As Figure 1.16 shows, the most critical years for the development of hydrogen-based demand and supply are the next 20 years from today. Given the long investment cycles in the introduction of new technologies (for example, solar PV needed constant policy support for more than a decade), the analysis suggests that the realisation of a hydrogen economy requires actions today. Delaying the deployment of hydrogen supply and demand technologies beyond the next 20 years entails higher costs than an early introduction at a smaller scale. This is because hydrogen becomes an essential component of a decarbonised system in the last two decades. By not having the infrastructure in place would require enormous capital outlays to be able to deliver the quantities needed in the energy system.

1.6.3 Impact on scaling-up the domestic hydrogen production

In the most of the assessed variants, the increase in hydrogen production from the levels seen in *Net-Zero* is mainly achieved via SMR/ATR with CCS. This is because both electrolysis and biomass gasification face barriers related to electricity and resource availability, respectively. Electrolysis cannot be deployed at a large scale due to the limited (large-scale) renewable electricity. Excess solar PV cannot be efficiently used to run electrolysers on a base-load basis, as this would require transmission losses from moving electricity from the lower to the upper grid levels. Thus, mainly hydropower and imported electricity can be cost-effectively used to run electrolysers for more than 2000 hours in a year to ensure their profitability. Similarly, the potential of domestic woody biomass is limited. Wood gasification with CCS needs to rely on imported bioenergy, if it is to be deployed at large scales. It is more cost-effective to directly import biogenic gas and use it in SMR/ATR with CCS, rather than importing wood for gasification, since SMR/ATR process is more efficient (Table 1.3).

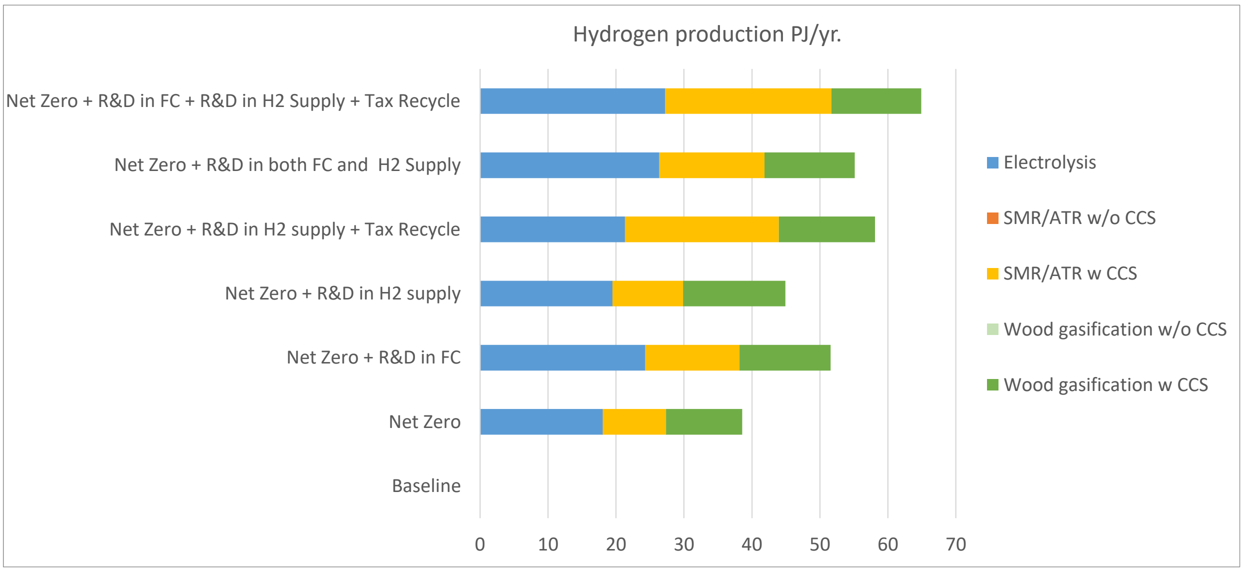
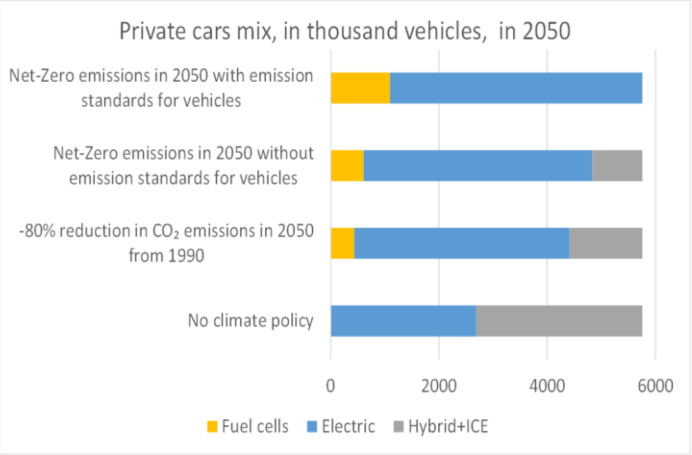


Figure 1.17: Hydrogen production mix in the different variants of the Net-Zero scenario in 2050.

In this regard, SMR/ATR with CCS becomes a crucial technology for increasing the domestic hydrogen production, beyond the levels seen in the *Net-Zero* scenario. However, as SMR/ATR with CCS delivers negative emissions only when it runs with biogenic gas, negative emissions technologies are needed elsewhere to offset the non-captured emissions from SMR/ATR when it is operating with natural gas. For instance, in the variants with the highest penetration of SMR/ATR with CCS, only 5% of the hydrogen production from this option is based on biomethane and delivers negative emissions. The rest 95% of the hydrogen is produced with natural gas with CCS, and there is an increased penetration of waste incineration plants with CCS to offset the emissions from gas-based hydrogen production.

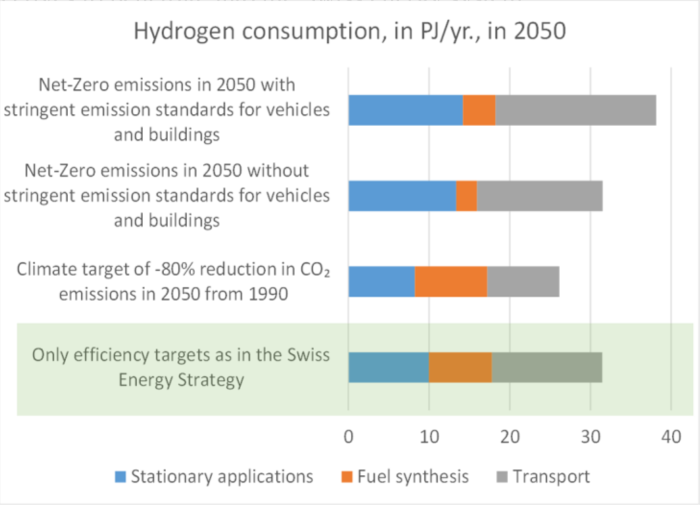
Box 2. The role of climate policy and vehicle emissions standards in the uptake of hydrogen



The intensity of the climate policy is a major driver for the penetration of hydrogen in the Swiss energy system. As shown in the figure, in the absence of emissions reduction targets there is no penetration of fuel cell cars. Moreover, the emission standards in private cars also play an important role. When stringent emissions standards are in place, then the share of fuel cell cars in the stock doubles compared to the opposite case, even when the overall climate targets are the same in both cases. This is because emissions standards induce a faster renewal of the vehicle stock and fosters the introduction of low-carbon technologies. Hence, the introduction of hydrogen can be brought earlier in time and this can accelerate its deployment. The figure also indicates that the fuel cell vehicles face strong competition in the transport sector from more mature technologies for decarbonisation, such as battery and plug-in electric cars in the private transport and the improved internal combustion (including hybrid) engines in the long-distance transport.

Box 3. The role of efficiency policies regarding final consumption in the uptake of hydrogen

long-term signals regarding climate objectives to penetrate into the Swiss energy system[9]



The Swiss energy strategy states ambitious efficiency targets regarding the final energy consumption per capita (-43% in 2035 from 2000 levels) and the direct electricity consumption per capita (-13% in 2035 from 2000 levels). Even in the absence of climate policy, a limit in the direct electricity consumption increases the penetration of fuel cell CHPs and vehicles, as they constitute an efficient option. The required hydrogen is mainly produced via SMR/ATR. As shown in the figure, the uptake of hydrogen in electricity and heat generation and transport is even higher than a normative scenario that reduces the CO_2 emissions by 80% in 2050 from 1990 levels[9]. This outcome suggests that when electrification of the demand is restricted or not possible, hydrogen has an incrreasing role to play. However, a hydrogen-based system does not lead to less primary energy consumption.

1.7 Conclusions

In this section, we highlight the key modelling work carried out to support the energy systems analysis in the Swiss case study, and we summarise the key findings from the scenario analysis focusing on policy recommendations.

1.7.1 Model development

The SWISS TIMES energy systems model was expanded to include the technologies of particular interest in ELEGANCY in order to assess deep decarbonisation scenarios. The model was enhanced to include production and consumption pathways of hydrogen and synthetic fuels, including power-to-X (X = gas, hydrogen, electricity, heating fuels, e-fuels). Negative emission technologies such as bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon capture and storage (DACCCS) were introduced in STEM, informed by the analysis in the context of the ELEGANCY project. The analysis in the ELEGANCY project benefited to a large extent from the data and modelling in the context of the SCCER Mobility project[10], which significantly developed the transport sector in STEM. Much of the modelling work done in ELEGANCY spills over to the SCCER Joint Activity Scenarios and Modelling[11] which looks at deep decarbonisation scenarios for Switzerland. Overall, the analysis performed in the context of ELEGANCY using STEM advanced the state-of-the-art of the model.

Hydrogen infrastructure development in a stylised configuration was implemented in STEM. A particular challenge was the modelling of new hydrogen distribution and storage infrastructure, due to a large number of possible configurations and sizes. Based on the present analogue of gas supply and refined oil distribution, a stylised representation of local hydrogen clusters is used, also informed by the activities in WP4 of ELEGANCY. The local hydrogen cluster in STEM includes a mix of pipelines and road delivery of hydrogen while assuming an optimal layout of the infrastructure.

1.7.2 Hydrogen technology diffusion and the role of H2-CCS

A strong climate policy accelerates deployment of hydrogen in the Swiss energy system. Renewable and low carbon-based hydrogen is an energy carrier of growing importance in a climate-neutral and low air pollution Swiss economy in 2050, as it represents an option to replace fossil fuels in hard to decarbonise sectors. Hydrogen can be directly used in fuel cell power plants and vehicles, or it can be used to produce synthetic hydrocarbon fuels and facilitate decarbonisation by using existing infrastructure (where it is technically and economically feasible).

The future success and timing of the hydrogen economy are highly dependent on technological developments and targeted demand-side measures. Key among them is the reduction of costs of fuel cell stacks and measures to promote hydrogen in new industrial applications, as well in those transport sectors that are hard to electrify with battery-electric vehicles. The analysis shows that uncertainties related to future costs of hydrogen production, storage and distribution technologies are less crucial compared to the hydrogen use technologies. Hydrogen supply and distribution technologies represent a relatively small part of the total

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[10] See https://www.sccer-mobility.ch
[11] See https://sccer-jasm.ch

hydrogen-related costs and fewer technical possibilities for major improvements compared to fuel cells.

The industry sector can be the first mover for hydrogen applications; transport scales up hydrogen uptake. The analysis shows that until 2030 hydrogen mostly penetrates in the industrial sectors given significant cost reductions can be realised for hydrogen-based CHP applications. However, the transport sector scales-up the uptake of hydrogen in the post-2040 period. The automotive applications constitute a key segment for the future of fuel cells and lead to improvements that can spill over to other applications, as well as they carry forward infrastructure development. The major competitor of fuel cell vehicles is the electric car in the private transport segment and energy-efficient hybrid/ICE engines in the long-distance freight and public transport, which are partly operated on biofuels and synthetic fuels.

Hydrogen in buildings faces high upfront costs and strong competition with existing infrastructures. The hydrogen penetration in the building sector (both residential and commercial) shows fewer prospects than industrial and mobility applications. The major obstacle is the cost of the fuel cell CHP units that compete with gas-based heating and heat pumps, which are already today mature technologies to provide low-temperature heat at high efficiency and comparably low costs. Blending of hydrogen with natural gas to use the existing infrastructure and reduce the upfront cost of technology switching in the demand sectors is not an economically viable option, because it increases the natural gas supply costs and diminishes the value of hydrogen. It may also change the quality of gas consumed in Switzerland and affect the design of gas infrastructure (EC, 2020; IEA, 2019). From the cost perspective, the analysis shows that 100% heating with hydrogen in the building sector is attractive for large complexes, via (possibly small-scale local) district heating networks.

Hydrogen becomes important in balancing the energy system at a seasonal scale. Next to the application of hydrogen in stationary and mobility sectors, hydrogen also plays a role in the Swiss energy system in balancing a renewable-based future electricity system by transforming electricity into hydrogen when electricity is abundant and cheap and by providing flexibility. It is used for both daily and seasonal storage, and also provides interlinks between different sectors and markets. In the latter case, hydrogen can also provide buffering functions (EC, 2020).

Hydrogen supply progressively shifts to renewable hydrogen (electrolysis, biogenic SMR/ATR and wood gasification with CO_2 capture). Natural gas reforming via SMR/ATR dominates the production mix by 2040. On the way to 2050, renewable-based hydrogen production is progressively deployed alongside the rollout of new renewable power generation. SMR/ATR units need to be equipped with CO_2 capture and storage by 2050 and natural gas as feedstock needs to be partly replaced by biomethane, especially when substantial negative emissions are needed. For the scaling-up of the hydrogen production from solid biomass, there are challenges related to the availability of biomass and the competition for this resource with other sectors in the energy system seeking for carbon-neutral energy sources.

Hydrogen infrastructure is likely to be developed in a stepwise manner, as in the gas and oil distribution analogue. The availability of infrastructure is a critical factor influencing the widespread use of hydrogen. The analysis reveals a cost-efficient stepwise approach regarding the hydrogen distribution infrastructure. Local clusters are formed first around industrial sites and areas with (relatively) high hydrogen demand. In a second phase, local clusters are connected to form a regional network. In the full-scale deployment of hydrogen, regional networks are connected, creating a nationwide hydrogen infrastructure. Today's analogue of gas and oil distribution can provide a basis for the modes of hydrogen distribution. Pipelines can supply dense urban areas or industrial sites that demand high volumes of hydrogen.

In contrast to hydrogen centres with dense infrastructure, the delivery of hydrogen to geographically dispersed refuelling stations and rural areas can be served with trucks. Gaseous hydrogen distribution seems to be more cost-efficient than liquid hydrogen or the usage of liquid organic hydrogen carriers (e.g., ammonia). This is because liquefaction is an energy-intensive process, while the liquid organic hydrogen carriers cannot directly be used in the demand sectors without further processing. However, the challenge with the gaseous hydrogen is that three times more volume is needed to provide the same energy as natural gas.

In the absence of specific supports, an early transformation of the Swiss energy system towards a hydrogen economy is unlikely. Even under extremely favourable technological developments for hydrogen-fuelled vehicles, the Swiss transportation sector could be at best in a mid-transition in 2050, compared to a 100% penetration of hydrogen. This outcome indicates the need for policy to help stimulating commercial demand for cleaner hydrogen and for proponents to demonstrate the feasibility of building on the current developments. In particular, the mid-term horizon until 2030/40 is crucial for the wider deployment of hydrogen in the long term. As investment cycles in the clean energy sector run for about 25 years, and the time needed for new energy technologies to penetrate existing markets is long, the time to act is now to realise the major technological developments in hydrogen demand and supply.

Boosting demand and supply of hydrogen requires various forms of support, but during the transition phase, these supports should not lead to stranded assets. To foster innovation and confidence of investors, long-term signals need to be established, demand for hydrogen needs to be created, and the risks of the investments need to be mitigated. Long-term signals include rigid climate policy. The creation of hydrogen demand can be facilitated by stringent emission and efficiency standards for vehicles and buildings, or market-based mechanisms such as taxation of fossil fuels. Industrial clusters may offer good opportunities for the deployment of low-carbon hydrogen and could be stimulated by a reinforcement of the emission trading scheme and carbon intensity reduction goals. Mitigation of the investment risk, and promotion of a higher diversity of market actors, can be achieved via new policy instruments such as carbon contracts of difference (EC, 2020), competitive bidding of hydrogen supply contracts or multi-year contracts for future hydrogen supply (IEA, 2019).

1.7.3 Carbon capture and storage

Negative emission technologies are needed to achieve net-zero CO_2 emissions in 2050. In the Swiss case study, about 8.6 $MtCO_2/yr$ of CO_2 needs to be captured in 2050. The sources of captured CO_2 are mainly municipal solid waste (MSW) incineration plants, industry with CO_2 emissions captured from combustion and process-related emissions, as well as the production of hydrogen and bio-liquids. Direct Air Capture is a backstop technology regarding the mitigation of climate change, and it is deployed after deployment of various energy efficiency improvement measures and renewable-based electrification, CO_2 capture in MSW incineration, industry and BECCS. The amount of negative emissions is about half of the total amount of the captured CO_2 emissions in 2050. Beyond 2050, the uptake of negative emission technologies (NET) is expected to increase.

For instance, the IPCC SR1.5 Report estimates that the global remaining CO_2 budget to restrict the temperature increase below 1.5°C by the end of the century with 66% probability is about 420 Gt CO_2eq from 2018 (IPCC, 2018). By adopting an egalitarian approach, the remaining Swiss budget is about 420 Mt CO_2eq. In the analysed net-zero scenario, the cumulative emissions from 2020 to 2050 are about 680 Mt CO_2, only from the energy system. This means there is a deficit in the budget of about 260 Mt CO_2 in 2050, which would need to be offset by increased deployment of negative emission technologies to comply with the 1.5°C climate target. Offsetting would need to be even higher if fewer mitigation measures are realised before 2050.

An early embedding of negative emission technologies in the Swiss climate policy is required if it is to limit extensive reliance on NETs in the post-2050 period. While effective measures to reduce CO_2 emissions are essential to successful climate policy, the analysis shows that a fast transition to net-zero is advisable. Carbon neutrality needs to be achieved at the latest by 2050. Therefore, an early embedding of carbon dioxide removal approaches, including negative emission technologies, need to be implemented in the climate policy to provide long-term signals to investors and stakeholders. Key among them is adequate CO_2 pricing, coordination with agricultural, energy, spatial planning and transport policy, as well as crediting the negative emission technologies as compensation measures to advance scaling to a marketable size.

CO_2 storage in Switzerland is a challenge, and a connection with European networks is a key requirement for the successful development of the CO_2 capture technology in Switzerland. According to our scenario assumptions, more than three-quarters of the captured energy and process-related CO_2 emissions need to be exported, as the domestic sequestration potential is still uncertain (especially for structures suitable for storing large amounts of CO_2). The domestic sequestration potential is assumed to be small in this analysis to reflect this uncertainty. The utilisation of CO_2 for fuel synthesis cannot deliver the negative emissions needed to achieve the net-zero target in 2050 (at the latest). Therefore, Switzerland relies on transport infrastructure across the EU and to have access to storage hubs, e.g., in Norway (Northern Lights Project). In this regard, international agreements and participation in projects of common interest (PCIs) that deal with cross border CO_2 storage infrastructure development need to be ensured (also in-line with Article 6 of the Paris Agreement). Not having the option of capturing and storing CO_2 in- and outside Switzerland would have significant implications on the achievement of ambitious Swiss climate goals and the associated costs.

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