Joint Activity Scenarios and Modelling

JASM Framework and drivers definition

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January 14, 2021

Supported by:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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Chapter 1

JASM Framework

At the core of the JASM framework are the energy system models that represent the whole energy system, modelling interdependencies between energy supply and demand (electricity, heat, transport services) (Section 1.1). Feeding into these energy system models are the results from a series of sectoral models (e.g., housing and electricity models). For both the energy system and the sectoral models, we use a set of harmonized assumptions (where applicable): drivers of energy use—population, economic growth, and climate (Section 1.2); resource availability (photovoltaics, wind, hydropower, and biomass) (Section 1.3); and technology characteristics (investment costs, conversion efficiency, etc.) (Section 1.4). We calculate energy demand exogenously from macro-economic drivers and current and future demand curves (Section 1.5). In a second step, we determined endogenously the optimal renovation levels needed to reduce these demands by applying energy efficiency cost curves for the residential and industrial sectors (Section 1.6), in this step the energy-system models determine the optimal level of investment on renovation measures and the corresponding demand reduction.

Using the JASM modelling framework, we evaluate the JASM scenarios that are defined along different policy dimensions including technology availability, market integration, and climate policy (Section 1.7). Then, we verify the results from the energy system models, checking whether the results are (1) consistent with grid constraints (system adequacy) and (2) consistent with case studies of local towns and cities (e.g., Baden). Finally, we evaluate the greater impacts for the society including Computable General Equilibrium (CGE) models from SimLab (Section 1.8).

In Figure 1.1 we map the JASM modelling framework, data inputs, and the individual contributions from each modelling group.

1.1 Energy system models

The JASM framework includes three energy system models: Swiss TIMES Energy system Model (STEM, PSI) (Panos et al., 2019, Kannan and Turton, 2014), Swiss Energy Scope (SES) from EPFL (Moret, 2017) and ETHZ (Marcucci et al., 2021). We use energy-system models with different capabilities in order to both evaluate robust, large structural trends (e.g., technology deployment) and the detailed transition, year-to-year, of the energy transition.

The SES models are snapshot models, i.e. they provide results for one single time period (e.g., a year) with a simpler representation of the energy system. We use these models to do uncertainty analyses over scenario results. STEM models the 2020-2050 time horizon, combining long-term investment

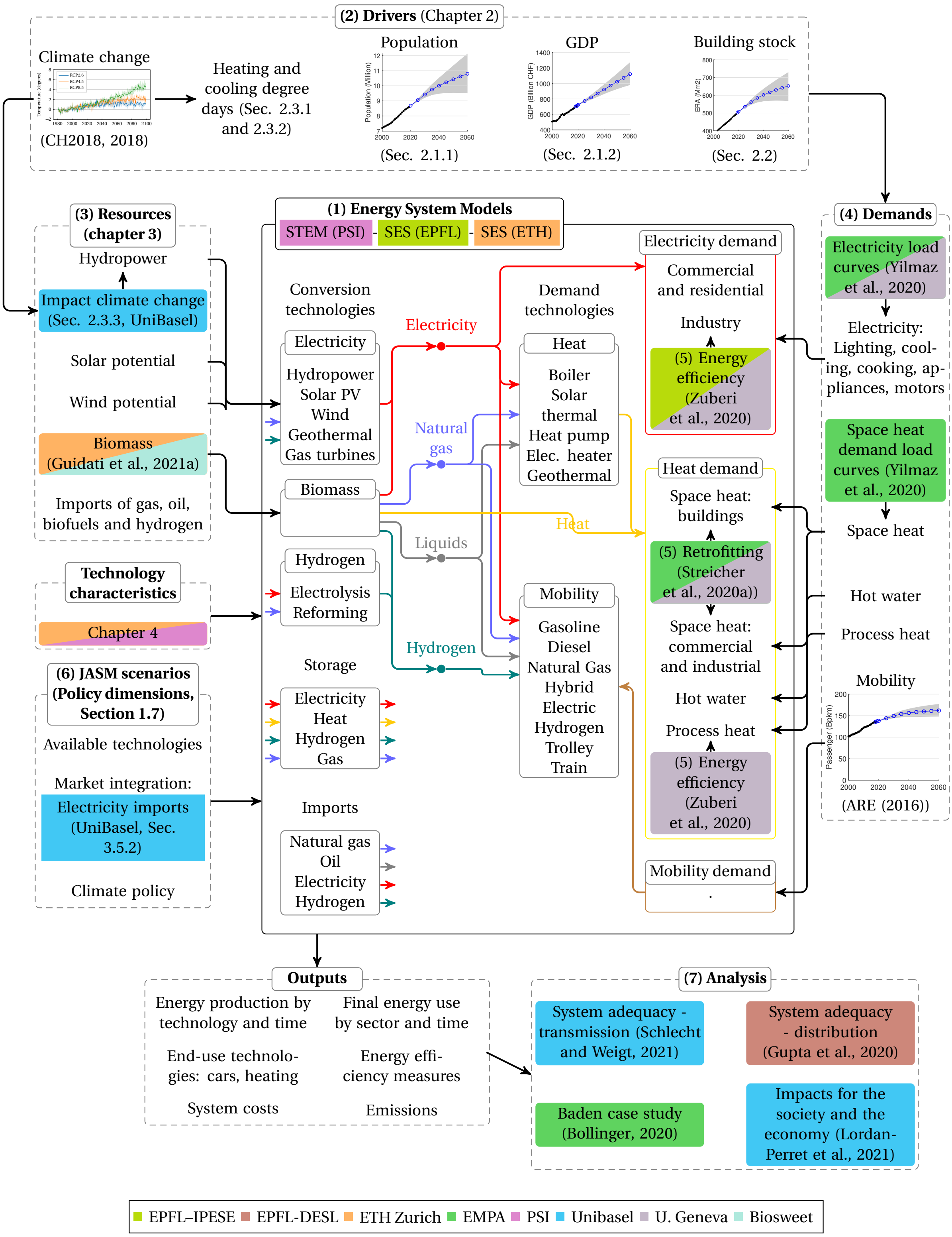


Figure 1.1: JASM framework

decisions with short-term operational constraints, and includes a significant level of detail in the representation of the energy system. Whereas the SES models allow us to consider a large set of scenarios quickly with fewer system details, the STEM model allows us to consider the transition pathways and system configurations in higher detail.

1.2 Harmonized drivers

The JASM drivers are factors that affect energy-use but that are not sensitive to domestic policies or changes in individual behavior: population, economic growth, global climate change, and technology characteristics.

In the JASM framework, we define variants for the drivers to capture the “sweep" of the possible future Switzerland: three variants (reference, high and low) for population, GDP, energy reference area (Section 2.1) and three variants for global climate change developments (RCP 2.6, 4.5 and 8.5, based on the CH2018 (2018) climate scenarios). We include the effect of the climate on:

- Heating and cooling demand: Heating and cooling demands are directly affected by outside temperatures. We use the changes in heating and cooling degree days to estimate the effect of climate change on demand (Sections 2.3.1 and 2.3.2).

- Hydropower: The potential of hydropower (both run-of-river plants and storage plants) depends on the availability of water inflows. Climate conditions and weather patterns dictate precipitation and melting, that is, water inflows. The U. Basel models water inflows and hydropower production using the assuptions in CH2018 (2018) climate scenarios (Section 2.3.3).

From a STEM analysis of these variants, we obtain distinct, deterministic pathways resulting from the combinations of these variants—a sensitivity analysis of the drivers on the results. The SES models instead model these variants as uncertain parameters with particular probability distributions, and conduct an uncertainty analysis with a Montecarlo sampling method.

1.3 Resources

In addition to the common drivers, we also use harmonized assumptions concerning the availability of domestic resources, including hydropower, solar photovoltaics, wind, biomass, and the prices of imported fuels (i.e., gas, oil, biofuels and hydrogen) (Chapter 3).

1.4 Technologies

We also harmonized the investment costs and the efficiencies of some of the most important technologies for the Swiss energy system (Chapter 4).

1.5 Energy demands

1.5.1 Yearly demands

We calculate the future energy service demands in the different end-use sectors with a reduced-form econometric model based on the harmonized drivers in Chapter 2 with the methods described in Panos et al. (2021) and Marcucci et al. (2021). We determine:

- space heat demand in the residential and commercial sectors from the future energy reference area (ERA) that we estimate using population as the main driver (Section 2.2). To calculate the ERA, we project the evolution of the building stock until 2060 by building type and age group following a building stock model (Section 2.2.2). We then determine the heating demand using the estimations from UNIGE regarding the specific heating demand per building type and age, as well as the new building standards;
- space heat demand in the industrial sector from the ERA, which uses GDP as explanatory variable;
- process heat demand using its relationship with economic development (GDP or GVA);
- warm water and electricity demand in the residential sector with population, while they follow the development of GDP for the industrial and commercial sectors;
- transport based on the Transport Outlook 2040 (ARE, 2016). We use the historical data from the BFS (2019f,g,e) and the ARE (2016) growth rates of passenger demand per capita and freight demand per GDP. We then determine the demands using the JASM reference, high, and low variants of population and GDP. For the projections after 2040, we assume a decreasing growth rate in the demand per capita and the demand per GDP for the passenger and freight demand, respectively.

1.5.2 Hourly load curves

Our energy system models have as an input the hourly demand for energy services (in the residential, commercial, industrial and transport sectors). In our JASM framework, EMPA, the UNIGE, and HSR Rapperswil (Yilmaz et al., 2020) estimated these hourly profiles for different sectors and weather conditions. UNIGE collaborated with the local utility company Service Industriels de Genève (SIG) and developed the ElectroWhat platform that decomposes the yearly electricity consumption of every Swiss municipality into estimated load curves per activity and per electric appliance. EMPA used different simulations with the CAESAR model to calculate the hourly profiles for commercial and residential buildings for today's building stock and future buildings with different retrofitting levels. HRS Rapperswil estimated the load curves for the space heating demand of single and multi-family houses using a simulation model.

1.6 Energy efficiency curves

We model the reduction of the energy demand from gains in energy efficiency based on the energy efficiency curves from UNIGE and EMPA. We use energy efficiency curves as inputs into our energy system models to relate potential energy savings with their cost (Chapter 5). Thus, our cost-optimizing energy system models will adopt energy efficient measures that are cost effective. UNIGE and EMPA calculated these energy efficiency: (1) For the industrial sector using a bottom-up approach (Zuberi et al., 2020) (UNIGE) and (2) for the buildings in the residential and commercial sectors using two different models: SwissRes (UNIGE) and CAESAR (EMPA) (Streicher et al., 2020a).

1.7 JASM Scenarios

The STEM and SES models evaluate scenarios defined along three dimensions: climate policy, available technologies, and market integration (with the EU or within Switzerland). In this section, we will discuss each of the selected dimensions in detail. We selected these dimensions first because each directly influences energy-use or energy generation and second because each dimension is a lever on which citizens and policymakers *can exert influence* to achieve net-zero emissions in Switzerland. As mentioned above, we consider other external drivers—population and GDP, global climate change, and technology characteristics—in combination with these three dimensions.

1.7.1 Climate policy dimension

In the climate policy dimension, we explore climate change mitigation targets, ranging from existing policies to the more ambitious net-zero CO_2 targets established by the Swiss Government. In 2015, Switzerland announced a long-term target of reducing GHGs by 70–85% in 2050 compared to 1990 levels (Swiss Federal Council, 2015). Later, in August 2019, the Federal Council decided that Switzerland should reduce its greenhouse gas (GHG) emissions to net-zero by 2050 (Swiss Federal Council, 2019). In both cases, the target states that part of the reduction can be achieved by measures abroad.

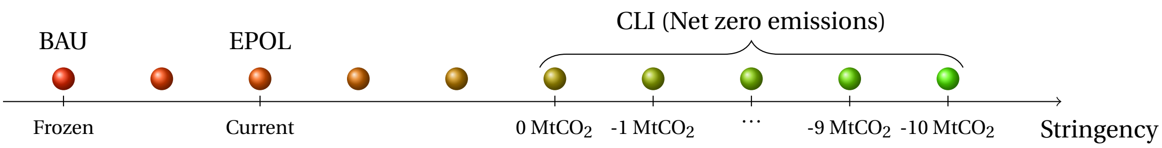


Figure 1.2: Climate dimension in JASM scenarios

We therefore consider three climate policy trajectories/targets: Business as Usual (BAU), Energy Policy (EPOL), and Climate Policy (CLI) (Figure 1.2). In BAU, we assume that all policies in place today will continue are their current stringency. In EPOL, we adopt the multiple objectives and measures of the Swiss Energy Strategy 2050 without a specific CO_2 target. Applied to the JASM framework, these two climate policies are exploratory and are analyzed by the STEM model only. The last climate policy in our JASM scenarios is the ambitious objective of reaching net-zero emissions ("CLI"). We aim at net-zero GHG emissions in the whole economy, however, the exact target for the energy system depends on reductions in other sectors and compensation abroad. Table 1.1 shows the GHG emissions for 1990, 2015 and 2018 and the JASM long-term targets. Some of the emissions outside the energy system, e.g. in agriculture, are difficult to mitigate (BAFU, 2020). Hence, if Switzerland aims at achieving net-zero GHG emissions domestically, it is likely that energy-related emissions need to go below zero. BAFU (2020) estimates that by 2050 the non-energy emissions that are difficult to avoid are 2 $MtCO_2$ for cement production and 4.8 $MtCO_2$ for agriculture/food production. However, Swiss targets explicitly mention compensations abroad. Therefore, we analyze targets on energy-related

CO_2 emissions between 0 $MtCO_2$ (assuming some compensation abroad) and -10$MtCO_2$ (without any compensation).

Table 1.1: Carbon targets in $MtCO_2$ equivalent. Historical values from national inventories (BAFU, 2020, Tables Summary 2, 1.A(a)s1-s4, 2(I)s1-2s). 2060 emissions difficult to avoid from BAFU (2020)

Source	Emissions ($MtCO_2$ equivalent)				
	1990	**2015**	**2018**	**2060**	**Target**
CO_2 emissions	**44.2**	**38.7**	**36.9**		
1. Energy CO_2 emissions	40.9	36.6	34.7	0	-10–0
1.A. Fuel combustion	40.9	36.6	34.7		
1.A.1. Energy industries	2.5	3.3	3.3		
. of which waste incinerators[a]	1.5	2.4	2.5		
1.A.2. Manufacturing industries and construction	6.5	4.9	4.8		
1.A.3. Transport	14.4	15.2	14.8		
1.A.4. Other sectors	17.3	13.0	11.7		
. of which commercial	4.8	3.9	3.5		
. of which residential	11.6	8.5	7.6		
. of which agriculture	0.8	0.6	0.6		
1.A.5. Other	0.2	0.1	0.1		
1.B. Fugitive emissions	0.03	0.03	0.03		
2. CO_2 from industrial processes	3.2	2.1	2.1		
. of which cement	2.6	1.7	1.7	2	2
. of which chemical industry	0.1	0.1	0.1		
. of which others	0.4	0.2	0.2		
3. CO_2 Agriculture, 5. Waste and 6. Others	0.10	0.07	0.07		
CH4 and N2O	**9.4**	**7.9**	**7.7**		
1. Energy	1.0	0.5	0.5		
2. Industry processes	0.6	0.6	0.6		
3. Agriculture	6.8	6.1	5.9	4.8	4.8
5. Waste	1.0	0.7	0.7		
FCs and SFx	**0.3**	**1.8**	**1.7**		
Compensation abroad				6.8	0–5.8
Total GHGs without LULUCF	53.8	48.4	46.3	0	0

[a] From Table 1.A(a)s4. Note that this only includes the fossil part of the incinerated waste. The biological part is not included in the GHG inventory, it corresponds to 1.3, 2.2, 2.3 $MtCO_2$ in 1990, 2015 and 2018, respectively.

1.7.2 Technology dimension

Along this dimension, we assume different states of technology availability due to both technology development and public acceptance. Starting from a state in line with current technology availability (conservative) to a final state that assumes accelerated technology development, increased social acceptance, and greater infrastructure investments (progressive). At the conservative starting point, we assume current technologies are available at currently estimated potentials and costs but that no significant changes to existing infrastructure or expanded public acceptance occur. In contrast, in the final progressive option, we include a larger set of technologies available in Switzerland at competitive prices due to technological breakthroughs and or increased acceptance.

1.7.3 Market integration dimension

Integrating into the European energy market is currently a topic of intense debate for consumers, policymakers, and market actors. The level of integration Switzerland decides on will have important implications for energy prices and “energy independence”. In our scenarios, *moderate* integration mirrors the current situation: balancing electricity imports and exports during the year without an electricity agreement and importing fossil fuels without any access to international markets for biofuels, hydrogen, or captured carbon. *High* integration assumes that there is an electricity agreement between Switzerland and the EU (as a result, the transmission capacity can be fully used), and an international market of biofuels, hydrogen, and captured carbon. We model this dimension by changing the net transfer capacities and imports prices of electricity (Section 3.5.2). The STEM model is able to model consumers in great detail; therefore, as a part of this dimension, STEM also includes “internal" integration within Switzerland. That is, prosumers participating in energy sales, both residential and commercial.

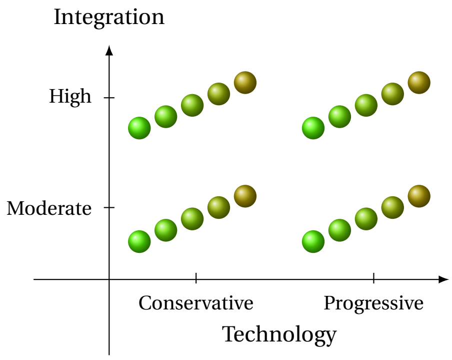
1.7.4 Scenarios overview and implementation

These three dimensions combine into the main JASM scenarios (Table 1.2). The table depicts the scenarios analyzed by each of the energy-system models. The precise implementation of the scenarios can be found in Panos et al. (2021), Li et al. (2020) and Guidati et al. (2021b).

1.7.5 Additional scenarios

We exploit the relative capabilities of the STEM and SES models to explore additional scenarios that model either intermediate states of the dimensions described above or additional dimensions. The STEM model, for instance, evaluates an additional scenario on reduced consumer participation. This reflects a world in which consumers assign higher value to traditional energy patterns and alternative objectives, such as protection of natural areas. Issues of energy security represent a prominent concern while priorities in the development of the energy system is given to centralized structures and domestic infrastructure. SES-ETH, on the other hand, develop an additional analysis on the availability of individual technologies (intermediate states between the conservative and the progressive states), assuming that only one of the technologies in the progressive state will become available (e.g. deep geothermal, CCS, or heat storage).

Table 1.2: JASM scenarios overview

Dimension	**BAU**	**EPOL**	**CLI**
Climate policy	Frozen	Current	Net zero emissions
. Target ($MtCO_2$)			0 -1 … -9 -10
Technology & integration			
Models			
STEM	x	x	x
SES			x x x x x

1.8 Analysis of the results

Following the realization of the main results by the energy system models, we conduct the following *ex-post* analyses.

1.8.1 Swiss energy perspective

From the three sets of energy system model results, we identify the results that are common to all three models (STEM-PSI, SES-ETHZ, and SES-EPFL) and, by extension, the results that are driven by a particular model approach. This comparison allows us to identify technologies that are very likely part of the future mix and the ones that most likely will not play a role. Based on these insights we are able to formulate concrete recommendations for policy measures and actions today. Furthermore, we are able to define the market drivers and the engineering and technical changes necessary to integrate technologies together to transform the energy system while achieving climate commitments. This analysis can be found in JASM (2021).

1.8.2 System adequacy

As a "sanity check" and an evaluation of the adequacy of the assumed electricity system configuration, we use the final energy system results as inputs into models of the transmission and distribution grids (Schlecht and Weigt, 2021). These analyses both indicate whether the resulting energy flows are plausible or whether there may be areas of congestion or grid overload. The analyses also indicate whether the assumed system configuration works across a large array of weather years regarding the impact of weather on demand as well as hydro, solar and wind resource availability in hourly resolution.

1.8.3 Baden case study: From the national to the local perspective

In a collaboration between EMPA and the Regionalwerke Baden (RWB), “Technical concepts for future heat supply to Baden Nord” (Bollinger, 2020), we verify that our results scale-down correctly. That is, what do national targets look like implemented locally?

1.8.4 Impacts for the society and the economy

Finally, we consider the “day-to-day" consequences of our modelling results on regular Swiss residents, including changes in life-style and economic implications Lordan-Perret et al. (2021). For this analysis we use the common results from energy-system models analyses (e.g., we mainly consider the results that are common to all scenarios—the “no-matter-what" changes we will see to our daily lives given an energy transition). This report serves as a “translation" of very technical results to more concrete lifestyle implications.

Chapter 2

JASM drivers

2.1 Macro-economic drivers

The objective of the JASM is to analyze different pathways for the reduction of energy-related emissions. A simple way of describing the main driving forces of emissions is the Kaya identity (Kaya, 1990):

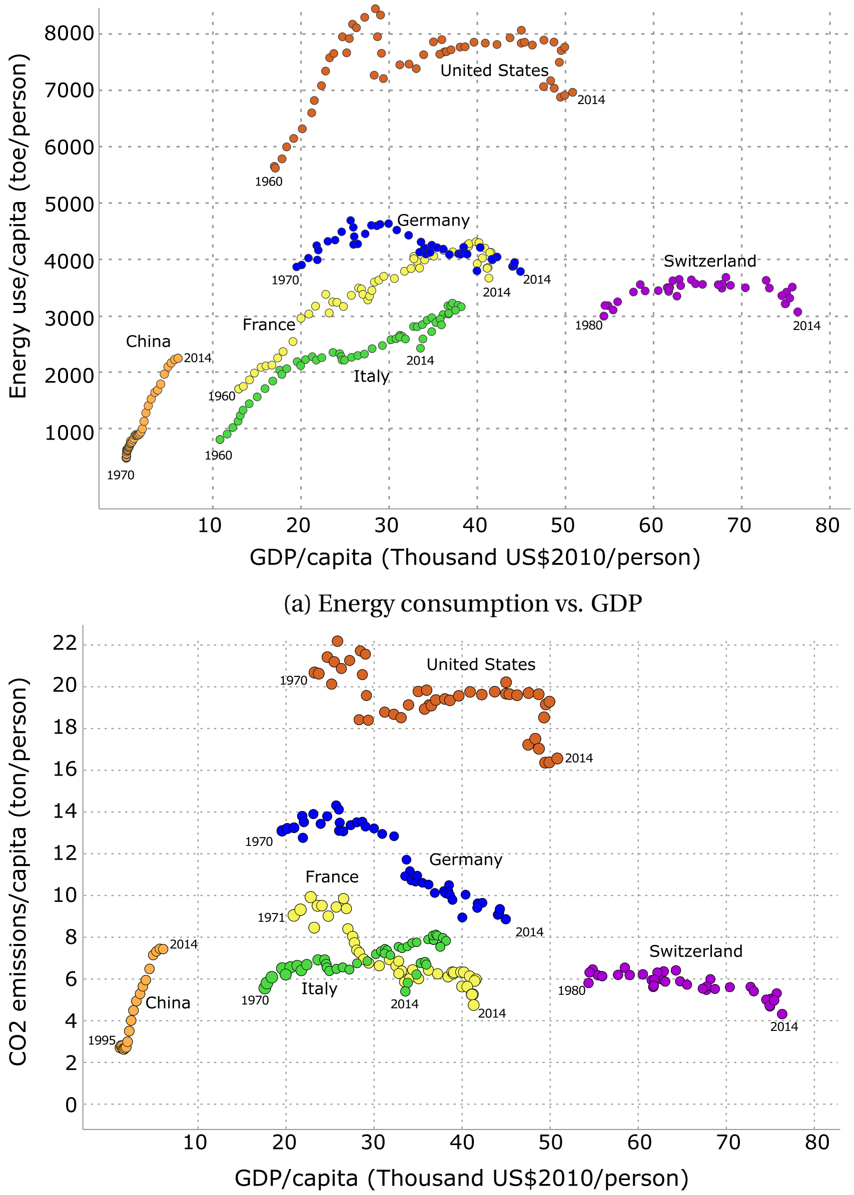
$$\mathrm{CO_2} = \underbrace{P}_{\text{Population}} \times \underbrace{\frac{GDP}{P}}_{\text{Economy}} \times \underbrace{\frac{E}{GDP}}_{\substack{\text{Economy/}\\ \text{technology}}} \times \underbrace{\frac{\mathrm{CO_2}}{E}}_{\substack{\text{Technology/}\\ \text{resources}}}$$

where P represents population, GDP, gross domestic product, and E, energy consumption. Rising CO_2 emissions are related to population growth, increasing per capita income (level of economic development), energy intensity (i.e., the amount of energy required to produce the economic output, which depends on economic and technology development), and the CO_2 emitted when producing the energy (which, in turn, depends on technology and resource choices). The top panel of Figure 2.1 shows the overall positive correlation between energy-use and GDP per capita for selected countries. In the lower panel, the relationship between CO_2 emissions and GDP per capita is less straightforward due to energy efficiency improvements.

The models in JASM determine for each JASM scenario the fourth term in the Kaya identity: the cost-effective amount of CO_2 emitted during energy production. We make assumptions about energy demand in our models and the models determine the optimal technology combination needed to supply this demand. Population, economic growth and climate are the main uncertain drivers used in JASM to project energy demand. We consider the dynamics of these variables and their links to the energy demand.

2.1.1 Population

The JASM population assumptions are based on the estimations from the BFS (BFS, 2020): a reference estimation (A-00-2020) and the 2 variants (B-00-2020 and C-00-2020). We use the historical data until 2018 from the BFS (2019a,b), the 2019 population from BFS (2020) and the projections from 2020



(a) Energy consumption vs. GDP

(b) Emissions vs. GDP

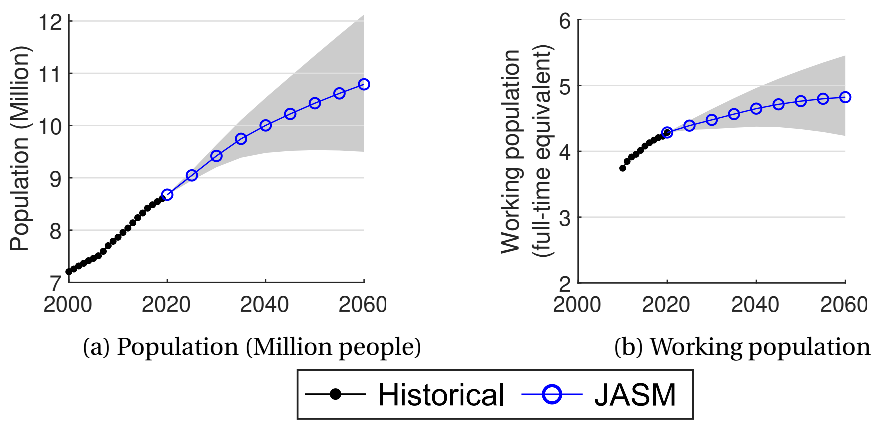
Figure 2.1: Historical relationship between energy consumption and GDP. Source www.gapminder.org

Table 2.1: Macro-economic drivers: JASM Variants

	2010	**2020**	**2030**	**2040**	**2050**	**2060**	**2010-2060**	**Reference**
Population (Million)								
Reference	7.86	8.68	9.42	10	10.43	10.79	0.63% p.a.	A-00-2020 (BFS, 2020)
High	7.86	8.68	9.63	10.53	11.34	12.12	0.87% p.a.	B-00-2020 (BFS, 2020)
Low	7.86	8.67	9.2	9.48	9.53	9.5	0.38% p.a.	C-00-2020 (BFS, 2020)
Number of households (Million households)								
Reference	3.49	3.84	4.23	4.49	4.66	4.83	0.68% p.a.	BFS (2019d, 2017)
High	3.49	3.85	4.32	4.73	5.07	5.43	0.93% p.a.	BFS (2019d, 2017)
Low	3.49	3.84	4.13	4.26	4.26	4.25	0.41% p.a.	BFS (2019d, 2017)
Working population (full-time equivalent)								
Reference	3.74	4.29	4.48	4.65	4.76	4.82	0.51% p.a.	A-00-2020 (BFS, 2020)
High	3.74	4.29	4.64	4.96	5.23	5.46	0.76% p.a.	B-00-2020 (BFS, 2020)
Low	3.74	4.29	4.34	4.37	4.34	4.23	0.25% p.a.	C-00-2020 (BFS, 2020)
GDP ($BCHF_{2010}$)								
Reference	608.8	725.3	820.3	922.1	1022.9	1121.4	1.23% p.a.	SECO (2018)
High	608.8	725.3	850.5	984.5	1123.3	1268.9	1.48% p.a.	SECO (2018)
Low	608.8	725.3	794.9	867.7	931.4	984.6	0.97% p.a.	SECO (2018)

Data available at https://data.sccer-jasm.ch/macroeconomic-drivers/

from BFS (2020). The reference population projection reaches 10.4 million people in 2050 and has an average annual growth rate between 2016 and 2060 of 0.63% p.a. Table 2.1 and Figure 2.2 present the population projections for the three variants (Reference, low and high). The number of households is based on the projections of the BFS (2017), we take the historical data from BFS (2019d) and update with the growth rates in BFS (2017).



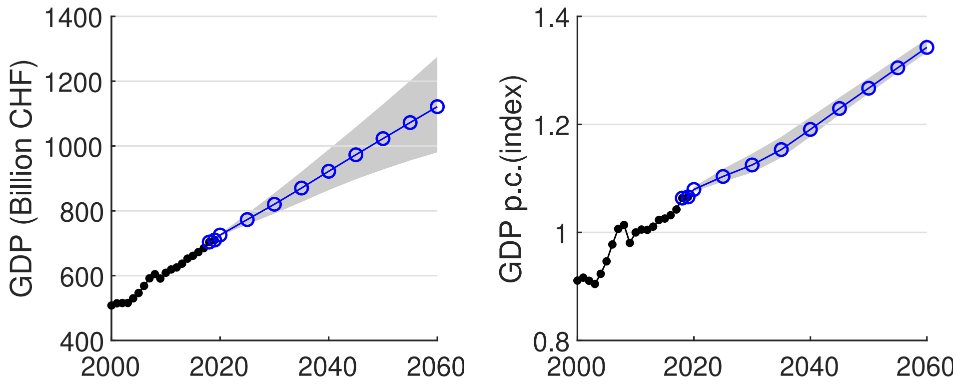
(a) Population (Million people) (b) Working population

Figure 2.2: Population assumptions

2.1.2 Gross domestic product

The JASM GDP assumptions are based on the projections from the State Secretariat for Economic Affairs (SECO, 2018), which are linked to the BFS (2020) population projections. We use the historical data from BFS (2019c) for 2010–2018 and SECO (2019) for 2019.

Figure 2.3a and Table 2.1 present the GDP and GDP per capita projections for our three variants in JASM (reference, low and high).



(a) GDP (Billion CHF$_{2010}$)

(b) Per capita GDP (index)

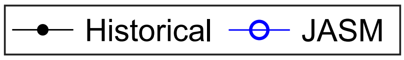


Figure 2.3: GDP and GDP per capita

2.2 Building stock

To estimate the heating demand in the building sector, the energy system models require, besides the population and GDP assumptions, the development of the building stock.

2.2.1 Energy Reference Area

The energy reference area (ERA) is the effective heated surface of a building. In JASM, the historical ERA for the residential sector was calculated by the University of Geneva (Streicher et al., 2018, 2019, Schluck et al., 2019). The 2016 value comes from Schluck et al. (2019) that used a comprehensive data set of the Swiss buildings stock with about 30,000 buildings and 23 descriptive features including construction period, building type, typology and canton. Table 2.2 presents the ERA in the residential, commercial and industrial sectors. Consistently with the Energy Statistics from the BFE (2018, p. 13), the ERA of the second homes and holiday houses is added to the commercial sector[1]. The occupancy factor (excluding second homes and holiday houses[2] from the total ERA) is 0.95, slightly higher than the 90% assumed by Jakob et al. (2016).

The ERA for the residential sector has been steadily growing over the past decades. This growth is linked to the increase in population but also to other trends such as smaller families and growing

[1]All second homes are treated as holiday houses.
[2]Zweit- und Ferienwohnungen

Table 2.2: Historical Sectoral Energy Reference Area (Mm2)

	2000	**2005**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Residential sector										
BFE (2018, Tables 9 and 17)										
. With temporarily used buildings[a]	416	448	486	494	501	509	516	524	532	540
. Without temporarily used buildings	386	413	444	450	455	462	469	476	482	488
JASM from Schluck et al. (2019)										
. With temporarily used buildings									505	
. Without temporarily used buildings									482	
Commercial sector										
BFE (2018, Tables 9 and 17)[b]										
. Commercial sector	140	146	152	153	155	156	158	159	161	162
. Temporarily used buildings	31	34	43	44	46	47	48	49	50	52
. Total	170	180	194	197	201	203	205	208	211	214
Industrial sector										
BFE (2018, Table 9)[b]	83	84	87	88	88	89	90	91	91	92

[a]Second homes and holiday houses (*Zweit- und Ferienwohnungen*)
[b]Based on Wüest Partner (2019)

income. In the same way, the ERA for the commercial and industrial sectors has grown mainly due to economic growth. To extrapolate the residential ERA to the future, we assume an increasing ERA with population with a logarithmic function. This represents both limited space for living in Switzerland and decreasing marginal ERA to population. We use the same methodology for the commercial sector. In the industrial sector we use the GDP as the explanatory variable. The resulting ERA are shown in Table 2.3.

Figure 2.4 shows the ERA per GDP, ERA per capita and total ERA for the three JASM variants of population and GDP.

2.2.2 Building stock

The demand for space heating depends on development of the building stock. Starting from today's building stock we estimate the future building stock for single, multi family houses and commercial buildings.

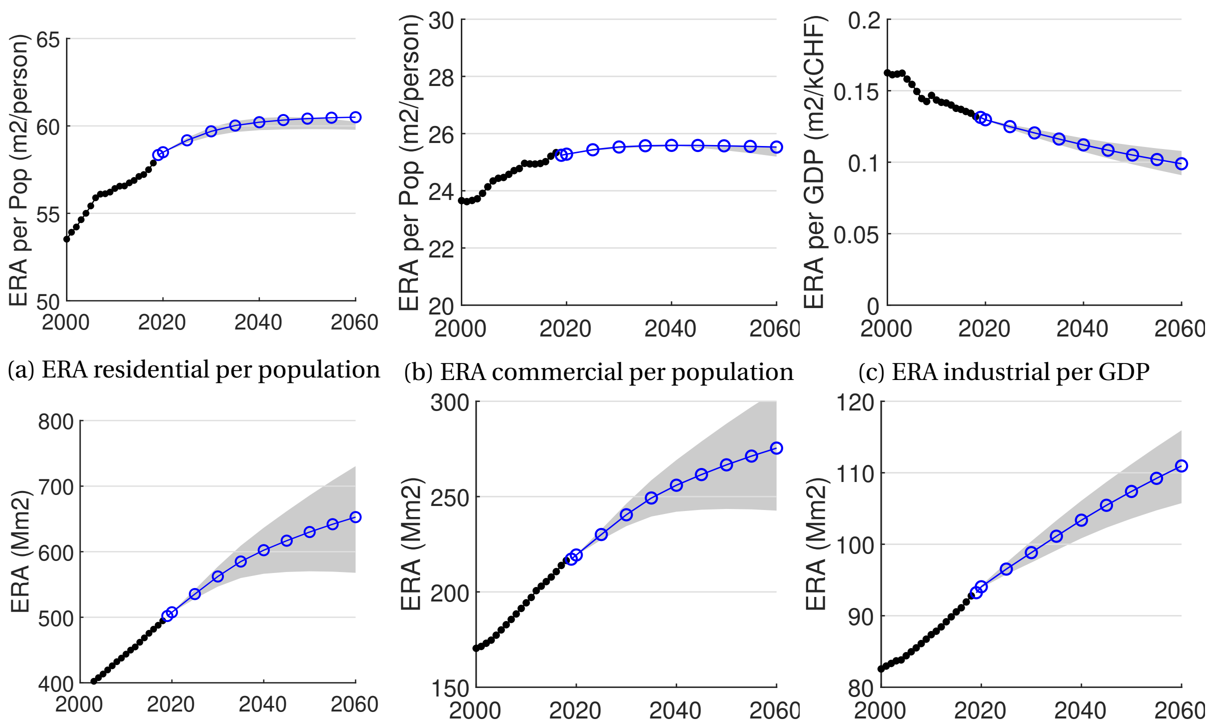
Current building stock: Residential sector

We start with the building stock in 2017 (Schluck et al., 2019). Figure 2.5 shows the distribution of the ERA and the useful energy demand by construction period and type. Houses built before 1945

Table 2.3: Projected Sectoral Energy Reference Area (Mm2)

Variant	2010	2018	2020	2030	2040	2050	2060	2010–2060
Residential (Mm2)								
Reference	443.7	494.6	507.6	562.2	602.3	630	652.7	0.77% p.a.
High	443.7	494.6	508	577.3	636.6	686	730.5	1% p.a.
Low	443.7	494.6	507.1	546.8	566.3	570.1	567.8	0.49% p.a.
Commercial (Mm2)								
Reference	194.3	216.5	219.4	240.5	256	266.7	275.4	0.7% p.a.
High	194.3	216.5	219.5	246.3	269.2	288.3	305.5	0.91% p.a.
Low	194.3	216.5	219.2	234.5	242.1	243.5	242.6	0.45% p.a.
Industry (Mm2)								
Reference	87.4	92.8	94.1	98.8	103.4	107.4	111	0.48% p.a.
High	87.4	92.8	94.2	100.4	106.1	111.2	115.9	0.57% p.a.
Low	87.4	92.8	93.9	97.4	100.8	103.6	105.7	0.38% p.a.

Data available at https://data.sccer-jasm.ch/era/

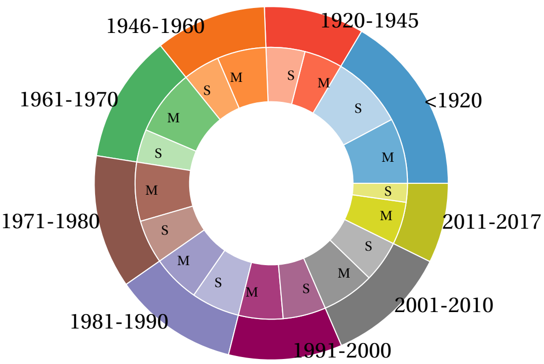


(a) ERA residential per population (b) ERA commercial per population (c) ERA industrial per GDP

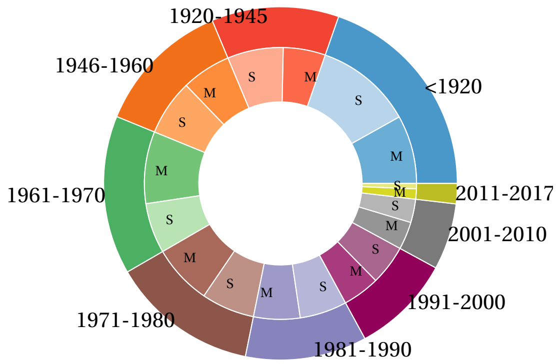
(d) ERA residential (Mm^2) (e) ERA commercial (Mm^2) (f) ERA industrial (Mm^2)

Figure 2.4: Sectoral Energy reference area

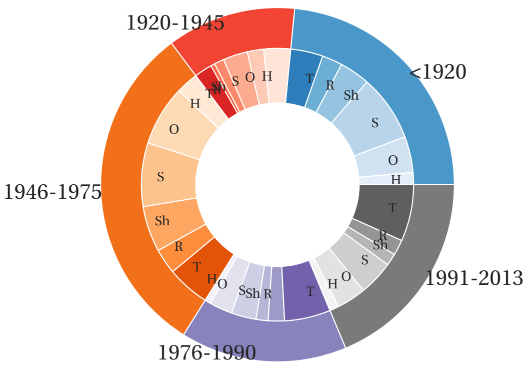
account for 25% of the total ERA and 30% of the useful demand. While those buildings built after 2001, account for 19% of the ERA and 11% of the demand. This is due to the significantly higher specific energy consumption of old buildings (Table 2.5).



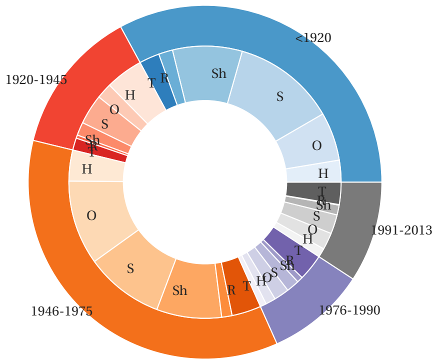
(a) Residential ERA by age and type



(b) Residential Useful energy demand by age and type



(c) Commercial ERA by age and type



(d) Commercial Useful energy demand by age and type

Figure 2.5: 2017 building stock by age and type: Single family houses (S), multi-family houses (M), hospitals (H), offices (O), schools (S), shops (Sh), rest of commercial buildings (R) and temporarily used buildings (T)

Current building stock: Commercial sector

In the commercial sector, we start with the ERA by building type published by Wüest Partner (2019). We then use the distribution by age classes from Jakob et al. (2019, p. 68). The specific demand by age and building type was calculated by EMPA with the CESAR model (Streicher et al., 2020a). We added the temporarily used buildings, whose ERA we know from the BFE (2018), we assume that the distribution into age classes corresponds to that in the residential sector (see previous section). Finally, we assume that the total space heating demand for the temporarily used building is 8 PJ based on BFE (2018)[3]. Figure 2.5 shows the distribution of the ERA and the useful energy demand by construction period and type.

[3] "Die Gesamtmenge, die vom Haushaltsbereich in den Dienstleistungssektor "verschoben" wird, liegt im Mittel der Jahre 2000 bis 2015 bei rund 14 PJ, davon sind rund 5.5 PJ Strom."

Future building stock

Following Müller (2006), Sandberg et al. (2016) and Sartori et al. (2016) we assume that the survival rate of the buildings follows a Weibull distribution. Hence the percentage of remaining buildings at time t follows the cumulative distribution function of the Weibull distribution, thus,

$$r(t) = \exp^{-\left(\frac{t-t_0}{\lambda}\right)^{\kappa}},$$

where λ and κ are the parameters that determine the kurtosis and skewness of the distribution (OECD, 2001). We use a $\kappa > 1$ to guarantee an S-shape. We use historical data and the share of historical buildings to estimate the parameter λ. With the survival rates we can calculate the ERA by age category (see Fig. 2.6 and Table 2.4). Since the current building stock is the same for all marker scenarios, the only difference between them is for the buildings built after 2017.

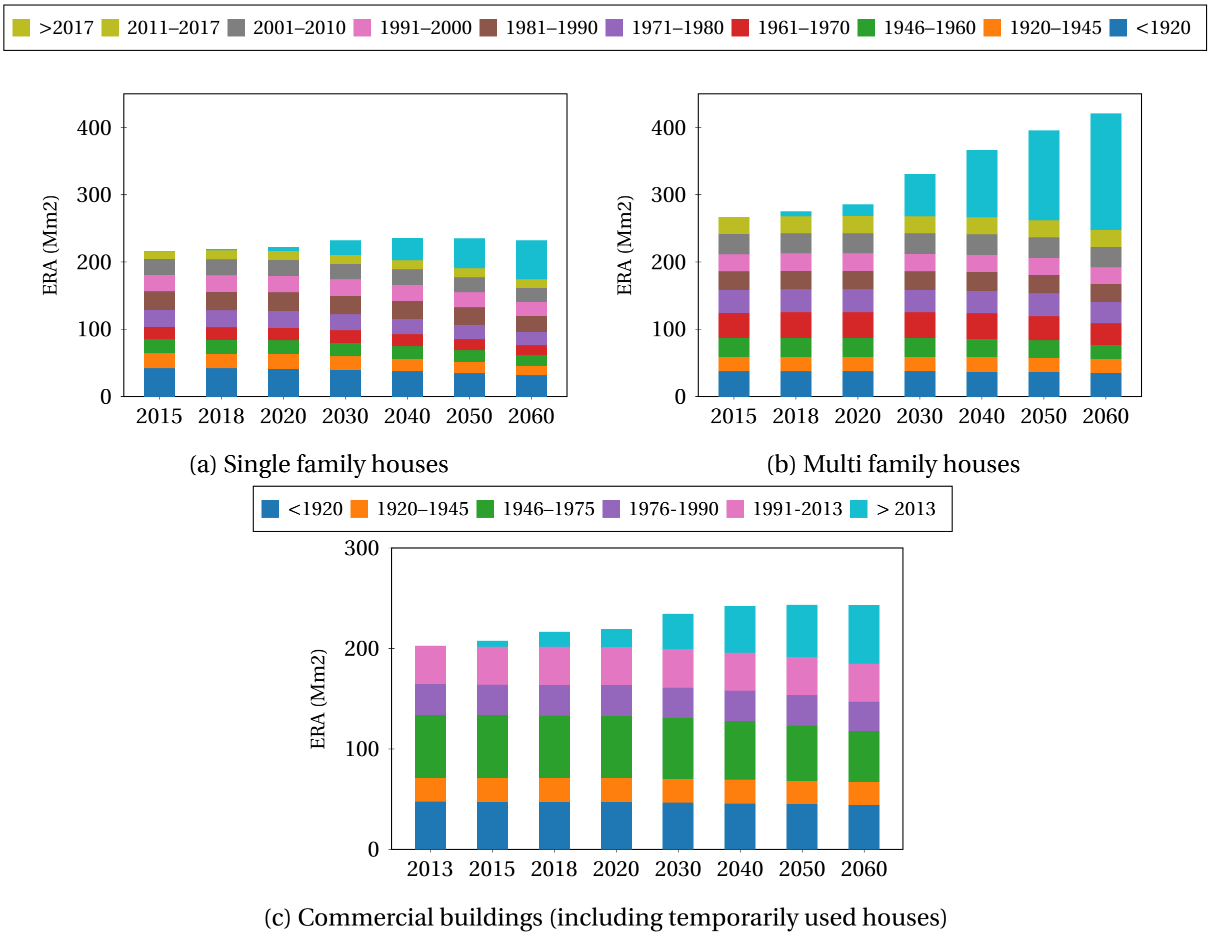


Figure 2.6: ERA by age in the residential and commercial sectors for the reference scenario

Table 2.4: Residential Energy Reference Area by age (Mm2)

Age	2016	2020	2030	2040	2050	2060	2020–2060
Single family houses							
<1920	42	41.4	39.6	37.3	34.6	31.5	-0.69% p.a.

Table 2.4: Residential Energy Reference Area by age (Mm2) (continued)

Age	2016	2020	2030	2040	2050	2060	2020–2060
1920-1945	22.2	21.8	20.6	19	17	14.6	-0.98% p.a.
1946-1960	21	20.6	19.9	18.8	17.3	15.3	-0.74% p.a.
1961-1970	18.9	18.7	18.2	17.3	16.2	14.6	-0.62% p.a.
1971-1980	25	24.9	24.3	23.5	22.2	20.3	-0.51% p.a.
1981-1990	27.7	27.6	27.2	26.5	25.4	23.6	-0.39% p.a.
1991-2000	24.5	24.5	24.2	23.7	22.7	21.1	-0.37% p.a.
2001-2010	23.8	23.7	23.5	23.1	22.1	20.7	-0.34% p.a.
2011-2017	10.8	13.6	13.6	13.4	13.1	12.4	-0.23% p.a.
>2017							
Reference	0	5.6	20.8	33.3	44.4	57.7	5.99% p.a.
High	0	5.8	24.6	41.9	58.4	77.1	6.71% p.a.
Low	0	5.5	16.9	24.3	29.4	36.5	4.83% p.a.
Multi family houses							
<1920	37.5	37.7	37.5	37.2	36.6	35.4	-0.16% p.a.
1920-1945	21.8	21.8	21.7	21.6	21.4	20.9	-0.1% p.a.
1946-1960	28	27.9	27.8	27.3	25.5	20.8	-0.73% p.a.
1961-1970	37.6	37.8	37.8	37.5	36.3	32.2	-0.4% p.a.
1971-1980	33.8	34.1	34.1	34	33.5	31.4	-0.21% p.a.
1981-1990	27.3	27.6	27.6	27.6	27.4	26.5	-0.1% p.a.
1991-2000	25.5	25.7	25.7	25.7	25.6	25.2	-0.05% p.a.
2001-2010	30.2	30.3	30.3	30.3	30.3	30.2	-0.01% p.a.
2011-2017	24.4	25.3	25.3	25.3	25.3	25.3	0% p.a.
>2017							
Reference	0	16.9	62.4	99.9	133.2	173	5.99% p.a.
High	0	17.3	73.7	125.6	175.2	231.3	6.71% p.a.
Low	0	16.6	50.8	72.9	88.3	109.4	4.83% p.a.

> Data available at https://data.sccer-jasm.ch/era/

Specific energy demand

From Schluck et al. (2019) and Streicher et al. (2020a) we have the specific energy demands for the current building stock (without any renovation). For the future building stock we assume that the buildings will comply with current *minenergie* standards[4] with a specific energy demand that decreases with time as shown in Table 2.5.

[4] Norm SIA 380/1

Table 2.5: Specific useful energy demand by construction period (kWh/m2)

Construction period	SFH	MFH and commercial
<1920	92.9	77.3
1920-1945	104.3	81.3
1946-1960	110.1	73
1961-1970	109.1	78.4
1971-1980	89.7	72.9
1981-1990	76.1	72.4
1991-2000	75.2	60.2
2001-2010	62.5	47.3
2011-2017	44.4	29.4
>2017		
. 2020	40	35
. 2030	35	30
. 2040	30	25
. 2050	25	20
. 2060	20	15

Data available at https://data.sccer-jasm.ch/building-stock/

2.3 Climate change

We consider three possible variants for temperature change in Switzerland based on the CH2018 scenarios (CH2018, 2018): No climate change mitigation (RCP 8.5), concerned climate change mitigation efforts (RCP 2.6), and a mid of the way variant (RCP 4.5). In the RCP8.5 climate-influencing emissions increase and hence global warming continues. The RCP 2.6 assumes immediate mitigation action so that the Paris Agreement target of limiting temperature increase to 2 °C is achieved and the increase of greenhouse gas emissions is halted within the next 20 years. The implications of these global CO_2 pathways for temperature increase in Switzerland were estimated by CH2018 (2018). Figure 2.7 presents the yearly average temperature increase for the three RCPs including the range and median of the 68 simulations available for each RCP.

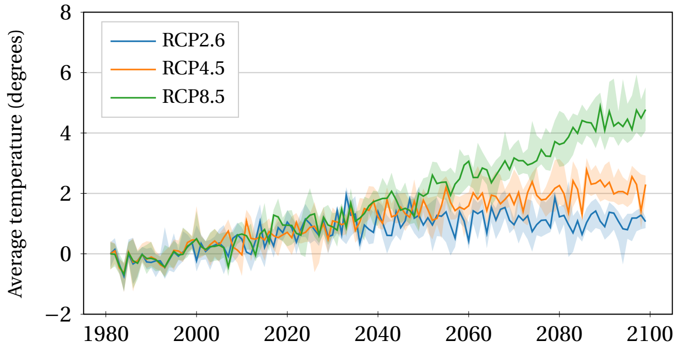
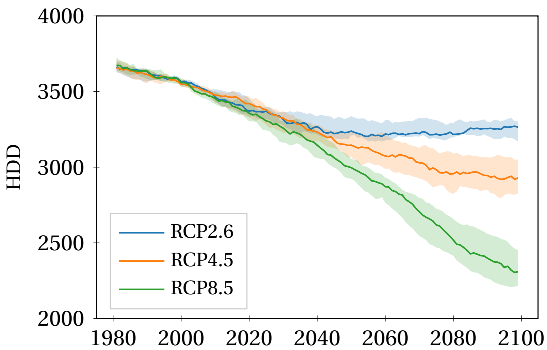


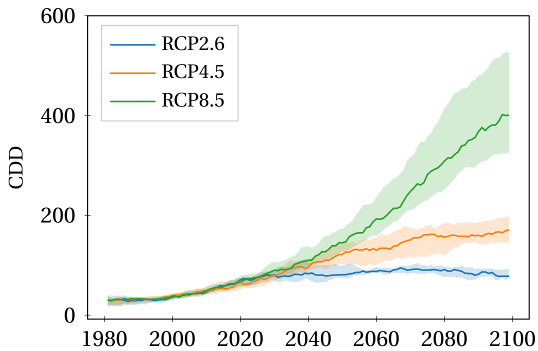
Figure 2.7: Temperature increase in three variants for global climate change. Base on CH2018 (2018), Berger and Worlitschek (2019)

> Data available at https://data.sccer-jasm.ch/climate-data/

Climate change affects heating demand, cooling demand and hydropower potentials.



(a) Heating degree days



(b) Cooling degree days

Figure 2.8: Population weighted cooling and heating degree days in RCP 8.5, RCP 4.5 and RCP 2.6 (Berger and Worlitschek, 2019)

> Data available at https://data.sccer-jasm.ch/climate-data/

2.3.1 Effect on heating demand

To determine the impact of the climate on the heating demand we use the simple but widely known approach of Heating Degree Days, using the most common definition HDD 20/12. For every day at which the average temperature is below the heating limit $T_l = 12\,°C$ we compute the difference of that temperature to an assumed building interior temperature $T_i = 20\,°C$. Berger and Worlitschek (2019) calculated the future HDDs of the three climate scenarios in CH2018 (2018) using a GIS-based approach combining the spatial distribution of temperature (and therefore HDDs) and population. Figure 2.8a presents the median and the first and third quartiles of the HDD calculated by Berger and Worlitschek (2019).

2.3.2 Effect on cooling demand

To determine the effect of climate change on the cooling demand we use the changes on cooling degree days (CDD). Cooling degree days are the number of degrees that a day's average temperature is above a certain threshold ($T_{max} = 18.3\,°C$). The changes in the CDD were calculated by Berger and Worlitschek (2019) for the three climate scenarios in CH2018 (2018). Figure 2.8b presents the median and the first and third quartiles of the CDD calculated by Berger and Worlitschek (2019).

2.3.3 Effect on inflow to hydropower

To determine the effect of climate change on the inflow to hydropower plants, we use discharge data from hydrologic modelling as input and pass it through an electricity model by U. Basel called Swissmod, which features a very detailed representation of 96% of Swiss hydropower stations.

In earlier work by Savelsberg et al. (2018), U. Basel has modelled the impact of climate change on Swiss hydropower generation using the Swissmod model based on input hydro discharge data from Speich et al. (2015). Savelsberg et al. (2018) describes the methodology in detail. However, the paper was still based on the SRES climate scenarios, which is superseded by the more recent Representative Concentration Pathway (RCP) scenarios.

Therefore, for JASM, a new dataset was prepared that works with the more recent Representative Concentration Pathways (RCP) scenarios (RCP 2.6, 4.5 and 8.5). For that purpose, we use the dataset underlying (Brunner et al., 2019). The dataset is based on the CH2018 (2018) climate scenarios and generated by the hydrologic precipitation-runoff-evapotranspiration model PREVAH (Viviroli et al., 2009a). The Brunner et al. (2019) dataset includes data from 39 climate model chains and comes at a 500m$*$500m spatial resolution.

To calculate inflows to hydropower stations, we first map the raster data to the Swiss Federal Office of the Environment's catchment area GIS dataset. As a second step, we use the Swissmod GIS database of catchment areas to map inflow to individual hydropower cascades. Subsequently, we calculate inflow based on historical production patterns and calibrate historical annual inflows to match expected total yearly hydropower production of individual hydropower stations. Savelsberg et al. (2018) describes the data processing approach in more detail.

The resulting inflow patterns are visualized in Figures 2.10 and 2.9. Especially in the RCP 8.5 scenario, clear trends can be observed, with a decline of total inflow to hydropower, but higher winter and lower summer inflows. The RCP 2.6 and 4.5 scenarios show similar changes, yet to a smaller extent.

When using the data, it must be noted that the data contains inflow and not production of Swiss hydropower plants. This means that models making use of the data have to ensure that hydropower capacity constraints are respected. As some hydropower plants spill water during summer peak inflows when inflows exceed capacity, production is usually lower than inflow, as can also be seen when comparing the data to historical production datasets by BFE (2020). A way to make use of the inflow dataset in energy system models it to calibrate the inflow dataset to the production dataset based on the joint historical climate periods and use the obtained calibration factors for future years. When using the data within Swissmod we use a fine-grained approach by ensuring the availability of hydropower capacity on a per-cascade basis.

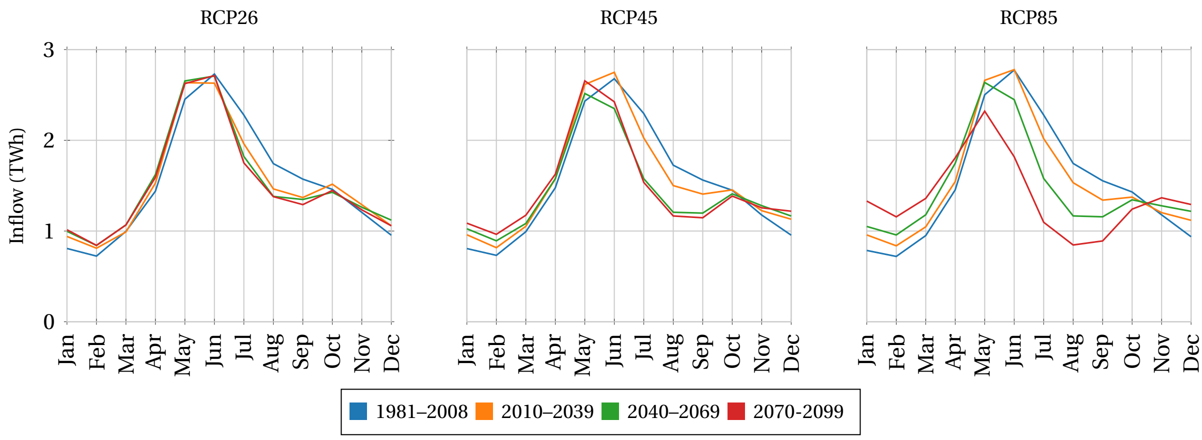


Figure 2.9: Inflows to run-of-river hydropower under different RCPs and climatic periods

Data available at https://data.sccer-jasm.ch/climate_hydro_inflows/

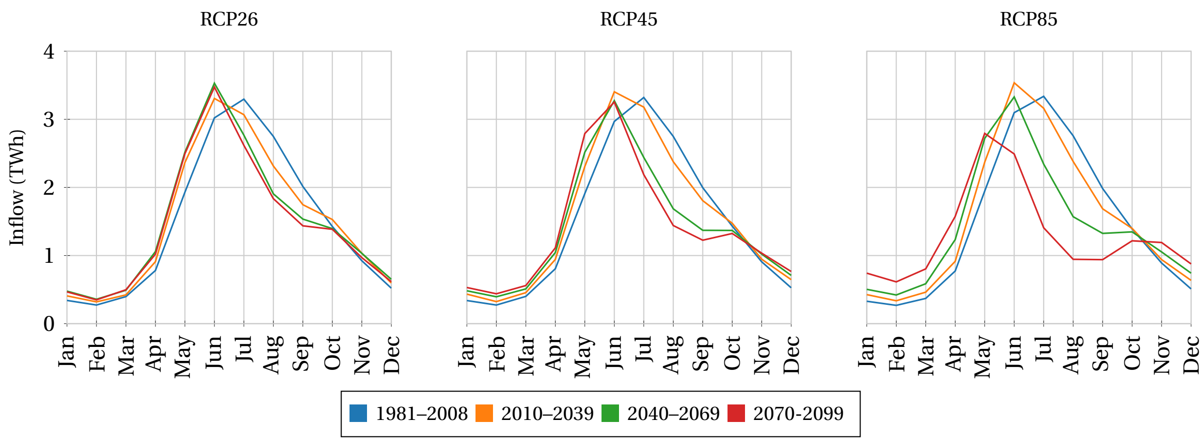


Figure 2.10: Inflows to dam hydropower under different RCPs and climatic periods

Data available at https://data.sccer-jasm.ch/climate_hydro_inflows/

2.3.4 Effect on representative Swiss Run-of-River power plants

WSL calculated the effect of climate change on the power production of eleven Run-of-River (RoR) power plants using flow duration curves Wechsler and Stähli (2019). The 11 RoR power plants represent different elevations, flow regimes and climatological regions and correspond to around 20% of the total RoR production. The FDC was calculated for the current and future climate CH2018 (2018) using the PREVAH hydrological model (Viviroli et al., 2009b), assuming present-day installed machinery and residual water flow requirements. Table 2.6 presents the changes in the generation in summer and winter for the individual power plants in each of the CH2018 (2018) scenarios.

Table 2.6: Annual RoR power production for the reference (1981–2010) and changes for future periods

Power plant (river)	**Altitude (m.a.s.l)**	**Reference (GWh/a)**		**% Change in summer**[a]			**% Change in winter**[b]		
		Winter	Summer	RCP2.6	RCP 4.5	RCP 8.5	RCP2.6	RCP 4.5	RCP 8.5
Birsfelden (Rhein)	265	331.9	229.9	-4.3%	-10.7%	-8.8%	1.8%	2.8%	5.4%
Albbruck-Dogern (Rhein)	318	307.6	277.1	-4.2%	-9.4%	-9.1%	1%	0.5%	1.8%
Windisch (Reuss)	337	6.4	5.9	-3.8%	-6.9%	-7.8%	1.7%	1.2%	1.9%
Aue (Limmat)	359	15.6	12.3	-5.8%	-12.8%	-12.5%	3.1%	4.1%	7.4%
Wildegg-Brugg (Aare)	361	151.5	139	-6.4%	-12.1%	-11.7%	0.6%	0.5%	1.5%
Lavey (Rhone)	451	239	174.9	-6.3%	-10.3%	-11.1%	3.4%	3.4%	6.8%
Reichenau (Rhein)	596	66.3	46.1	-2%	-6.9%	-6.2%	6.6%	4.8%	8.9%
Biaschina (Ticino)	618	226.4	133.3	-1.8%	-11.4%	-11.1%	13.1%	10.6%	14.8%
Amsteg (Reuss)	815	331.8	127.8	-14.4%	-20.9%	-22.5%	19.1%	25.5%	37.9%
Aletsch (Massa)	1444	131.8	54.1	4.2%	5.4%	7.9%	22.2%	25.7%	40.2%
Glaris (Landwasser)	1473	4.3	3.3	0.7%	-0.8%	0.1%	11.2%	12.8%	18.1%

[a] April to September
[b] October to March

In most of the RoR power plants analyzed the electricity generation decreases in summer and increases in winter with the increase in global temperature. Exceptions are power plants that are influenced by strong melting processes (power plants at higher altitudes).

Figure 2.11 presents the sum of the 11 power plants for the three climate scenarios. The results are consistent with those presented in the previous section. The RoR power plants have a significant reduction in the inflow in summer and an increase in winter. Wechsler and Stähli (2019) found for the RCP 8.5 in the period 2045–2074: A decrease in the summer months of -19.7% in July, -26.5% in August and -23.2% in September; and in increase in winter of +25% in January, +23% in February and +19% in March. While the results from Savelsberg et al. (2018) obtained changes for the RCP 8.5 in the period 2040–2069 of: -30.70% in July, -33.15% in August and -25.54% in September, while in winter +33.6% in January, 32.9% in February and 24.1% in March.

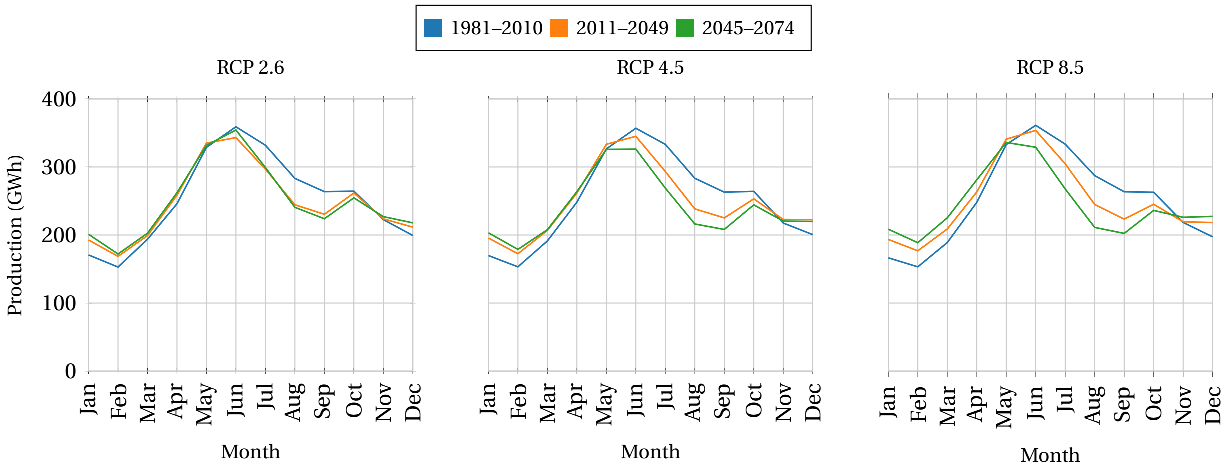


Figure 2.11: Hydropower production for Run-of-river (RoR) power plants in the CH2018 scenarios (CH2018, 2018, Wechsler and Stähli, 2019)

Chapter 3

Resources

3.1 Hydropower

Hydropower is the backbone of the Swiss electricity system, supplying around 60% of today's electricity. Roughly half of it is produced with run-of-river power stations and the other half with storage lakes. While run-of-river power plants are not dispatchable, storage plants are highly flexible at time scales ranging from hours to days and even months.

SCCER-SoE (2020) estimates a long term hydropower production in 2050 of 36 TWh/a. This amount considers already that the production during the last years was higher due to an absolute reduction of glacier volume. The analysis by SCCER-SoE (2020) also studied the effect of different factors on the hydropower potential, including increased residual flows, protection to fish migration, refurbishment of existing plants, and construction of new plants. Table 3.1 shows that these factors lead to a large uncertainty of roughly +/- 10%. The effect of climate change on the hydropower potentials is estimated in Section 2.3.3.

Table 3.1: Impact of various factors on annual hydropower production in 2050 (SCCER-SoE, 2020)

	Change in TWh/a		
Impact category	**Pessimistic**	**Medium**	**Optimistic**
Increased residual flows	-3.6	-2.3	-1.9
Measures to protect fish migration	-1.0	-0.4	-0.2
Refurbishment of existing plants	+0.4	+0.8	+2.0
New plants	+1.1	+2.3	+3.1
Total	**-3.1**	**+0.4**	**+3.0**

3.2 Photovoltaics

Walch et al. (2019) did an assessment of different studies to estimate rooftop PV potentials. They include the 6 studies in Table 3.2.

Table 3.2: Solar potentials estimates from different studies, data from Walch et al. (2019, Table 2)

Study	Roof coverage (%)	Capacity factor (%)	Potential (TWh)
IEA (2002)	55%	10	15.0
Assouline et al. (2017)	60.5%	13.6	17.9
Assouline et al. (2018)	60.5%	13.6	16.3
Klauser (2016)	72.2%	13.6	53.1
Buffat et al. (2018)	70.1%	10.3	41.3
Walch et al. (2020)	56.4%	13.8%	25

The BFE publised in April, 2019 (BFE, 2019) a maximum potential for roof and facades in Switzerland of 67 TWh. We considered a maximum potential, slightly more conservative, of 50 TWh from Bauer et al. (2019).

3.3 Wind

Wind power could contribute to the future energy system as a complement to solar power, especially in those hours without sunshine. Table 3.3 summarizes the potentials calculated in different studies compiled by Bauer et al. (2017).

Table 3.3: Wind potentials estimates from different studies from Bauer et al. (2017)

	Potential (TWh)	
Study	**2035**	**2050**
Prognos (2012, Table 6-14)	1.7	4.2
Prognos (2012, Table 6-14) - Variant C	0.7	1.4
VSE (2012)	0.7–1.5	2–4
Cattin et al. (2012, p. 21)		
. Variants 1A and 2A (with noise restrictions)	-	2.7–4.5
. Variants 1B and 2B (with restrictions of noise and public acceptance)	-	1.7–2.2
ARE (2017)	-	4.3

We use a wind potential in the range of 1.7–4.3 TWh/a. Following Bauer et al. (2017), if we assume an average capacity per turbine of 3 MW and an average yearly load hours of 1500–1800 h/a, the minimum potential requires around 315–380 wind turbines while the maximum potential 800–950.

3.4 Biomass and waste potentials

Biomass and waste are important resources for the future Swiss Energy System. ETH and Biosweet estimated the potentials of different biomass resources and waste for the use in the energy system (Guidati et al., 2021a). These potentials were estimated for the three variants of GDP and population described in Chapter 2 (Table 3.4 depicts the reference variant).

Table 3.4: Energy potential of biomass and waste categories in the reference variant (PJ)

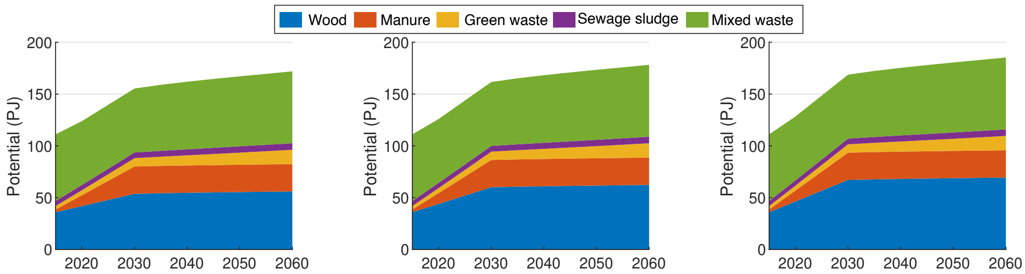
		Energy Potential (PJ)									
Category	**Feedstock**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**
(A) Wood	Forest wood										
	Scenario (1)	17.1	20.1	23.0	26.0	26.0	26.0	26.0	26.0	26.0	26.0
	Scenario (2)	17.1	22.2	27.2	32.3	32.3	32.3	32.3	32.3	32.3	32.3
	Scenario (3)	17.1	24.5	31.9	39.4	39.4	39.4	39.4	39.4	39.4	39.4
	Wood from landscape	2.3	3.2	4.0	4.8	4.8	4.8	4.8	4.8	4.8	4.8
	Wood residues	7.4	7.5	7.6	7.7	7.7	7.7	7.7	7.7	7.7	7.7
	Waste wood	9.1	11.1	13.2	15.3	15.9	16.3	16.6	17.0	17.3	17.6
(B) Manure	Animal manure (dry)	2.5	10.5	18.4	26.3	26.3	26.3	26.3	26.3	26.3	26.3
(C) Green waste	Collected organic waste	3.3	3.9	4.6	5.4	6.2	7.1	8.1	9.1	10.1	11.2
	Agricultural byproducts	0.1	0.9	1.8	2.6	2.6	2.6	2.6	2.6	2.6	2.6
(D) Sewage sludge	Fresh sewage sludge (dry)	4.9	5.1	5.3	5.5	5.7	5.8	6.0	6.1	6.2	6.3
(E) Mixed fossil/	Imports	4.2	2.8	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
organic waste	Export	5.9	3.3	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Other waste fraction	22.8	24.7	27.3	29.8	31.6	33.1	34.5	35.9	37.1	38.5
	Municipal waste	31.4	30.9	31.4	31.9	32.1	32.1	31.9	31.7	31.3	30.9
	including green waste	*2.8*	*2.5*	*2.4*	*2.2*	*2*	*1.7*	*1.5*	*1.2*	*0.9*	*0.6*

Data available at https://data.sccer-jasm.ch/biomass-potentials/

The potentials estimated in Guidati et al. (2021a) include three different wood potential scenarios depending on economic restrictions and the management policy. Figure 3.1 depicts the potentials in the reference variant for the three wood scenarios. Total potentials of biomass excluding mixed waste are in the range of 98.3–120.2 PJ in 2060. Waste potentials are projected to be 70 PJ by 2060.

3.5 Imports and import prices

Imports of energy carriers are part of the assumptions used by the energy system models. The variants of the maximum imports and the prices of imports of energy carriers, described in this chapter, are used to represent the market integration dimension of the JASM scenarios.



(a) Low wood (b) Medium wood (c) High wood

Figure 3.1: Biomass and waste potentials for the reference variant

3.5.1 Oil, gas, biofuels and hydrogen

The import price of oil and gas are based on the 2017 Energy Technology Perspectives (IEA, 2017). We determined an econometric relationship between the IEA future prices and the Swiss prices for the past. This relationship is applied to get the projection of the Swiss Border Prices based on the overarching IEA price projections. Oil and gas prices for 2020 are adjusted for COVID-19 crisis. We do so by following the evolution of the brent price in the first 6 months of 2020, as reported in EIA (2020) and Trading Economics, assuming a recovery of the price in the next 6 months close to the levels seen at the beginning of 2020.

Regarding the price of biofuels, the prices until 2030 are projected following FAO (2019). After 2030, the reference variant uses the growth of the marginal costs from the Modern Jazz scenario in WEC (2019). For the high price variant, we used the relative increase in bioenergy price between the Jazz and Symphony scenarios in WEC (2019), and applied it to the price trajectory of the reference variant.

Finally, the import costs of hydrogen are calculated as a mix of production cost of fossil and renewable hydrogen based on IEA (2019). We assume use the price in 2020 of the steam methane and autothermal reforming processes from IEA (2019, Fig. 9). In the reference variant, we use a growth rate that follows the gas price. In the high price variant, we assume an increasing share of renewable hydrogen (100% fossil without CCS in 2030; 70% SMR/ATR CCS and 30% electrolysis in 2040; 50/50 SMR CCS/-electrolysis in 2050; and 40/60 SMR CCS/electrolysis in 2060). The cost of SMR/ATR moves with the gas price, while the cost of electrolysis is taken from IEA. In both the variants the transportation cost is added by assuming a 2000km pipeline from Norway to Switzerland (2 US dollar per kgH2).

Table 3.5: Import price of energy carriers (CHF_{2010}/GJ): JASM variants

	2017	**2020**	**2030**	**2040**	**2050**	**2060**	**2020-2060**	**Reference**
Oil								
Reference	9.6	8.8	18.5	20.7	22.8	24.7	2.61% p.a.	Reference Technology Scenario (IEA, 2017)
High	9.6	8.8	26	30.7	35.3	39.3	3.82% p.a.	JASM
Low	9.6	8.8	11	10.7	10.3	10	0.32% p.a.	Beyond 2DS Scenario (IEA, 2017)
Gas								
Reference	6.2	3.1	9.3	10.4	11	11.3	3.3% p.a.	Reference Technology Scenario (IEA, 2017)
High	6.2	3.1	11.2	13.8	15.5	16.5	4.27% p.a.	JASM
Low	6.2	3.1	7.4	6.9	6.5	6.2	1.76% p.a.	Beyond 2DS Scenario (IEA, 2017)

Table 3.5: Import price of energy carriers (CHF_{2010}/GJ): JASM variants (continued)

	2017	2020	2030	2040	2050	2060	2020-2060	Reference
Biodiesel								
Reference	43.4	42.7	49.7	52.4	55	57.1	0.73% p.a.	FAO (2019) and Modern Jazz Scenario (WEC, 2019)
High	43.4	42.7	56.4	65.7	70.8	72	1.31% p.a.	Unfinsihed Symphony Scenario (WEC, 2019)
Low	43.4	42.7	41.4	40.1	40.1	40.1	-0.16% p.a.	JASM
Ethanol								
Reference	29.7	30.4	39.4	41.9	44.3	46.3	1.06% p.a.	FAO (2019), WEC (2019) and IEA (2020)
High	29.7	30.4	48.2	59.2	64.1	67.4	2.01% p.a.	Unfinsihed Symphony Scenario (WEC, 2019)
Low	29.7	30.4	30.6	24.6	24.6	25.2	-0.46% p.a.	JASM
Hydrogen								
Reference	0	26.9	40.1	42.7	44.7	46.1	1.35% p.a.	IEA (2019)
High	0	26.9	41.6	44.4	52.1	59.8	2.02% p.a.	IEA (2019)
Low	0	26.9	38.5	41.1	37.3	32.3	0.46% p.a.	JASM

Data available at https://data.sccer-jasm.ch/import-prices/

3.5.2 Electricity imports

Switzerland has historically relied on electricity imports to cover times when domestic electricity production was insufficient to cover demand. The import prices largely determine whether it is more advantageous for Switzerland to produce more domestically, and thus invest in additional capacity, or continue to (partially) rely on its neighbors. The key parameters that determine how much electricity Switzerland will import are both the electricity prices of neighboring countries (henceforth called electricity import prices) and the net transfer capacities (i.e., the part of the capacity of cross-border electricity transmission lines that is effectively available for imports).

We base our assumptions for transmission line capacities and other inputs to our electricity market model (such as demand time series, generation capacities and fuel prices) on the Ten Year Network Development Plan (TYNDP) produced by the European Network of Transmission System Operators for Electricity (ENTSO-E) in its 2018 edition (ENTSO-E, 2018). This report provides a consistent, forward-looking set of scenarios for the electricity system in Europe.

Net transfer capacities

In the JASM scenarios, the quantity of electricity that can be imported from the individual neighboring countries is restricted by the net transfer capacities (NTCs). NTCs indicate how much physical line capacity is available to transfer electricity across the interconnector tie lines between two countries after taking security aspects into account; thus, NTCs are less than the built capacity. The concept of net transfer capacities is described in more detail in ENTSO-E (2015).

Table 3.6 depicts the net transfer capacities between Switzerland and neighbouring countries for variants that use two CO_2 price pathways: *current* and the *decarbonization*. These two price pathways

Table 3.6: Average annual net transfer capacities (GW) from ENTSO-E (2018)

Variant	both	both	current	decarb
Year	**2020**	**2030**	**2040**	**2040**
From-to				
Switzerland–Germany	4.6	5.6	6.5	6.5
Switzerland–France	1.3	1.3	2.8	3.8
Switzerland–Italy	4.2	6	6	6.0
Switzerland–Austria	1.2	1.7	1.7	1.7
Germany–Switzerland	2.7	3.3	4.1	4.1
France–Switzerland	3.2	3.7	5.2	6.2
Italy–Switzerland	1.9	3.0	3.7	3.7
Austria–Switzerland	1.2	1.7	1.7	1.7

Data available at https://data.sccer-jasm.ch/net_transfer_capacities/

give a broad view on how transmission investments could vary under the (ENTSO-E, 2018) scenario assumptions.

Electricity import prices

Electricity prices are another important determinant of electricity imports. In an efficient electricity market, countries import electricity from neighboring countries in any time period where domestic short-term marginal production costs for electricity exceed prices for imports from abroad. In other words, when the price of imports is less than the price of producing domestically.

To determine the prices for imports (i.e., the prevailing wholesale electricity prices of Swiss neighboring countries), we use the electricity market model Swissmod (Schlecht and Weigt, 2014/04), which models the central-European electricity market in hourly resolution. To run the model, we need assumptions on generation capacities, demand time series, input fuel prices and CO_2 prices. We take generation capacities, demand time series, and input fuel prices from ENTSO-E (2018).

For CO_2 prices assumed abroad, i.e. in the European Union we deviate from ENTSO-E (2018). We deviate from the CO_2 prices assumed in ENTSO-E (2018) as ENTSO-E assumes an atypical price path with CO_2 prices first increasing from 2025 to 2030 and then decreasing again in 2040. Such a price path would be at odds with most other CO_2 price assumptions in the literature (such as of European Commission, 2016, or European Commission, 2011, p. 37). Therefore, we instead base our CO_2 price assumption for the *current* scenario for 2030 on European Commission (2016) to obtain a gradually increasing price path in conjunction with the ENTSO-E (2018) CO_2 prices for 2025 and 2040. All CO_2 prices for the year 2035 are linearly interpolated between 2030 and 2040 as ENTSO-E (2018) does not contain data for 2035. Overall our CO_2 price assumptions give two steadily increasing price paths (Table 3.7), with the CO_2 price in the *current* scenario increasing at a slower pace than the JASM decarbonization scenario.

Table 3.7: CO2 price paths

Scenario	2025	2030	2035	2040
current	25.7	30	37.50	45
based on	ENTSO-E (2018)	European Commission (2016)	linear	ENTSO-E (2018)
	best guess		interpolation	sustainable
	coal before gas		between '30 and '40	transition
decarb	25.7	84.3	105.15	126
based on	ENTSO-E (2018)	ENTSO-E (2018)	linear	ENTSO-E (2018)
	best guess	sustainable	interpolation	global
	coal before gas	transition	between '30 and '40	climate action

Data available at https://data.sccer-jasm.ch/hourly_electricity_prices/

The resulting electricity import prices for the *current* scenario are shown in Figure 3.2 and for the decarbonization scenario in Figure 3.3. In both figures, prices have significant inter-hourly variation within the years and an increase of price levels across years from 2025 to 2040. The price increase is more pronounced in the decarbonization scenario due to the CO_2 price level increasing more significantly in that scenario. In 2040, a number of hours with very high price peaks can be observed. This indicates hours in which all available generation or transmission capacity is reached and demand has to be voluntarily or involuntarily reduced. Such high price spikes are important for investment refinancing in liberalized electricity markets but would yield higher investment levels in endogenous investment models. For the JASM scenarios, the price spikes in 2040 mean that in these hours it would be too expensive for Switzerland to import from neighboring countries, so the Swiss electricity system has to effectively rely entirely on domestic production during those hours.

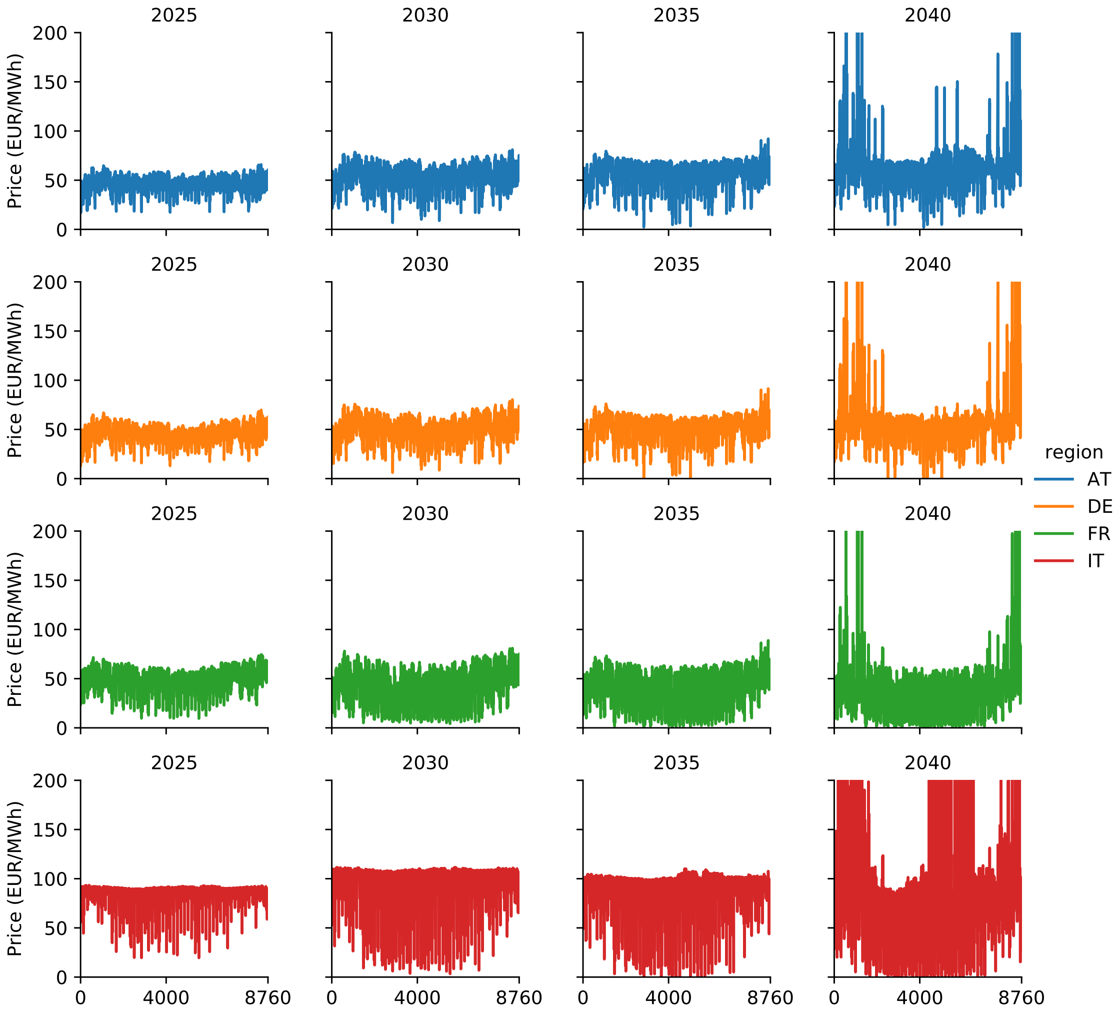


Figure 3.2: Electricity import prices for the *current* scenario

Data available at https://data.sccer-jasm.ch/hourly_electricity_prices/

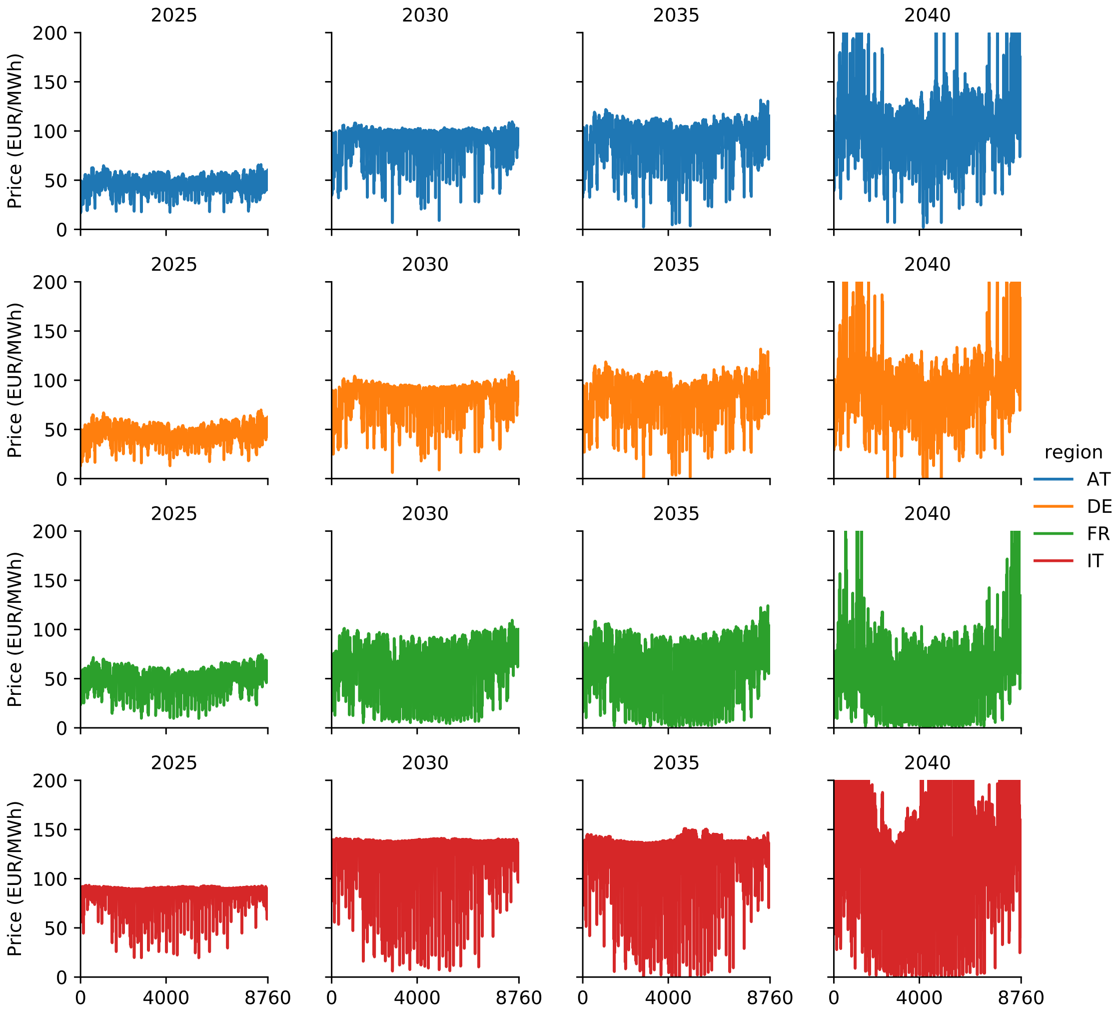


Figure 3.3: Electricity import prices for the decarbonization scenario

Data available at https://data.sccer-jasm.ch/hourly_electricity_prices/

Chapter 4

Technologies

In JASM we harmonized the 2050/2060 investment costs and efficiencies of some of the most important technologies for the energy system in Switzerland. Moreover, given the relevance of biomass to reach the net-zero emissions goal, we analyzed, together with BIOSWEE,T the most relevant conversion pathways for biomass and waste in Switzerland. In this Chapter we present the harmonized technology characteristics and the conversion pathways for biomass and waste.

4.1 Technologies for electricity, heat and hydrogen production

We include technologies for electricity production, heat production, combined heat and power and hydrogen production. Table 4.1 shows the different technologies, their investments costs and efficiency.

Table 4.1: Electricity, heat and hydrogen technologies

Technology	**Fuel**	**Inv. cost (CHF/kW)**			**Efficiency (%)**			**Reference**
		Ref	**Low**	**High**	**Ele**	**Heat**	**H_2**	
Electricity production (cost per kWe)								
Solar PV		1000–1200	700	1600				Bauer et al. (2017, 10kW, p. 47)
Wind		2000						Bauer et al. (2017, p. 294)
Hydro Dams		6000						Bauer et al. (2017, Hydro general, p. 44)
Hydro Run of River		6800						Bauer et al. (2017, p. 45)
Geothermal		10000						Bauer et al. (2017, 5.5 MW including plant and well, p. 469)
Gas combined cycle	CH4	900			60			Bauer et al. (2017, p. 650)
. With CCS		1500–1600			55			Bauer et al. (2017, p. 651)
Hydrogen combined cycle	Hydrogen	900			63			JASM assumption: same cost as CCGT
Waste combined cycle	Waste	6000	5000	7000	33			Bauer et al. (2017, Existing KVA in Switzerland, p. 444 - last column)

Table 4.1: Electricity, heat and hydrogen technologies (continued)

Technology	Fuel	Inv. cost (CHF/kW)			Efficiency (%)			Reference
		Ref	Low	High	Ele	Heat	H_2	
. With CCS		7800	6800	8800	25–30			
Combined heat and power (cost per kWe)								
Gas industrial CHP	CH4	700			44	42		Bauer et al. (2017, 1MW, p. 653)
Gas medium size CHP	CH4	1500			30–40	37–47		Bauer et al. (2017, 0.1MW, p. 653)
Sewage sludge CHP	Sewage sludge	6000	4500	7500	20 –26	53–56		JASM assumption: same cost as waste
Biogas medium size CHP	Biogas	9500			34	65		
Wood CHP	Wood	1900–2500	500	1300	26	55		JASM assumption
Waste industrial CHP	Waste	2069	1600	2600	20	58		Bauer et al. (2017, Existing KVA in Switzerland, p. 444 - last column)
Waste CHP	Waste	6000			20	58		Bauer et al. (2017, Existing KVA in Switzerland, p. 444 - last column)
. With CCS		7300–7800			10–17	40–55		
Heat production (cost per kWth)								
Gas industrial boiler	CH4	44–90				70–82		Radov et al. (2009, p. 91)
Gas medium size boiler	CH4	150–200				80–85		Radov et al. (2009, p. 91)
Gas decentralized boiler	CH4	1000 –1450				80 –95		
Oil industrial boiler	Oil	33–80				70–80		
Oil medium size boiler	Oil	130–200				80–85		
Oil decentralized boiler	Oil	900–1350				80 –90		
Hydrogen industrial boiler	Hydrogen	44–90				80–82		JASM assumption: same cost as gas
Hydrogen medium size boiler	Hydrogen	150–200				80 –85		JASM assumption: same cost as gas
Wood industrial boiler	Wood	75–650				60–80		Radov et al. (2009, p. 83)
Wood medium size boiler	Wood	200–950				70–80		Radov et al. (2009, p. 83)
Wood decentralized boiler	Wood	1615–2000				72–80		Radov et al. (2009, p. 83)
Waste industrial boiler	Waste	58–650				54–75		
Electric industrial boiler	Electricity	30–275				85–95		Radov et al. (2009, p. 93)
Electric medium size boiler	Electricity	325–650				95		Radov et al. (2009, p. 93)
Electric decentralized boiler	Electricity	650				95		Radov et al. (2009, p. 93)
Water source heat pump - Medium size	Electricity	2000				400		

Table 4.1: Electricity, heat and hydrogen technologies (continued)

Technology	**Fuel**	**Inv. cost (CHF/kW)**			**Efficiency (%)**			**Reference**
		Ref	**Low**	**High**	**Ele**	**Heat**	**H_2**	
Water source heat pump - Decentralized	Electricity	2300	1300	3300		400		
Ground source heat pump - Decentralized	Electricity	2500–2600	1700	3600		400		Radov et al. (2009, p. 79)
Air source heat pump	Electricity	2100–2500	1200	3000		300		Radov et al. (2009, p. 75)
Solar thermal medium size		600–2100						
Solar thermal decentralized		1500–4400	1200	1700				
Deep geothermal industrial		3000	2000	4000				
Deep geothermal medium size		3000	2000	4000				
Hydrogen production (cost per kW H_2)								
Electrolysis	Electricity	700–1000	600	1500			70	Christensen (2020), IEA (2019)
Steam methane reforming (with CCS)	Natural Gas	1300–1500	1000	2000			77	IEA (2019, Reforming with CCS, Assumptions, p. 3)
Autothermal reforming	Natural Gas	1300–1500	1000	2000			77	JASM assumption: Same as steam reforming

> Data available at https://data.sccer-jasm.ch/energy-conversion-technologies-stem,
> https://data.sccer-jasm.ch/energy-conversion-technologies-ses,
> https://data.sccer-jasm.ch/energy-conversion-technologies-ses-eth,
> https://data.sccer-jasm.ch/energy-conversion-technologies-psi and
> https://data.sccer-jasm.ch/energy-conversion-decentralized_technologies

4.2 Biomass conversion routes

Biomass is a special resource that can be used for the production of electricity, heat, and other fuels including methane, hydrogen and liquid biofuels. Therefore, together with Biosweet, we modelled in detail the different conversion routes available in Switzerland. Figure 4.1 presents the different technology pathways for biomass (based on the JASM-Biosweet (Guidati et al., 2021a)). It shows the routes that are currently available and those that could be developed in the future.

Wood can be used in direct combustion (7a) and gasification (5a). Wood combustion (7a) produces heat at different temperatures. Low temperature heat can be used for domestic uses and high temperatures for industrial purposes. Wood can also be combusted to drive a power cycle producing electricity and heat (7b). An alternative route is wood gasification (5a). Here the basic constituents of wood (carbon, hydrogen and oxygen) are recombined in the presence of an oxidant (air or oxygen) to produce a syngas composed of carbon monoxide, hydrogen, CO_2 and other species. This syngas can be subsequently processed to synthetic natural gas (via a methanation reaction, 5b and 5g) or hydrogen (via a water gas shift reaction, 5d). Alternatively, the syngas may be combusted in a gas motor or

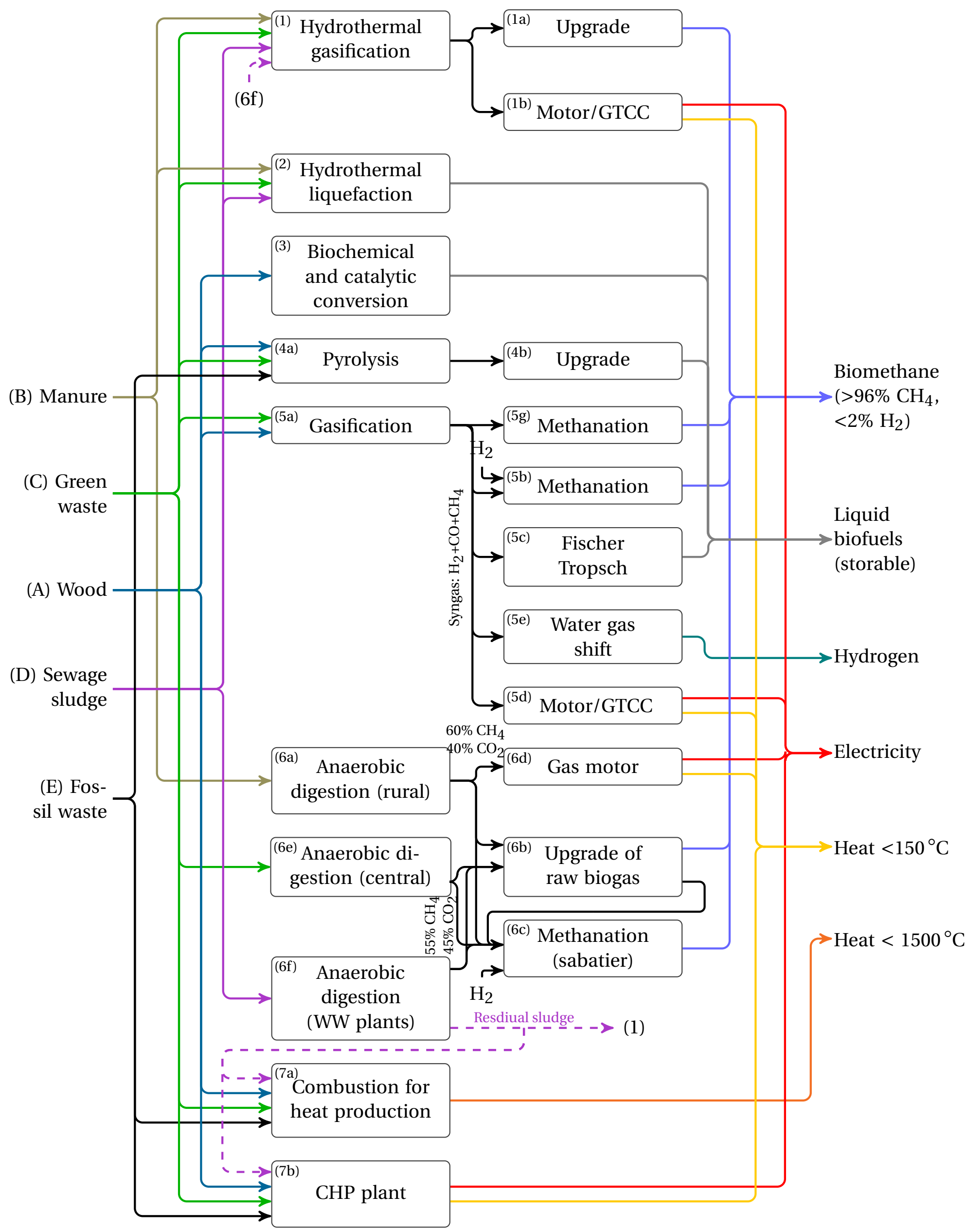


Figure 4.1: Mapping of Biomass Technologies and Resources

a gas turbine combined cycle to produce electricity and heat (5d).

Manure can be used in anaerobic digestion (6a) that produce raw biogas, a mixture that usually contains around 40-60% methane and the rest is mostly CO_2. Today, in Switzerland, the biogas produced from anerobic digestion is used mostly in small internal combustion engines to produce electricity and heat. The latter is used on-site as much as needed and the rest is discarded. A future energy system may profit from another route, namely an upgrading of the raw biogas (6b) to biomethane (by separating CO_2 and other species), which can then be injected into the natural gas grid. This gas may then be used for a variety of processes, including seasonal storage in neighboring countries such as Germany or France. The separated CO_2 may be further combined with hydrogen from electrolysis to produce additional methane via a Methanation (Sabatier) reaction (6c). Such an alternative route is hindered by the fact that the average farm size in Switzerland is very small. As shown in the report by WSL (Thees et al., 2017), even a reasonable amount of electricity production via the first route requires already a collection of manure within a 1 km range. All subsequent steps such as biogas cleaning, electrolysis or methanation would require an even larger size to be technically feasible and profitable.

Green waste can be used in central anerobic digestors (6e) and combustion plants (7b) and (7c).

Concerning sewage sludge, current Swiss regulations enforce the energetic use of sewage sludge from waste water treatment plants (WW, *Abwasser-Reinigungsanlagen*) with a cascade utilization (Thees et al., 2017, p. 279ff). The fresh sewage sludge undergoes goes first to an anaerobic digestor (6f) that produces biogas, which can be used on-site or injected into the gas grid after gas cleaning. The residual sludge is then combusted in waste incineration plants, specialized sludge incinerators and cement plants.

Other potential future conversion pathways are (1) hydrothermal gasification and (2) hydrothermal liquefaction for wet biomass; and (3) biochemical and catalytic conversion for wood.

The detailed description of the different conversion processes can be found in the JASM-Biosweet report (Guidati et al., 2021a). Table 4.2 presents the characteristics of some of the technologies in Figure 4.1 (we include the characteristics of the technologies using biomass resources for the production of electricity and heat in Table 4.1).

4.3 Transport technologies

> The data for transport technologies is available at https://data.sccer-jasm.ch/transport-cars/

Table 4.2: Biomass and hydrogen technologies (Guidati et al., 2021a)

	Technology	Feedstock	Product	Inv. cost (CHF/kW)			Eff (%)	Elec. use (MWhel/ MWh)	Reference
				Ref	Low	High			
(4)	Pyrolysis	Wood	Liquid biofuel	2600–2800			48–67	0	IEA (2020)
(5a) + (5b)	Gasification + methanation	Wood	Methane	2900	2300	3500	63	0	Schildhauer (2018)
(5a) + (5e)	Gasification to H2 (dual fluidized bed)	Wood	Hydrogen	2000	1500	2500	62	0.11	NREL (2011)
	. With CCS	Wood	Hydrogen	2300	1800	2800	62	0.21	
(5a) + (5e)	Gasification to H2 (sorption enhanced reforming)	Wood	Hydrogen	2000	1500	2500	71	0.18	NREL (2011)
	. With CCS	Wood	Hydrogen	2300	1800	2800	71	0.28	
(5a) + (5e)	Gasification to H2 (entrained flow)	Wood	Hydrogen	2000	1500	2500	66	-0.11	NREL (2011)
	. With CCS	Wood	Hydrogen	2300	1800	2800	66	0.03	
(6a) + (6b)	Anaerobic digestion (rural)	Manure	Methane	800–1200			37	0	Ro et al. (2007)
(6e) + (6b)	Anaerobic digestion (central)	Green waste	Methane	1200			37	0	Ro et al. (2007)
(6f) + (6b)	Anaerobic digestion (waste water treatment)	Sewage sludge	Methane	1200–2100			54	0	Ro et al. (2007)
(6c)	Methanation (Sabatier)	Biogas (55% CH4, 45% CO2) + H2	Methane	900	800	1000	83	0.01	Witte et al. (2018)

Data available at https://data.sccer-jasm.ch/biomass-conversion-technologies/

Chapter 5

Energy efficiency

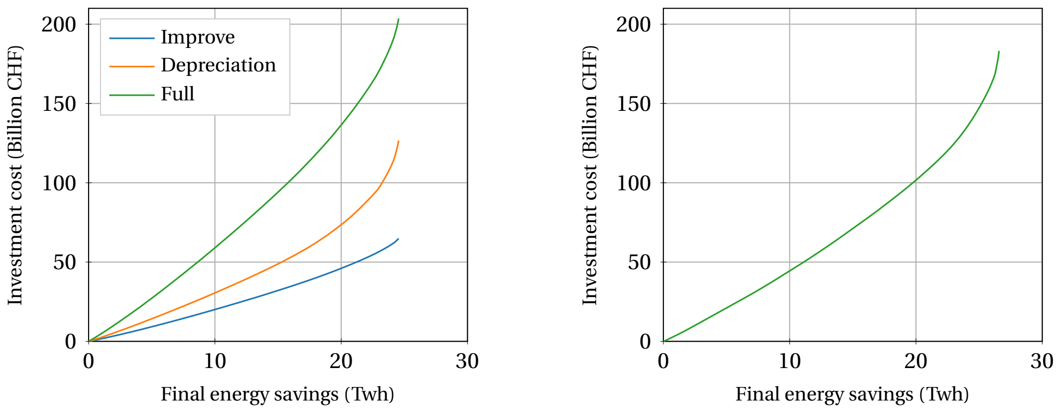
5.1 Residential sector

The insulation level of walls, windows and other parts of the building envelope changes the energy efficiency of the building. For this reason renovations are particularly important in the residential sector. Streicher et al. (2020a) determined a relationship between energy savings and investment costs for the residential building stock using two different models. First, Streicher et al. (2020b) uses the SwissRes model to calculate the investment costs of the renovation packages for the 2016 building stock using three different approaches (Fig 5.1a). The first approach (full) includes all investment costs (related and not-related to energy efficiency improvements). The second approach (depreciation) accounts for the costs of the energy efficiency improvements plus a residual value to each building element. The third approach (improvement) accounts only for the cost of energy efficiency improvements. Swissres looks at retrofitting packages as opposed to single measures as package retrofitting is an optimal way to realize efficiency gains and costs savings. That is, retrofit packages contain complementary measures. Second, EMPA uses the CESAR model (Murray et al., 2020) to calculate annual heating energy savings and the investment costs associated with different retrofit scenarios for a set of residential building archetypes in Switzerland (Fig 5.1b). The costs with the CESAR model correspond to the Full cost approach of the calculation with the SwissRes model.

5.2 Commercial sector

Streicher et al. (2020a) calculated using the CESAR model the saving potentials and the corresponding investment costs for hospitals, offices, schools and shops. There calculation includes nine archetypes for each building type. The buildings covered by the CESAR model account for 66% of the total ERA in 2013, the remaining ERA corresponds to restaurants, hotels, agriculture buildings, transport buildings and other commercial buildings. To get the energy efficiency curve for the whole commercial sector they first upscale, for each building type, the estimation from the nine archetypes to the full building stock. Second, they assume that the missing building types have savings potentials per area (in kWh/m2) and investment costs per energy saved (in CHF/kWh) that correspond to the average of the rest of the buildings. Finally, they added the temporarily used buildings assuming a distribution into age classes that corresponds to that in the residential sector.

The investment costs included in this energy efficiency curve correspond to the full costs. Hence,



(a) SwissRes model (Streicher et al., 2020b)   (b) CESAR model (Murray et al., 2020)

Figure 5.1: Energy efficiency cost curves for the Swiss building stock

> Data available at https://data.sccer-jasm.ch/energy-efficiency-residential-swissres/ and https://data.sccer-jasm.ch/retrofit-savings-cesar/

we calculate the equivalent to the depreciation scenario (in the previous section) assuming that the share of the total costs that corresponds to the energy efficiency improvements are the same as in the residential sector. We obtain the energy efficiency curve in Figure 5.2.

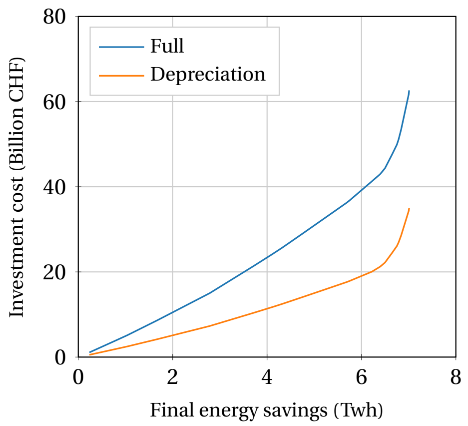


Figure 5.2: Energy efficiency cost curve for the Swiss commercial sector. From Streicher et al. (2020a)

> Data available at https://data.sccer-jasm.ch/retrofit-savings-cesar/

5.3 Industrial sector

Zuberi et al. (2020) (based on Zuberi and Patel (2019), Zuberi et al. (2018, 2017), Zuberi and Patel (2017)) calculated energy potential savings and costs for various industrial sectors in Switzerland. The estimation is done using techno-economic data on energy efficiency measures from multiple sources which majorly include Energy Agency of the Swiss Private Sector (EnAW), ProKilowatt scheme by Swiss Federal Office of Energy, individual companies etc. The analysis includes the two most energy consuming sectors and systems i.e. chemicals and pharmaceuticals and cement, and process heat and electric motor driven systems. Process heating and electric motor systems correspond to more or less 50% and 30% of the Swiss industrial final energy demand. Figure 5.3 presents the energy efficiency curves for heat and electricity.

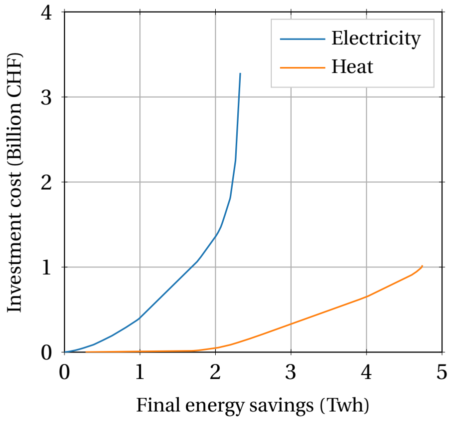


Figure 5.3: Energy efficiency cost curve for the Swiss industry. From Zuberi and Patel (2019), Zuberi et al. (2018, 2017), Zuberi and Patel (2017)

> Data available at https://data.sccer-jasm.ch/energy-efficiency-industry/

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