CROSS Scenarios and Drivers Definition

Version: CROSS-v2022-09

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Abbreviations

BAU	Business as usual
BCHF$_{2017}$	Billion Swiss Franc 2017
CCS	Carbon capture and storage
CDD	Cooling degree day
CH4	Methane
CHF	Swiss Franc
ENTSO-E	European Network of Transmission System Operators for Electricity
EP2050+	Energy Perspectives 2050+
ERA	Energy reference area
EUD	End-use demand
FEC	Final energy consumption
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic information system
HDD	Heating degree day
ITMO	Internationally transferred mitigation outcomes
LHV	Low heating value
LULUCF	Land Use, Land-Use Change and Forestry
MFH	Multi family house
N2O	Nitrous oxide
NDC	National Determine Contribution
NET	Negative Emission Technology
NTC	Net transfer capacities
PV	Photovoltaics
RCP	Representative concentration pathway
RoR	Run of river
SFH	Single family house
TYNDP	Ten Year Network Development Plan

Chapter 1

Introduction

The CROSS scenarios and drivers report is a document from the SWEET-CROSS activity. In this report, we define a set of scenarios, collect and calculate various relevant input parameters for the SWEET consortia with an aim to improve the consistency across the research projects. These scenarios and input parameters are intended to be a reference point from which all consortia can further develop their own scenario analyses.

It is important to note that the CROSS scenarios are not static in time. They co-evolve as the SWEET consortia produce new outputs and insights and as the energy market and policy landscape evolve in Switzerland and in key world regions. Hence, the scenario dimensions and key assumptions can be updated by the SWEET consortia (e.g., resource potentials) whenever new insights are available from their analyses performed or with new developments of the energy market and policy context. For this reason, we have established a scenario versioning scheme for the CROSS scenarios. This is necessary to keep track of the changes in the main assumptions over time. The versioning refers to the updates to the scenario narratives, underlying data, or key assumptions. When referring to the scenarios dimensions and values contained in this report, you should refer to the version **CROSS-v2022-09**.

The procedure for the definition of CROSS scenarios consists of the following steps:

1. Definition of the CROSS narratives: CROSS-V2022-09 scenarios are defined along two policy dimensions: i) the ambition of the Swiss climate change mitigation policy, based on the Swiss Long-Term Climate Strategy (Swiss Federal Council, 2021); and ii) the developments in the international energy markets and trade. These dimensions have an important influence on the future configuration of the Swiss energy system during the energy transition (Chapter 2).

2. Quantification of key input assumptions: Besides the two policy dimensions, we quantify reference values and ranges for other variables that are relevant for the development of the future Swiss energy system, including:

    - population, gross domestic product (GDP), and energy reference area (ERA)(Chapter 3);
    - global climate change development, including its effect on heating and cooling demand and hydropower (Chapter 4);
    - energy services demand (Chapter 5);
    - availability of domestic resources, including hydropower, solar photovoltaics, wind, and biomass (Chapter 6); and
    - prices of imported fuels (i.e., gas, oil, biofuels and hydrogen) (Section 6.5).

    This specification aims to provide a set of harmonised "reference" values and ranges for the different models within the SWEET consortia.

3. Further elaboration and implementation of the CROSS scenarios by the models of the SWEET consortia: In this step, the SWEET consortia describe how they implement the CROSS scenarios within their modelling toolbox, describing in detail each scenario's assumptions relevant for each model. This last step foresees possible deviations of key CROSS assumptions from their reference values. When such a deviation occurs, it must be documented (and justified[1]). Furthermore, any additional scenario assumption needed by particular models within the different SWEET consortia needs to be documented.

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[1] For example, suppose economic growth or energy demand is an output from a model within a SWEET consortium. In that case, it could make sense that this output is used for the SWEET consortium instead of the "reference" value of CROSS.

Chapter 2

Scenarios definition

The CROSS scenarios are defined along two dimensions: climate policy and energy market integration. We selected these dimensions because firstly each directly influences energy-use or energy generation and secondly each dimension is one of the levers on which citizens and policymakers *can exert influence* to achieve net-zero emissions in Switzerland.

In the climate policy dimension, we consider the goal of the Swiss Federal Council to reduce the greenhouse gas (GHG) emissions to net-zero by 2050 (Swiss Federal Council, 2019). The Swiss Federal Council (2021) does not determine specific domestic and international shares for emission reductions. Moreover, the Swiss National Determined Contribution (NDC) states (BAFU, 2021d):

> [...] In the long-term Switzerland aims to reduce its greenhouse gas emissions to net-zero by 2050. [...] Switzerland will realise its NDC mainly domestically and will partly use internationally transferred mitigation outcomes (ITMOs) from cooperation under Article 6 [...].

Therefore, in the CROSS scenarios, we consider the following two developments concerning the use of ITMOs to reduce greenhouse gas emissions in Switzerland:

- Net zero GHG – domestic: We assume that the net-zero emissions target by 2050 is to be achieved solely with domestic measures., i.e. the target is achieved using carbon capture and storage (CCS) and Negative Emission Technologies (NETs) in Switzerland but the captured CO_2 can be stored abroad.
- Net zero GHG – carbon removal abroad: In this variant, the net-zero emissions target in 2050 can also be achieved with the use of ITMOs.

In the energy market integration dimension, we assume different developments concerning the integration of Swiss and international energy markets. This dimension becomes increasingly important for the Swiss energy transition as Switzerland needs access to quantities of low-carbon fuels and energy carriers, such as electricity, biofuels or synthetic fuels. Therefore, this dimension plays an important role in the future configuration of the Swiss energy system and in the technical feasibility and affordability of the Swiss energy transition. We consider two distinct narratives concerning the integration and access of Switzerland to European and global energy markets[1]:

1. High integration: The world gradually shifts to a sustainable and integrated global low-carbon energy system. Governments are aware of the need to use new energy sources, develop clean technologies further, and foster international collaboration to achieve the Paris Agreement targets. As a result, Switzerland is well integrated into the European and global energy markets.

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[1] These narratives are inspired and transferred from the SWEET SURE project

Imports of electricity and low-carbon or carbon-free energy carriers and fuels are secured via agreements between Switzerland and the EU and bilateral agreements between Switzerland and other countries. The imported fuels and energy carriers are available for Switzerland in good quantities.

2. Low integration: The globally connected energy sector diversifies with investments in both carbon-intensive and low-carbon energy sources, depending on the best available local solutions and (the rather limited in some geographies) renewable resource potentials. The global energy system becomes very fractured, and investors do not get clear and strong signals for clean energy sources and technologies. This investing behaviour limits the quantities of clean energy sources available for cross-border trade are reduced, as countries need these resources to meet their own demands. As a result, signing agreements between Switzerland and the EU or other countries regarding imports of electricity and other low-carbon or carbon-free energy carriers is a formidable task due to limited exports from other countries. In such a world, Switzerland opts for a "reduced dependency on energy imports”.

The resulting four CROSS scenarios are summarised in Figure 2.1. The labels for each dimension in the table refer to the storylines described above. Section 2.1 describes the climate dimension in detail, including the corresponding carbon targets for the energy sector. Section 2.2 translates the two variants concerning energy market integration into assumptions concerning imports of electricity and low-carbon energy carriers.

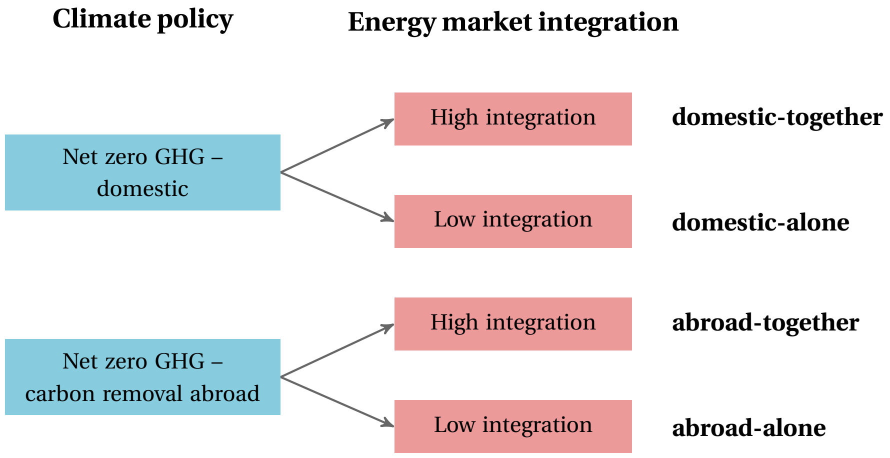

Figure 2.1: CROSS-v2022-09 scenarios overview

2.1 Climate policy dimension

In the climate dimension, we analyse scenarios that aim at reaching net-zero GHG emissions by 2050. Following the Long-Term Climate Strategy (Swiss Federal Council, 2021), the net-zero target:

1. means achieving a balance between GHG emissions and carbon dioxide removal;
2. covers the emissions within Swiss national borders (Section 2.1.1);
3. covers all GHGs (not just CO_2) and includes all sectors in the GHG inventory (energy, industrial processes and product usage, agriculture, land use, land use changes and forestry (LULUCF),

waste and others). This is of particular importance because some methane (CH4) and nitrous oxide (N2O) emissions outside the energy sector are difficult to avoid (Section 2.1.2);

4. does not determine specific domestic and international shares for emission reductions (Section 2.1.3);
5. also includes the emissions from international aviation and shipping attributable to Switzerland[2].

2.1.1 National emissions

The net-zero target refers to national GHG emissions (Swiss Federal Council, 2021), which means that the territorial or point of sale principle (for transport fuels) applies. The territorial principle implies that emissions that Switzerland generates abroad are not included in the Swiss GHG emissions, this is of particular importance for imported electricity. For transport fuels, the point of sale principle implies that the emissions are attributed to the country where the fuel is used, this is the case of gas, gasoline, diesel, or hydrogen. For our net-zero target, we therefore consider that: (1) the use of imported electricity, hydrogen and biofuels produces zero CO_2 emissions; and (2) imported goods have zero embodied emissions.

2.1.2 Emissions difficult to avoid

GHG emissions in some processes outside the energy sector are technologically difficult to avoid. These emissions include:

- Industry:
  - Chemical and pharma industries (IPCC inventory category 1.A.2): BFE (2020c) projects 1.2 $MtCO_2e$ by 2050, of which 0.8 $MtCO_2e$ can be removed with CCS, which results in 0.4 $MtCO_2e$ remaining emissions difficult to avoid.
  - Cement and chemical industry (IPCC inventory category 2): BFE (2020c) projects 2.4 $MtCO_2e$ by 2050 that cannot be prevented with measures to increase efficiency or through the replacement of fossil fuels. Most of them are geogenic emissions generated during manufacturing processes of cement, i.e. during the burning of raw materials (limestone). These emissions can be largely reduced with CCS. If we assume a capture rate of 90 percent, the remaining emissions difficult to avoid are 0.2 $MtCO_2e$ by 2050.
- Agriculture and food production (IPCC inventory category 3): According to the BFE (2020c), the emissions difficult to avoid from agriculture and food production will be 4.6 $MtCO_2e$ by 2050, in an optimal scenario with changes in consumption and production patterns and technical optimizations. None of the emissions from agriculture can be captured with CCS, resulting in 4.6 $MtCO_2e$ of remaining emissions difficult to avoid.
- Waste water treatment and solid waste disposal (IPCC inventory category 5): BFE (2020c) projects around 0.5 $MtCO_2e$ emissions difficult to avoid by 2050 from solid waste disposal and waste water treatment.

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[2] Although, in 2018, GHG emissions from international aviation were 5.7 $MtCO_2e$ BAFU (2021c), we do not include them in the CROSS-v2022-09 scenario definition.

Adding over the categories, we obtain a total of remaining emissions difficult to avoid outside the energy sector of 5.7 $MtCO_2e$. The remaining emissions difficult to mitigate from the Swiss Climate Strategy (Swiss Federal Council, 2021) correspond to 7 $MtCO_2e$. The differences is that the Energy Perspectives 2050+ (EP2050+) (BFE, 2020c) also includes some emissions difficult to avoid in the energy sector. However, since the modeling in CROSS focuses on energy, we calculate our target including only those emissions difficult to avoid outside the energy sector (see Section 6.4.1 for the details about emissions from waste incineration). For reference, Table 2.1 presents historical emissions and emissions difficult to avoid in all sectors.

Table 2.1: GHG inventory for 1990, 2000, 2010 and 2019 by category from BAFU (2021b,c) and projected emissions in 2050 from BFE (2020c)

	GHG Emissions ($MtCO_2$ equivalent)						
	Historical				**2050 emissions difficult to avoid**		
Category	**1990**	**2000**	**2010**	**2019**	**Total**	**CCS**	**Remaining**
1. Energy	41.9	42.3	43.2	35.1	4.2	−4.9	−0.7
1.A. Fuel combustion	41.5	41.9	42.9	34.9	4.2	−4.9	−0.7
1.A.1. Energy industries	2.5	3.2	3.8	3.4	2.6	−4.1	−1.5
waste incineration plant - fossil (1.A.1.a.iv)	1.5	2	2.3	2.5	2.6	−2.3	0.3
waste incineration plant - biological part[3]	1.3	1.6	2.1	2.3	1.5	−1.4	0.2
waste incineration plant - compensated biomass growth	−1.3	−1.6	−2.1	−2.3	−1.5	0	−1.5
1.A.2. Manufacturing industries and construction	6.6	6.0	5.9	4.7	1.2	−0.8	0.4
1.A.3. Transport	14.7	16	16.3	14.9	0.03	0	0.03
1.A.4. Other sectors	17.5	16.5	16.7	11.8	0.4	0	0.4
1.A.4.a. Commercial	4.9	5.0	4.9	3.5	0.2	0	0.2
1.A.4.b. Residential	11.8	10.8	11.1	7.7	0.1	0	0.1
1.A.4.c. Agriculture	0.83	0.81	0.71	0.6	0.05	0	0.05
1.A.5. Other	0.22	0.15	0.14	0.12	0	0	0
1.B. Fugitive emissions	0.44	0.41	0.31	0.25	0.04	0	0.04
2. Industrial processes	4.3	3.9	4.6	4.5	2.4	−2.2	0.2
thereof: Cement (2.A.1)	2.6	1.7	2.0	1.7			
thereof: Chemical industry (2.B)	0.6	0.79	0.74	0.81			
3. Agriculture	6.7	6.0	6.1	5.9	4.6	0	4.6
5. Waste	1.1	0.89	0.86	0.76	0.50	0	0.51
thereof: Solid waste disposal (5.A)	0.77	0.53	0.44	0.29	0.08	0	0.08
thereof: Waste water treatment and discharge (5.D)	0.21	0.23	0.26	0.30	0.35	0	0.35
6. Others	0.01	0.01	0.01	0.01	0.01	0	0.01
Total	**54.0**	**53.1**	**54.9**	**46.2**	**11.7**	**-7.1**	**4.6**

2.1.3 Carbon dioxide removal

Reaching the net-zero GHG emissions target requires compensation of the emissions difficult to avoid through carbon dioxide removal within Switzerland or abroad.

Carbon dioxide removal abroad is a long-term option to compensate the GHG emissions difficult to avoid (Swiss Federal Council, 2021). Switzerland has already signed bilateral agreements with Peru,

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[3] These emissions are not included in the total emissions from Fuel Combustion, because of their biogenic origin. They can be found in Table 1.A(a)s4.

Ghana, Senegal, Georgia, Vanuatu, Dominica, Thailand, Morocco, and Chile under Article 6 of the Paris Agreement. At the same time, Switzerland has established agreements regarding international CCS and NETs with Iceland (joint declaration of intent, BAFU (2021a)) and the Netherlands (memorandum of understanding, BAFU (2022)).

We consider the following two variants regarding the use carbon ITMOs to reduce GHG emissions in Switzerland:

- Net zero GHG – domestic: We assume that the net-zero emissions target by 2050 is to be achieved solely with domestic measures, therefore the total emissions difficult to avoid are to be removed in Switzerland, using CCS or NETs. However, the captured CO_2 can be stored abroad.
- Net zero GHG – carbon removal abroad: In this variant, the net-zero emissions target in 2050 can also be achieved with partial use of ITMOs. For the cost of using ITMOs, the carbon price calculated by global models in achieving the net-zero target can be used: an interquartile range of 200–900 $US\$_{2010}$ and an average of 500 $US\$_{2010}$ (Riahi et al., 2021).

Table 2.2 presents the two variants considered in the CROSS scenarios. In both variants, we assume that Switzerland has access to carbon storage abroad (Section 6.5.3).

Table 2.2: Emissions reduction target in the energy sector

Variant	**Carbon removal ($MtCO_2$)**		
	Domestic	**Abroad**	**Total**
Net zero GHG – domestic	-5.7$MtCO_2$	0$MtCO_2$	-5.7$MtCO_2$
Net zero GHG – carbon removal abroad	0$MtCO_2$to -5.7$MtCO_2$	Up to -5.7$MtCO_2$	-5.7$MtCO_2$

2.2 Energy market integration dimension

In CROSS, we assess two distinct developments concerning the integration and access of Switzerland to European and global energy markets: low and high integration. The variants consider access to international markets for electricity, biofuels, hydrogen, and carbon sequestration. Table 2.3 summarizes the variants for each of the energy markets. All values are starting points that will be updated in the future (e.g. from SWEET studies, BFE system-adequacy study, etc.).

2.2.1 Electricity

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 (NTCs, i.e., the part of the capacity of cross-border electricity transmission lines that is effectively available for imports).

We, therefore, model market integration by changing the NTCs and import prices of electricity. For models that do not represent neighboring countries, we assume an upper limit of yearly net imports.

Table 2.3: Geopolitical dimension variants in CROSS scenarios

Commodity	**Variant**	**Quantification**
Electricity	Low	30% of the NTC can be utilized
	High	100% of the NTC can be utilized
Biofuels and biomass	Low	No imports at all
	High	Upper limit on annual imports in 2050 of 56 PJ (7 biomass/pellets, 5 biofuels and 44 PJ biomethane) (BFE, 2020a, Tabelle 4)
Synthethic e-fuels	Low	No imports at all
	High	Upper limit on annual imports in 2050 of 64 PJ, Scenario Zero-C(BFE, 2020c)
Hydrogen	Low	No imports at all
	High	Upper limit on annual imports of 40 PJ

We use the NTC estimations for the TYNDP18 global climate action in Table 6.9. We assume that in the low variant, 30% of the NTC can be utilized. The High electricity market integration assumes that there is an electricity agreement between Switzerland and the EU and, as a result, the NTC can be fully utilized.

2.2.2 Biomass, biofuels and synthetic e-fuels

Regarding solid, liquid and gaseous biomass, biofuels and synthetic e-fuels, we consider two market integration variants. In the low variant, we assume zero imports. In the High variant, we consider imports of biomass and biofuels, limited to 56 PJ (7 PJ of biomass/pellets, 5 PJ of biofuels and 44 PJ of biomethane) following the assumptions of the EP2050+ (BFE, 2020a). And for synthetic e-fuels we consider 64 PJ following the assumptions of the Zero-C scenario of the EP2050+ (BFE, 2020c). Table 6.8 presents the import prices.

2.2.3 Hydrogen

Unlike the electricity market, the hydrogen market does not exist and the infrastructure required for the trade of hydrogen needs to be developed. For that reason, we consider two variants that differ on the development of the hydrogen infrastructure. In the low variant, we assume that the hydrogen infrastructure is not developed, hence zero imports of hydrogen are allowed. In the high variant, we assume that Switzerland has access to an international market of hydrogen with an upper limit on the maximum trade volumes of 40 PJ (estimated as the sum of end-use consumption of hydrogen and synthetic diesel in the EP2050+ Zero-Basis scenario (BFE, 2020e, Tabelle 10.01)). Table 6.8 presents the import prices.

Chapter 3

Macro-economic drivers

Population and economic growth are uncertain drivers that affect energy demand. In this chapter, we present reference values and ranges for these variables which are based on official projections. We also include the assumptions of the EP2050+ (BFE, 2020c).

Table 3.1: Macro-economic drivers

	2010	**2020**	**2030**	**2040**	**2050**	**2010–2050**[a]	**Reference**
Population (Million)							
Reference	7.9	8.7	9.4	10.0	10.4	0.70% p.a.	A-00-2020 (BFS, 2022a, 2020a)
High	7.9	8.7	9.6	10.5	11.3	0.91% p.a.	B-00-2020 (BFS, 2022a, 2020a)
Low	7.9	8.7	9.2	9.5	9.5	0.48% p.a.	C-00-2020 (BFS, 2022a, 2020a)
EP2050+	7.8	8.7	9.5	10.0	10.3	0.68% p.a.	EP2050+ (BFE, 2020c, Tabelle 1)
Number of households (Million households)							
Reference	3.5	3.9	4.2	4.5	4.8	0.82% p.a.	AM-00-2020 (BFS, 2021b,a)
High	3.5	3.9	4.3	4.7	5.1	1.01% p.a.	BM-00-2020 (BFS, 2021b,a)
Low	3.5	3.9	4.2	4.3	4.4	0.61% p.a.	CM-00-2020(BFS, 2021b,a)
EP2050+	3.5	3.8	4.2	4.5	4.6	0.76% p.a.	EP2050+ (BFE, 2020e)
Working population (full-time equivalent)							
Reference	3.7	4.3	4.4	4.6	4.7	0.59% p.a.	A-00-2020 (BFS, 2022b, 2020b)
High	3.7	4.3	4.6	4.9	5.2	0.83% p.a.	B-00-2020 (BFS, 2022b, 2020b)
Low	3.7	4.2	4.3	4.3	4.3	0.35% p.a.	C-00-2020 (BFS, 2022b, 2020b)
EP2050+	3.8	4.1	4.3	4.4	4.4	0.40% p.a.	EP2050+ (BFE, 2020c, Tabelle 1)
GDP (BCHF$_{2017}$)							
Reference	603.0	695.6	846.4	981.6	1125.1	1.57% p.a.	BIP-A (BFS, 2022c, SECO, 2022)
High	603.0	695.6	860.0	1031.0	1220.9	1.78% p.a.	BIP-B (BFS, 2022c, SECO, 2022)
Low	603.0	695.6	836.2	938.0	1036.0	1.36% p.a.	BIP-C (BFS, 2022c, SECO, 2022)
EP2050+	603.0	713.0	805.0	893.0	968.0	1.19% p.a.	EP2050+ (BFE, 2020c, Tabelle 1)

[a] Average yearly growth rate between 2010 and 2050

Data available at https://sweet-cross.ch/data/macroeconomic-drivers-cross/

3.1 Population

The CROSS population assumptions are based on the estimations from the BFS (2020a): a reference estimation (A-00-2020) and the 2 variants (B-00-2020 and C-00-2020). We use historical data until 2020 from the BFS (2022a), and projections after 2020 from BFS (2020a). The reference population projection reaches 10.4 million people in 2050 and has an average annual growth rate between 2010 and 2050 of 0.7% p.a. Table 3.1 presents the population projections for the three variants (reference, low and high). The number of households is based on the projections of the BFS (2021a), we take the historical data from BFS (2021b) and update with the growth rates in BFS (2021a). To calculate the working population, we use the historical data from BFS (2022b) and the projections from BFS (2020b).

3.2 Gross domestic product

The CROSS GDP assumptions (Table 3.1) are based on the projections from the State Secretariat for Economic Affairs (SECO, 2022), which are linked to the BFS (2020a) population projections. We use the historical data from BFS (2022c) for 2010–2021.

Chapter 4

Climate change

We consider three 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 4.1 presents the yearly average temperature increase for the three RCPs including the range and median of the 68 simulations available for each RCP.

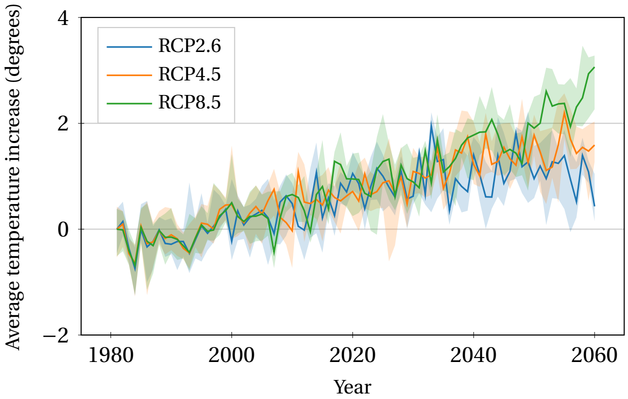


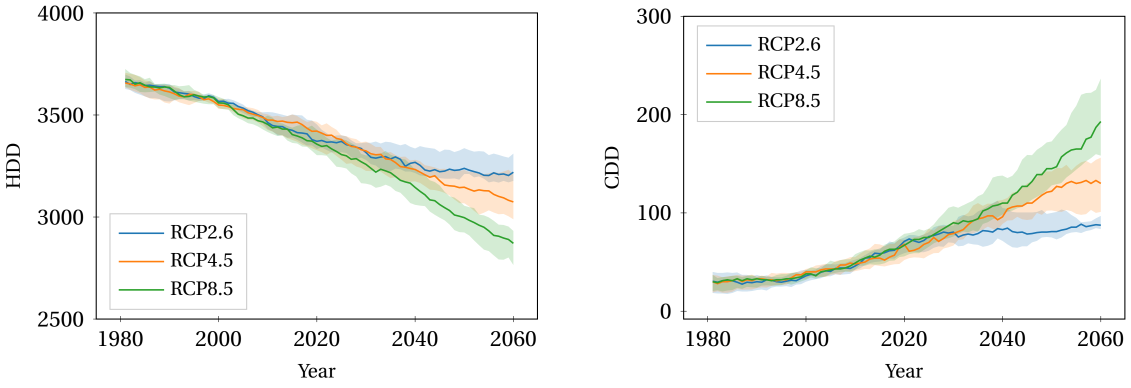
Figure 4.1: Temperature increase in three variants for global climate change. Based on CH2018 (2018), Berger and Worlitschek (2019)

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

We consider the effect of global climate change developments on heating and cooling demand and hydropower.

4.1 Effect on heating and cooling demand

Heating and cooling demands are directly affected by outside temperatures. We estimate the changes in heating degree days (HDD)[1] and cooling degree days (CDD)[2] due to climate change. Berger and Worlitschek (2019) calculated future HDDs and CDDs of the three RCP variants for the temperature increase in all models in CH2018 (2018). They used a GIS-based approach combining the spatial distribution of temperature (and therefore HDDs) and population. Figure 4.2 presents the median and the first and third quartiles of the HDDs and CDDs calculated by Berger and Worlitschek (2019).



(a) Heating degree days

(b) Cooling degree days

Figure 4.2: 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/

In CROSS, we estimate HDDs by taking the historical measured data from Berger and Worlitschek (2019) and applying the growth rates of the median values for each RCP variant. The resulting HDDs are shown in Table 4.1, we also compare to the HDDs in the EP2050+ scenarios BAU (Business as Usual)(BFE, 2020d) and Zero Basis (BFE, 2020e). Using these HDDs, we provide estimations for residential heating demand in Section 5.1.

4.2 Effect on inflow to hydropower

Climate change also has an effect on water availability, which affects hydropower monthly and annual potentials. We describe the effect of the three RCP variants in Section 6.1.1.

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[1] We use the most common definition of 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 $T_i = 20\,°C$.

[2] Cooling degree days are the number of degrees that a day's average temperature is above a certain threshold ($T_{max} = 18.3\,°C$).

Table 4.1: Heating degree days

Variant	**2010**	**2020**	**2030**	**2040**	**2050**	**2010–2050**
RCP2.6	3770	3351	3296	3248	3219	−0.39% p.a
RCP4.5	3770	3350	3255	3166	3080	−0.50% p.a
RCP8.5	3770	3353	3254	3141	2993	−0.57% p.a
EP2050+, Zero Basis (BFE, 2020e)	3586	3191	3105	3054	3030	−0.42% p.a.
EP2050+, BAU (BFE, 2020d)	3586	3182	3089	2997	2928	−0.51% p.a.

Data available at https://sweet-cross.ch/data/hdd/

Chapter 5

Energy service demands

From the harmonized drivers in Chapter 3, we calculate the future energy service demands in the different end-use sectors with a reduced-form econometric model based ((Panos et al., 2021) and Marcucci et al. (2021a)). We determine:

- space heating demand in the residential and commercial sectors from the future energy reference area (ERA), specific heating demand and climate change. We use population as explanatory variable to calculate the ERA in the residential and commercial sectors and GDP for industry;
- process heat demand using its relationship with economic development (GDP);
- warm water and electricity demand (appliances, motors, etc., without heat pumps or electric vehicles) follows population in the residential sector and GDP for the industrial and commercial sectors;
- transport based on the Transport Outlook 2050 (ARE, 2021).

All the demands estimated in this section correspond to end-use energy demand (EUD). These demands should not be confused with final energy consumption (FEC). FEC is defined as "the energy which reaches the final consumer's door". In other words, the FEC is the amount of input fuel needed to satisfy the (EUD) in energy services. As an example, in the case heat production with a gas boiler, the FEC is the amount of gas consumed by the boiler; the EUD is the amount of heat produced by the boiler, i.e. the heating service needed by the final user.

5.1 Space heating end-use demand

To estimate the space heating demand in the building sector, we require development of the building stock, energy efficiency improvements and climate change. In this section, we calculate the space heating demand and possible changes due to climate change. However, we do not account for energy efficiency improvements which are normally modelled as investment decisions in the energy system models.

5.1.1 Building stock

The ERA is the effective heated surface of a building. In CROSS, we use the historical data from BFE (2021, Tables 11 and 19). We substract the ERA of second homes and holiday houses from the residential sector and added them to the commercial sector[1]. To extrapolate the residential ERA to the

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[1] All second homes are treated as holiday houses.

future, we assume an increasing ERA with population with a logarithmic function for both residential and commercial sectors. For the industrial sector, we use the GDP as the explanatory variable. The resulting ERAs are shown in Table 5.1.

Table 5.1: Energy Reference Area by sector (Mm2)

	2010	**2020**	**2030**	**2040**	**2050**	**2010–2050**
Residential (Mm2)						
Reference	423.6	487.2	535.5	573.9	600.5	0.88% p.a.
High	423.6	487.2	548.4	605.2	652.5	1.09% p.a.
Low	423.6	487.2	522.3	541.1	544.7	0.63% p.a.
EP2050+ (BFE, 2020e)	423.8	484.9	537.9	573.8	594.1	0.85% p.a.
Commercial (Mm2)						
Reference	206.1	230.4	244.3	257.3	266.2	0.64% p.a.
High	206.1	230.4	248.7	267.8	283.8	0.80% p.a.
Low	206.1	230.4	239.9	246.2	247.4	0.46% p.a.
EP2050+ (BFE, 2020e)	205.9	230.9	243.7	250.9	251.6	0.50% p.a.
Industry (Mm2)						
Reference	87.4	94.5	98.5	104.1	109.2	0.56% p.a.
High	87.4	94.5	99.1	106.0	112.3	0.63% p.a.
Low	87.4	94.5	98.1	102.4	106.1	0.49% p.a.
EP2050+ (BFE, 2020e)	75.7	65.9	65.4	65.0	64.3	−0.41% p.a.

Data available at https://sweet-cross.ch/data/era-cross/

Since the heating demand depends on the age of the buildings, we distribute the total ERA in Table 5.1 across building types and ages. For this, we use use historical values from Schluck et al. (2019), in the residential sector; and Wüest Partner (2019), Jakob et al. (2019), in the commercial sector. 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 (See Marcucci et al. (2021b) for details on the estimation). The projected building stock for the residential sector including single family houses (SFHs) and multi family houses (MFHs) and the different construction periods are shown in Table 5.2. Since the current building stock is same for all variants, the only difference between them is for the buildings built after 2017. Each building type has a specific demand. We use the specific demand for the existing stock from Schluck et al. (2019) and Streicher et al. (2020). For the future building stock, we assume that the buildings will comply with current *minenergie* standards[2] with a specific energy demand that decreases with time as shown in last column in Table 5.2.

Table 5.2: Residential ERA (Mm2) and specific useful energy demand (kWh/m2/year) by building type and construction period

	Energy reference area (Mm2)						**Specific demand**
Construction period	**2016**	**2020**	**2030**	**2040**	**2050**	**2020–2050**	**(kWh/m2/year)**
Single family houses							
<1920	42.0	41.4	39.6	37.3	34.6	−0.60% p.a.	92.9
1920-1945	22.2	21.8	20.6	19.0	17.0	−0.82% p.a.	104.3

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[2] Norm SIA 380/1

Table 5.2: Residential ERA (Mm2) and specific useful energy demand (kWh/m2/year) by building type and construction period (continued)

	Energy reference area (Mm2)						**Specific demand**
Construction period	**2016**	**2020**	**2030**	**2040**	**2050**	**2020–2050**	**(kWh/m2/year)**
1946-1960	21.0	20.6	19.9	18.8	17.3	−0.59% p.a.	110.1
1961-1970	18.9	18.7	18.2	17.3	16.2	−0.48% p.a.	109.1
1971-1980	25.0	24.9	24.3	23.5	22.2	−0.38% p.a.	89.7
1981-1990	27.7	27.6	27.2	26.5	25.4	−0.28% p.a.	76.1
1991-2000	24.5	24.5	24.2	23.7	22.7	−0.25% p.a.	75.2
2001-2010	23.8	23.7	23.5	23.1	22.1	−0.23% p.a.	65.2
2011-2017	10.8	13.6	13.6	13.4	13.1	−0.13% p.a.	44.4
>2017							40 in 2020, 25 in 2050
Reference	0.0	0.5	14.1	26.2	37.0	15.09% p.a.	
High	0.0	0.5	17.3	34.0	50.0	16.25% p.a.	
Low	0.0	0.5	10.9	18.0	23.1	13.29% p.a.	
Multi family houses							
<1920	37.5	37.7	37.5	37.2	36.6	−0.10% p.a.	77.3
1920-1945	21.8	21.8	21.7	21.6	21.4	−0.06% p.a.	81.3
1946-1960	28.0	27.9	27.8	27.3	25.5	−0.30% p.a.	73.0
1961-1970	37.6	37.8	37.8	37.5	36.3	−0.14% p.a.	78.4
1971-1980	33.8	34.1	34.1	34.0	33.5	−0.06% p.a.	72.9
1981-1990	27.3	27.6	27.6	27.6	27.4	−0.02% p.a.	72.4
1991-2000	25.5	25.7	25.7	25.7	25.6	−0.01% p.a.	60.2
2001-2010	30.2	30.3	30.3	30.3	30.3	0.00% p.a.	47.3
2011-2017	24.4	25.3	25.3	25.3	25.3	0.00% p.a.	29.4
>2017							35 in 2020, 20 in 2050
Reference	0.0	1.6	42.4	78.6	111.1	15.09% p.a.	
High	0.0	1.6	52.0	102.0	150.1	16.25% p.a.	
Low	0.0	1.6	32.6	54.1	69.3	13.29% p.a.	

> Data available at https://sweet-cross.ch/data/era-cross/

5.1.2 Space heating end-use demand – before energy efficiency measures

The specific demands is the last column in Table 5.2 assume a theoretical constant climate. To estimate the heating demand in the different climate scenarios, we assume a linear relationship between the HDD (Table 4.1) and the heating demand. Table 5.3 presents the end-use demand[3] for space heating for the constant climate cases and the three RCP scenarios. We also include an estimation of the end-use demand from the final energy consumption in the BAU and Zero Basis scenarios of the EP2050+ (BFE, 2020d,e), assuming an efficiency of 86%.

Table 5.3: Space heating end-use demand (TWh)

	Climate	**2010**	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
Residential (TWh)								
Reference	Constant	46.0	35.7	37.3	37.9	38.3	37.8	−0.49% p.a.

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[3] We calculate end-use demand from the final energy statistics (BFE, 2021), assuming an efficiency of 86%.

Table 5.3: Space heating end-use demand (TWh) (continued)

	Climate	**2010**	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
	RCP 2.6	46.0	35.7	36.9	36.8	36.7	35.9	−0.62% p.a.
	RCP 4.5	46.0	35.7	36.5	36.5	35.9	34.5	−0.72% p.a.
	RCP 8.5	46.0	35.7	36.3	36.4	35.5	33.4	−0.80% p.a.
High	Constant	46.0	35.7	37.5	38.3	39.2	39.2	−0.40% p.a.
Low	Constant	46.0	35.7	37.1	37.5	37.4	36.4	−0.59% p.a.
EP2050+, BAU		45.8	36.0	37.3	36.0	33.3	31.0	−0.97% p.a.
EP2050+, Zero Basis		45.8	36.1	37.3	35.7	32.0	29.3	−1.11% p.a.
Commercial (TWh)								
Reference	Constant	21.7	16.7	16.0	16.2	16.5	16.4	−0.69% p.a.
	RCP 2.6	21.7	16.7	15.8	15.8	15.8	15.6	−0.82% p.a.
	RCP 4.5	21.7	16.7	15.6	15.6	15.4	15.0	−0.92% p.a.
	RCP 8.5	21.7	16.7	15.6	15.6	15.2	14.5	−1.00% p.a.
High	Constant	21.7	16.7	16.0	16.4	16.8	17.0	−0.61% p.a.
Low	Constant	21.7	16.7	15.9	16.1	16.1	15.9	−0.78% p.a.
EP2050+, BAU		19.4	16.0	14.1	12.9	11.2	10.1	−1.62% p.a.
EP2050+, Zero Basis		19.4	16.1	13.4	11.8	9.5	8.2	−2.13% p.a.
Industry (TWh)								
Reference	Constant	5.6	3.1	3.2	3.1	2.9	2.8	−1.72% p.a.
	RCP 2.6	5.6	3.1	3.2	3.0	2.8	2.6	−1.85% p.a.
	RCP 4.5	5.6	3.1	3.1	3.0	2.7	2.5	−1.95% p.a.
	RCP 8.5	5.6	3.1	3.1	3.0	2.7	2.5	−2.03% p.a.
High	Constant	5.6	3.1	3.2	3.1	3.0	2.9	−1.65% p.a.
Low	Constant	5.6	3.1	3.2	3.0	2.8	2.7	−1.80% p.a.
EP2050+, BAU		5.2	3.3	2.8	2.5	2.0	1.6	−2.90% p.a.
EP2050+, Zero Basis		5.2	3.3	2.7	2.3	1.7	1.3	−3.41% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

5.2 Warm water end-use demand

The drivers for the projection of warm water demand are population for the residential and commercial sectors and GDP for the industrial sector. We use the historical final energy statistics (BFE, 2021) to calibrate the model and we calculate useful energy demand assuming an efficiency of 80%. Table 5.4 presents the resulting demand. We also include an estimation of the end-use demand from the BAU and Zero Basis scenarios of the EP2050+ (BFE, 2020d,e), assuming an efficiency of 80%.

Table 5.4: Warm water end-use demand (TWh)

	2010	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
Residential (TWh)							
Reference	6.9	7.1	7.1	7.0	6.9	6.8	−0.04% p.a.
High	6.9	7.1	7.3	7.4	7.5	7.6	0.24% p.a.
Low	6.9	7.0	6.8	6.7	6.3	6.0	−0.36% p.a.
EP2050+, BAU	6.7	7.1	7.2	7.3	7.3	7.3	0.21% p.a.
EP2050+, Zero Basis	6.7	7.1	7.0	6.8	6.6	6.4	−0.11% p.a.
Commercial (TWh)							

Table 5.4: Warm water end-use demand (TWh) (continued)

	2010	2019	2025	2030	2040	2050	2010–2050
Reference	2.7	2.6	2.4	2.3	2.2	2.1	−0.67% p.a.
High	2.7	2.6	2.5	2.5	2.4	2.3	−0.39% p.a.
Low	2.7	2.5	2.3	2.2	2.0	1.8	−0.98% p.a.
EP2050+, BAU	2.5	2.2	1.9	1.8	1.8	1.9	−0.68% p.a.
EP2050+, Zero Basis	2.5	2.2	1.8	1.8	1.9	1.9	−0.68% p.a.
Industrial (TWh)							
Reference	0.65	0.44	0.40	0.39	0.37	0.37	−1.44% p.a.
High	0.65	0.45	0.42	0.41	0.41	0.41	−1.13% p.a.
Low	0.65	0.43	0.38	0.36	0.34	0.32	−1.76% p.a.
EP2050+, BAU	0.81	0.52	0.45	0.39	0.31	0.25	−2.90% p.a.
EP2050+, Zero Basis	0.81	0.53	0.43	0.36	0.26	0.20	−3.44% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

5.3 Process heat end-use demand

Process heat is thermal energy supplied at a level higher than space heating of warm water. It is mostly used in specific industrial sectors with a small contribution in the commercial sector. We relate process heat demand to GDP. We use the historical final energy statistics (BFE, 2021) to calibrate the model. We assume that industrial process heat corresponds to the categories *Prozesswärme, Sonstige* and *Antriebe, Prozesse* in BFE (2021, Table 28) and we calculate useful energy demand assuming an efficiency of 70%. Table 5.5 presents the resulting demand.

Table 5.5: Process heat end-use demand (TWh)

	2010	2019	2025	2030	2040	2050	2010–2050
Commercial (TWh)							
Reference	0.47	0.52	0.55	0.58	0.65	0.73	1.13% p.a.
High	0.47	0.52	0.56	0.6	0.70	0.81	1.36% p.a.
Low	0.47	0.52	0.54	0.56	0.61	0.67	0.89% p.a.
EP2050+	0	0	0	0	0	0	–
Industrial (TWh)							
Reference	17.7	16.7	16.1	16.5	17.0	17.9	0.03% p.a.
High	17.7	16.7	16.1	17.0	18.1	19.6	0.26% p.a.
Low	17.7	16.7	16.1	16.0	16.0	16.3	−0.21% p.a.
EP2050+, BAU	17.6	16.9	16.7	16.5	16.4	16.2	−0.21% p.a.
EP2050+, Zero Basis	17.6	16.9	16.0	15.2	14.0	13.0	−0.75% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

5.4 Electricity demand from electric appliances

In the electricity demand from electric appliances we include cooking, lighting, ICT, cooling, processes (refrigerators, dishwashers, etc), electric motors, air conditioning and other appliances [4]. It is important to note that this electricity demand does not include electricity use to produce the end-use demand of space heating, industrial heat or transport, it only accounts for appliances.
The drivers used for the projections are population in the residential and commercial sectors and GDP in the commercial and industrial sectors. Table 5.6 presents the resulting demand.

Table 5.6: Electricity demand from electric appliances (TWh)

	2010	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
Residential (TWh)							
Reference	12.7	12.0	11.7	11.5	11.2	10.9	−0.38% p.a.
High	12.7	12.0	11.8	11.8	11.8	11.9	−0.17% p.a.
Low	12.7	12.0	11.6	11.3	10.6	10.0	−0.59% p.a.
EP2050+, BAU	12.2	12.1	11.4	11.6	12.3	12.7	0.10% p.a.
EP2050+, Zero Basis	12.2	12.1	11.3	11.3	11.6	11.6	−0.13% p.a.
Commercial (TWh)							
Reference	16.3	16.7	16.1	15.8	15.1	14.1	−0.35% p.a.
High	16.3	16.7	16.4	16.4	16.1	15.5	−0.12% p.a.
Low	16.3	16.7	15.9	15.3	14.2	12.9	−0.58% p.a.
EP2050+, BAU	16.7	16.0	16.9	17.0	16.6	15.1	−0.25% p.a.
EP2050+, Zero Basis	16.6	15.9	15.9	15.1	13.2	11.5	−0.91% p.a.
Industrial (TWh)							
Reference	15.4	14.7	13.9	13.5	12.9	12.3	−0.55% p.a.
High	15.4	14.7	14.1	14.0	13.8	13.5	−0.32% p.a.
Low	15.4	14.7	13.7	13.1	12.2	11.2	−0.78% p.a.
EP2050+, BAU	15.5	13.9	13.8	13.7	13.4	12.9	−0.46% p.a.
EP2050+, Zero Basis	15.5	13.8	12.9	12.1	10.8	9.7	−1.16% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

5.5 Transport demand

The transport demand is based on the Transport Outlook 2050 (ARE, 2021). To calculate the three variants of the transport demand, we use the historical data from the BFS (2021d,c) and the ARE growth rates in the reference, high and low variants. Tables 5.7 and 5.8 present the passenger and freight transport projections from the different scenarios. Motorized personal transport corresponds to the categories personal cars, motorcycles, mopeds and fast e-bikes and other private.; Passenger rail corresponds to trams, trolleybuses and trains; and Road freight corresponds to trucks and light duty vehicles.

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[4] From the *Analyse des schweizerischen Energieverbrauchs 2000 – 2020 nach Verwendungszwecken* (BFE, 2021) we include the following categories by sector. Residential: *Klima , Lüftung, HT*; *Unterhaltung, I&K*; *Kochen / Geschirrspülen*; *Beleuchtung*; *Waschen & Trocknen,Kühlen & Gefrieren*; and *sonstige Elektrogeräte*. Commercial: *Beleuchtung*; *Klima, Lüftung, HT*; *I&K , Unterhaltung*; *Antriebe, Prozesse*; and *sonstige*. Industrial: *Beleuchtung*; *Klima, Lüftung, HT*; *I&K, Unterhaltung*; *Antriebe, Prozesse*; and *sonstige*

Table 5.7: Passenger transport demand (Billion passenger-kilometer)

	2010	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
Motorized personal transport							
Reference	90.9	103.1	105.6	107.4	107.7	104.8	0.36% p.a.
High	90.9	103.1	106.5	109.6	113.1	113.7	0.56% p.a.
Low	90.9	103.1	104.8	105.3	102.3	96.1	0.14% p.a.
EP2050+	90.9	101.8	106.0	109.3	113.5	115.2	0.59% p.a.
Buses							
Reference	2.5	3.0	3.1	3.2	3.6	3.9	1.10% p.a.
High	2.5	3.0	3.1	3.3	3.8	4.2	1.31% p.a.
Low	2.5	3.0	3.1	3.2	3.4	3.5	0.88% p.a.
EP2050+	3.0	3.4	3.7	3.9	4.2	4.3	0.90% p.a.
Passenger rail							
Reference	21.1	23.9	24.5	25.6	28.5	30.7	0.94% p.a.
High	21.1	23.9	24.7	26.1	29.9	33.3	1.15% p.a.
Low	21.1	23.9	24.3	25.1	27.1	28.1	0.72% p.a.
EP2050+	20.2	22.9	25.2	26.7	28.8	30.1	1.00% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

Table 5.8: Freight transport demand (Billion ton-kilometer)

	2010	**2019**	**2025**	**2030**	**2040**	**2050**	**2010–2050**
Road							
Reference	16.9	17.1	17.3	18.0	19.6	21.2	0.57% p.a.
High	16.9	17.1	17.6	18.6	20.9	23.2	0.80% p.a.
Low	16.9	17.1	17.1	17.4	18.4	19.3	0.33% p.a.
EP2050+	16.9	17.6	18.6	19.5	21.2	22.5	0.72% p.a.
Freight rail							
Reference	9.8	10.1	10.9	11.7	12.5	13.5	0.80% p.a.
High	9.8	10.1	11.1	12.1	13.4	14.8	1.04% p.a.
Low	9.8	10.1	10.7	11.3	11.8	12.3	0.57% p.a.
EP2050+	9.9	10.9	12.8	13.7	14.1	14.7	0.99% p.a.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/

Chapter 6

Resources

6.1 Hydropower

Hydropower is the backbone of the Swiss electricity system, supplying approximately 60% of today's electricity. Roughly half of it is produced with run-of-river (RoR) power stations and the other half with storage lakes.

Boes et al. (2021) estimated 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 Boes et al. (2021) also studied the effect of different factors on the hydropower potential, including increased residual flows, protection to fish migration, refurbishment of existing plants, construction of new plants, and climate change. Table 6.1 shows the impact of these factors for three different scenarios in Boes et al. (2021).

Table 6.1: 2050 Hydropower potential from Boes et al. (2021)

Long term potential (Boes et al., 2021)	36 TWh/a		
	Change in TWh/a		
	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
Climate change	−2.0	−1.0	0.0

In CROSS (Table 6.2), we assume three variants that differ in the level of social acceptance, reflected on the refurbishment of existing plants and the construction of new plants.

Table 6.2: 2050 Hydropower potential: CROSS variants

Long term potential (Boes et al., 2021)	36 TWh/a		
	Change in TWh/a		
	Low	Reference	High
Increased residual flows	−2.3	−2.3	−2.3
Measures to protect fish migration	−0.4	−0.4	−0.4
Refurbishment of existing plants	0.4	0.8	2.0
New plants	1.1	2.3	3.1
2050 potential	**34.8**	**36.4**	**38.4**

6.1.1 Effect of climate change

The potential of hydropower (both RoR plants and storage plants) depends on the availability of water inflows. Climate conditions and weather patterns dictate precipitation and melting, that is, water inflows. Climate change has two effects on hydropower production. First effect is on the total yearly potential. Boes et al. (2021) estimated the effect of climate change on the yearly potential for three scenarios: optimistic, medium and pessimistic. We map these scenarios to our climate change variants: RCP 2.6, RCP 4.5 and RCP 8.5, respectively.

Second, climate change affects the monthly water availability. Marcucci et al. (2021b) modelled the impact of climate change on the monthly hydropower production for the three RCP climate scenarios in CH2018 (2018). They used the Swissmod model based on input hydro discharge data from Brunner et al. (2019). The resulting inflow patterns are visualized in Figure 6.1. 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.

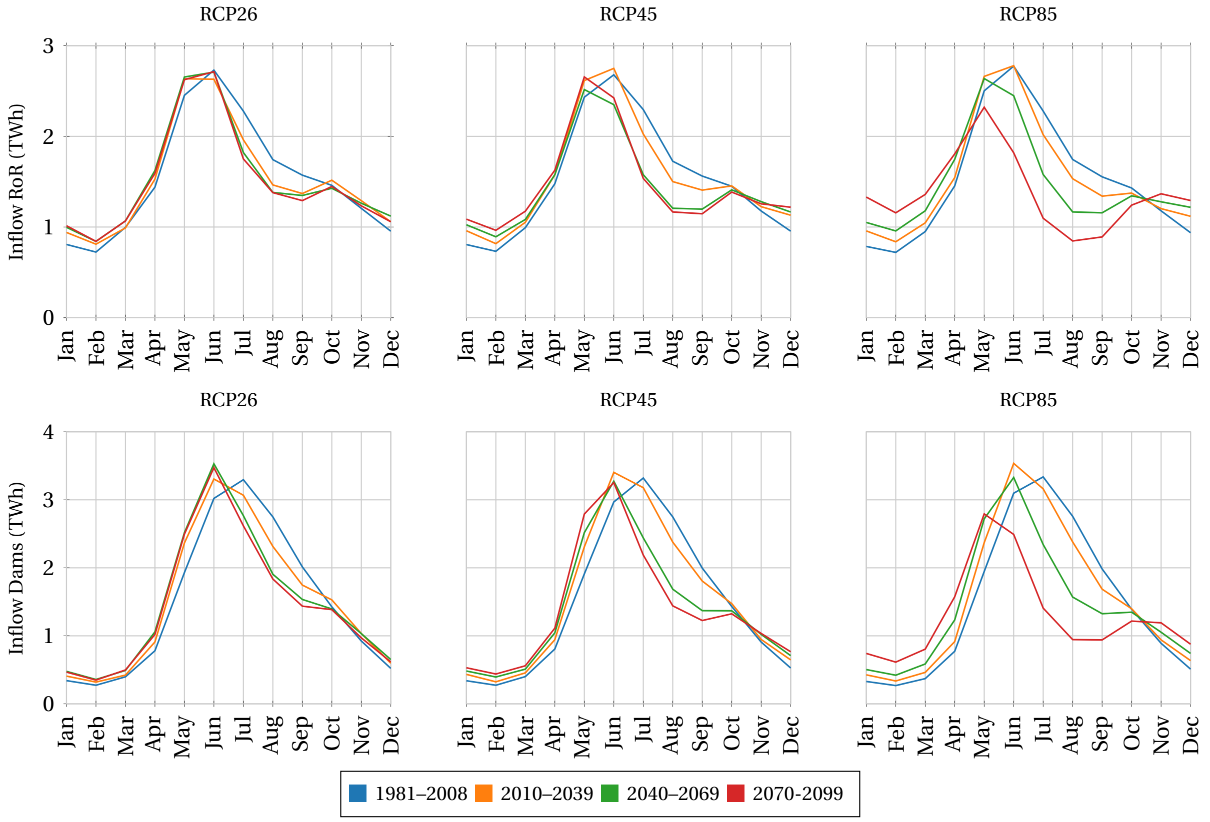

Figure 6.1: Inflows to run-of-river hydropower and dams under different RCPs and climatic periods

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

The changes due to climate change in Figure 6.1 are estimated for inflows and not production. To make use of the inflow dataset for the RCPs, Marcucci et al. (2021a) calibrated the inflow dataset to the production dataset based on the joint historical climate periods and used the obtained calibration factors for future years (Figure 6.2). The results show an important decrease in the inflow in the summer months (July, August and September) and an increase in winter (January, February and March) relative to the historical values.

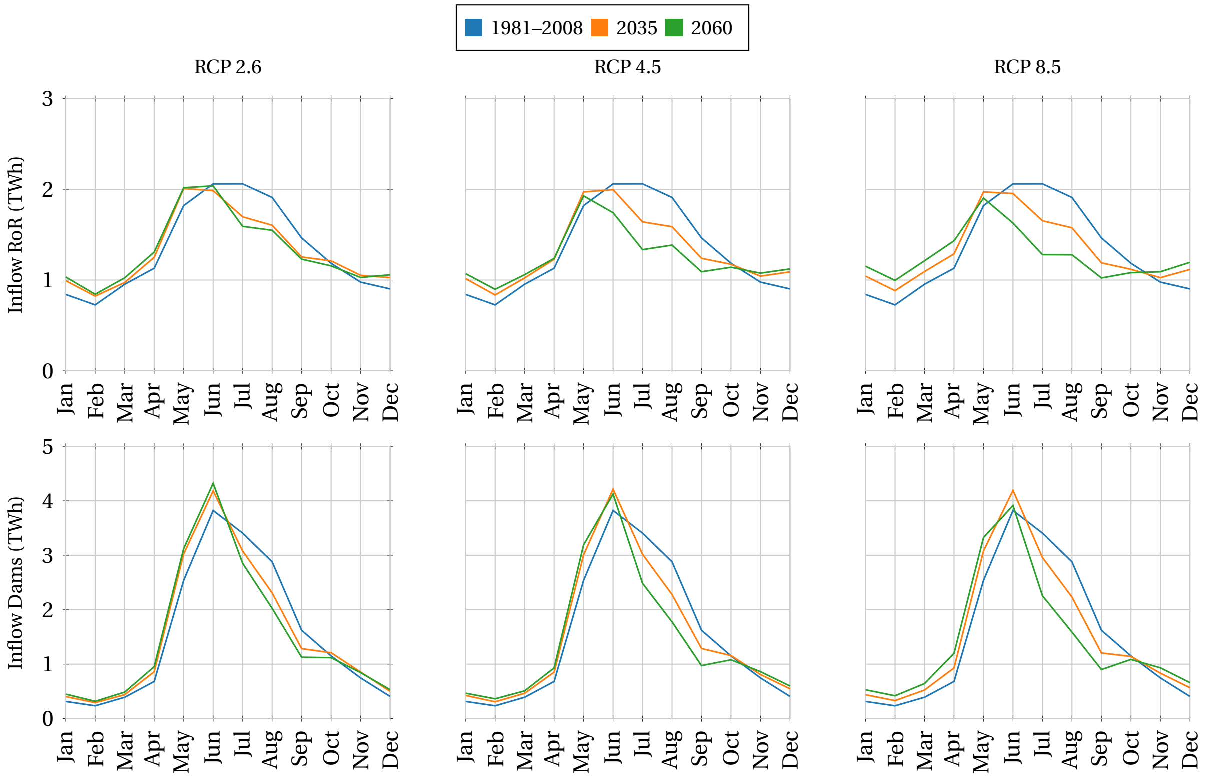

Figure 6.2: Hydropower monthly profile for the three RCP scenarios

Data available at https://sweet-cross.ethz.ch/data/hydropower-climate/

6.2 Solar photovoltaics

Different studies have estimated the solar photovoltaics (PV) potential for Switzerland. Table 6.3 presents a summary of different studies for rooftop, facades and mountain potentials. Based on those studies, in CROSS we consider three variants for solar photovoltaics as shown in Table 6.4.

Table 6.3: 2050 solar photovoltaic potentials estimates from different studies

Study	**Rooftop**			**Facades**	**Mountains**
	Roof coverage (%)	**Capacity factor (%)**	**Potential (TWh)**	**Potential (TWh)**	**Potential (TWh)**
Dujardin et al. (2021)					30 (above 800 m, not in urban areas)
Walch et al. (2020)	56.4%	13.8	25		
Remund et al. (2019)	Roofs		23.3	8.2	3.3
	Roads		2.5		
	Parking lots		3.9		

Table 6.3: 2050 solar photovoltaic potentials estimates from different studies (continued)

Study	**Rooftop**			**Facades**	**Mountains**
	Roof coverage (%)	**Capacity factor (%)**	**Potential (TWh)**	**Potential (TWh)**	**Potential (TWh)**
	Highways		3.9		
BFE (2019)	70% of roofs of more than 10 m2 with at least “good” annual solar radiation		50	17	
Bauer et al. (2019)	All roofs		63		
	72%: Roofs with solar irradiance >1000 kWh/m2/year		50		
	40%: Roofs with solar irradiance >2000 kWh/m2/year		30		
Assouline et al. (2018)	60.5%	13.6	16.3		
Buffat et al. (2018)	70.1%	10.3	41.3		
Assouline et al. (2017)	60.5%	13.6	17.9		
Klauser (2016)	72.2%	13.6	53.1		
IEA (2002)	55.0%	10	15.0		

Table 6.4: 2050 solar photovoltaics potential: CROSS variants

Variant	**2050 potential (TWh/a)**			
	Rooftop	**Facades**	**Mountains**	**Total**
Reference	40	4	3	47
High	50	8	30	88
Low	30	0	0	30

6.3 Wind

Table 6.5 summarizes the potentials calculated in different studies. Based on these studies, in CROSS, we consider three variants for wind potential (Table 6.6): a low variant of 1.7 TWh/a, a reference variant of 4.3 TWh/a and a high variant 15 TWh/a.

Table 6.5: 2050 wind potentials estimates from different studies

Study	**Potential (TWh)**
BFE (2022)	
Mitteland	17.5
Jura and Alpine valleys	7.8
Alps	4.2
Dujardin et al. (2021)	15
Suisse Eole (2020)	
Sustainable for locations with wind average of > 4.5m/s	30
Sustainable for locations with wind average of > 5m/s	20
Realistic	9
BFE (2020c)	4.3

Table 6.5: 2050 wind potentials estimates from different studies (continued)

Study	Potential (TWh)
ARE (2017)	4.3
Bauer et al. (2017)	4.3
VSE (2012)	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

Table 6.6: 2050 Wind potential: CROSS variants

Variant	2050 potential (TWh/a)
Reference	4.3
High	15.0
Low	1.7

6.4 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., 2021). We updated these potentials with the CROSS assumptions on GDP and population described in Chapter 3 (Table 6.7 depicts the reference variant). The potentials estimated in Guidati et al. (2021) include three different wood potential scenarios depending on economic restrictions and the management policy. Total potentials of biomass excluding mixed waste for the reference population and GDP growth are in the range of 100–113 PJ in 2050 (depending on the wood scenario). Waste potentials are projected to be 74 PJ by 2050.

Table 6.7: 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	15.8	16.3	16.6	17.0	17.3	17.5
(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

Table 6.7: Energy potential of biomass and waste categories in the reference variant (PJ) (continued)

		Energy Potential (PJ)									
Category	**Feedstock**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**	**2060**
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	24.4	28.4	31.6	34.1	36.7	39.4	42.1	44.9	47.9
	Municipal waste	31.4	30.8	31.4	31.8	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*	*1.4*	*1.2*	*0.9*	*0.6*

Data available at https://sweet-cross.ch/data/biomass-potentials-cross/

6.4.1 Waste incineration plants (IPCC category 1.A.1.a.iv)

Waste incineration plants are a special category where we need special considerations.

- Waste composition in 2050: Around 37 per cent of total waste is of biogenic origin by 2050 and the remaining is fossil-based (BFE, 2020c).
- Emissions from waste in 2050: 4 $MtCO_2$ are emitted by waste incinerators, 1.5 $MtCO_2$ (37%) of biogenic origin and the remaining 2.5 $MtCO_2$ is fossil-based (BFE, 2020c). Since carbon capture and storage can be used in waste incinerators, assuming 90% capture rate, 3.6 $MtCO_2$ can be captured. Given that the biogenic portion is captured by the biomass while growing, the net emissions (when using CCS) are the fossil fraction minus the total CO_2 captured: -1.1 $MtCO_2$.
- Lower heating value (LHV): According to the VBSA (2020) the LHV for waste is between 11 and 12 MJ/kg. We assume a LHV of 11.5 MJ/kg.
- Amount of waste in 2050: The CO_2 content of waste (VBSA, 2020, Eq. 1) is calculated following:

$$C_{\text{total}}\ [\text{g/kg}] = 264 + \big(LHV\,[\text{MJ/kg}] - 10\big) \times 98/5,$$

  we can, therefore, estimate the total amount of waste that goes to the waste incinerators (from the 4 $MtCO_2$ in BFE (2020c)) to 3.7 Mt (or 42.8 PJ).

6.5 Imports and exports

6.5.1 Oil, gas, biofuels and hydrogen

Table 6.8 presents the assumptions for import prices of oil, gas, biofuels and hydrogen. The import price of oil and gas are based on the 2021 World Energy Outlook (IEA, 2021). These prices are adjusted by accounting the recent developments in the prices and futures prices for the next three years. Following the approach developed in JASM (Marcucci et al., 2021b), we get the Swiss Border Prices using an econometric relationship between the IEA future prices and the Swiss prices for the past.

Biofuels and hydrogen prices are from the JASM project (Marcucci et al., 2021b), where the price of biofuels were projected until 2030 following FAO (2019) and WEC (2019). The hydrogen prices in JASM were calculated as a mix of production cost of fossil and renewable hydrogen based on IEA (2019).

Table 6.8: Import price of energy carriers (CHF/GJ)

	2017	2020	2030	2040	2050	2020–2050	Reference
Oil							
Reference	9.6	6.9	13.3	14.3	14.7	2.56% p.a.	IEA (2021)
High	9.6	6.9	15.7	20.7	20.7	3.74% p.a.	IEA (2021)
Low	9.6	6.9	5.9	4.8	3.9	−1.85% p.a.	IEA (2021)
EP2050+, BAU	8.2	11.7	15.0	17.5	21.9	2.10% p.a.	BFE (2020d)
EP2050+, Zero Basis	8.2	11.4	11.3	10.1	7.0	−1.60% p.a.	BFE (2020e)
Gas							
Reference	6.2	10.2	10.2	10.0	10.3	2.86% p.a.	IEA (2021)
High	6.2	11.6	11.6	16.7	17.0	4.58% p.a.	IEA (2021)
Low	6.2	4.1	4.1	4.0	3.5	−0.83% p.a.	IEA (2021)
EP2050+, BAU	5.5	6.8	7.8	8.5	9.6	1.20% p.a.	BFE (2020d)
EP2050+, Zero Basis	5.5	6.7	7.2	7.3	5.1	−0.92% p.a.	BFE (2020e)
Biodiesel							
Reference	43.4	42.7	49.7	52.4	55	0.85% p.a.	Marcucci et al. (2021b)
High	43.4	42.7	56.4	65.7	70.8	1.7 % p.a.	Marcucci et al. (2021b)
Low	43.4	42.7	41.4	40.1	40.1	−0.22% p.a.	Marcucci et al. (2021b)
Ethanol							
Reference	29.7	30.4	39.4	41.9	44.3	1.27% p.a.	Marcucci et al. (2021b)
High	29.7	30.4	48.2	59.2	64.1	2.52% p.a.	Marcucci et al. (2021b)
Low	29.7	30.4	30.6	24.6	24.6	−0.7 % p.a.	Marcucci et al. (2021b)
Hydrogen							
Reference	0	26.9	40.1	42.7	44.7	1.7 % p.a.	Marcucci et al. (2021b)
High	0	26.9	41.6	44.4	52.1	2.23% p.a.	Marcucci et al. (2021b)
Low	0	26.9	38.5	41.1	37.3	1.09% p.a.	Marcucci et al. (2021b)

Data available at https://sweet-cross.ch/data/import-prices-cross/

6.5.2 Electricity imports

Net transfer capacities (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.

Marcucci et al. (2021b) estimated NTCs between Switzerland and neighbouring countries and import prices for two scenarios with different CO_2 price pathways. The calculation is done with the electricity market model Swissmod (Schlecht and Weigt, 2014) using assumptions for transmission line capacities and other inputs (such as demand time series, generation capacities and fuel prices) from 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). The CO_2 price pathways are based on the TYNDP18 sustainable transition and TYNDP18 global climate action. Table 6.9 depicts the net transfer capacities and the electricity import prices are available at https://data.sccer-jasm.ch/hourly_electricity_prices/.

Table 6.9: Average annual net transfer capacities (GW) from ENTSO-E (2018)

	TYNDP18 scenario					
	Sustainable transition			**Global climate action**		
From-to	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**
Switzerland–Germany	4.6	5.6	6.5	4.6	5.6	6.5
Switzerland–France	1.3	1.3	2.8	1.3	1.3	3.8
Switzerland–Italy	4.2	6.0	6.0	4.2	6.0	6.0
Switzerland–Austria	1.2	1.7	1.7	1.2	1.7	1.7
Germany–Switzerland	2.7	3.3	4.1	2.7	3.3	4.1
France–Switzerland	3.2	3.7	5.2	3.2	3.7	6.2
Italy–Switzerland	1.9	3.0	3.7	1.9	3.0	3.7
Austria–Switzerland	1.2	1.7	1.7	1.2	1.7	1.7

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

6.5.3 Carbon sequestration

Recent studies found that CO_2 storage potentials in Switzerland are low (Diamond et al., 2019) and to achieve net zero emissions, storage alternatives must be found abroad. Estimates for the storage potential in the North Sea amount to more than 100 $GtCO_2$ (IOGP – International association of oil & gas producers, 2019). In CROSS, we assume that Switzerland has access to the storage potential in the North Sea. This potential is unlimited and has a prices of transport and storage of 100 CHF/tCO_2 for transport (BFE, 2020b, Abbildung 15).

Bibliography

ARE, 2017. Sachpläne und Konzepte - Konzept Windenergie. Basis zur Berücksichtigung der Bundesinteressen bei der Planung von Windenergieanlagen.

ARE, 2021. Schweizerische Verkehrsperspektiven 2050. Technical Report. Bundesamt für Raumentwicklung (ARE). URL: https://www.are.admin.ch/are/de/home/mobilitaet/grundlagen-und-daten/verkehrsperspektiven.html.

Assouline, D., Mohajeri, N., Scartezzini, J.L., 2017. Quantifying rooftop photovoltaic solar energy potential: A machine learning approach. Solar Energy 141, 278 – 296. URL: http://www.sciencedirect.com/science/article/pii/S0038092X16305850, doi:`https://doi.org/10.1016/j.solener.2016.11.045`.

Assouline, D., Mohajeri, N., Scartezzini, J.L., 2018. Large-scale rooftop solar photovoltaic technical potential estimation using random forests. Applied Energy 217, 189 – 211. URL: http://www.sciencedirect.com/science/article/pii/S0306261918302496, doi:`https://doi.org/10.1016/j.apenergy.2018.02.118`.

BAFU, 2021a. Declaration of Intent with Iceland on Cooperation on Climate Change Mitigation. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate--international-affairs/staatsvertraege-umsetzung-klimauebereinkommen-von-paris-artikel6.html. online; posted 1-October-2020.

BAFU, 2021b. Evolution of Switzerland's greenhouse gas emissions since 1990 (April 2021). URL: https://www.bafu.admin.ch/dam/bafu/en/dokumente/klima/fachinfo-daten/THG_Inventar_Daten.xlsx.download.xlsx/Evolution_GHG_since_1990.xlsx.

BAFU, 2021c. GHG inventory 1990-2019. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/state/data/climate-reporting/latest-ghg-inventory.html.

BAFU, 2021d. Switzerland's information necessary for clarity, transparency and understanding in accordance with decision 1/CP.21 of its updated and enhanced nationally determined contribution (NDC) under the Paris Agreement (2021–2030) . URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate--international-affairs/switzerland_s-submissions-within-the-framework-of-international-/eingaben-der-schweiz-im-rahmen-der-internationalen-
html.

BAFU, 2022. Memorandum of Understanding between the State Secretary for Economic Affairs and Climate Policy of the Netherlands and the Head of the Federal Department of Environment, Transport, Energy and Communications of Switzerland on Cooperation on Carbon Capture and Storage and Carbon Dioxide Removal. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate--international-affairs/staatsvertraege-umsetzung-klimauebereinkommen-von-paris-artikel6.html. online; posted 1-October-2020.

Bauer, C., Cox, B., Heck, T., Zhang, X., 2019. Potentials, costs and environmental assessment of electricity generation technologies – An update of electricity generation costs and potentials. Technical Report. Paul Scherrer Institut. URL: https://www.bfe.admin.ch/bfe/de/home/news-und-medien/publikationen/_jcr_content/par/externalcontent.external.exturl.pdf/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvOTgyNi5wZGY=.pdf.

Bauer, C., Hirschberg, S., Bäuerle, Y., Biollaz, S., Calbry-Muzyka, A., Cox, B., Heck, T., Lehnert, M., Meier, A., Prasser, H.M., Schenler, W., Treyer, K., Vogel, F., Wieckert, H., Zhang, X., Zimmermann, M., Burg, V., Bowman, G., Erni, M., Saar, M., Tran, M., 2017. Potentials, costs and environmental assessment of electricity generation technologies. Technical Report. Paul Scherrer Institut.

Berger, M., Worlitschek, J., 2019. The link between climate and thermal energy demand on national level: A case study on Switzerland. Energy and Buildings 202, 109372. URL: http://www.sciencedirect.com/science/article/pii/S037877881931120X, doi:`https://doi.org/10.1016/j.enbuild.2019.109372`.

BFE, 2019. Schweizer Hausdächer und -fassaden könnten jährlich 67 TWh Solarstrom produzieren. URL: https://www.bfe.admin.ch/bfe/de/home/news-und-medien/medienmitteilungen/mm-test.msg-id-74641.html.

BFE, 2020a. Energieperspektiven 2050+ – Exkurs Biomasse – Potenziale und Einsatz in den Szenarien Quelle. URL: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html.

BFE, 2020b. Energieperspektiven 2050+ – Exkurs Negativemissionstechnologien und CCS – Potenziale, Kosten und Einsatz. URL: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html.

BFE, 2020c. Energieperspektiven 2050+. Kurzbericht. URL: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html.

BFE, 2020d. Energieperspektiven 2050+. Szenarienergebnisse WWB. URL: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html.

BFE, 2020e. Energieperspektiven 2050+. Szenarienergebnisse ZERO Basis. URL: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html.

BFE, 2021. Analysis of energy consumption 2000–2020 by specific use (Analyse des schweizerischen Energieverbrauchs 2000 – 2020 nach Verwendungszwecken). Technical Report. BFE. URL: https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/analysis-of-energy-consumption-by-specific-use.html.

BFE, 2022. Windpotenzial Schweiz 2022. URL: https://www.newsd.admin.ch/newsd/message/attachments/72771.pdf.

BFS, 2020a. Szenarien zur Bevölkerungsentwicklung der Schweiz und der Kantone 2020-2050. Technical Report. Bundesamt für Statistik. URL: https://www.bfs.admin.ch/asset/de/px-x-0104000000_102.

BFS, 2020b. Szenarien zur Entwicklung der Erwerbsbevölkerung 2020–2050 – Erwerbsquote und Erwerbsbevölkerung nach Staatsangehörigkeit (Kategorie), Jahr, Geschlecht, Beobachtungseinheit, Alter und Szenario-Variante. URL: https://www.pxweb.bfs.admin.ch/pxweb/de/px-x-0301000000_101/.

BFS, 2021a. Anzahl Privathaushalte nach dem Szenario AM–00–2020, 2020–2050. Technical Report. Bundesamt für Statistik. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/zukuenftige-entwicklung/haushaltsszenarien.assetdetail.16344849.html.

BFS, 2021b. Private households by canton and household size, 2010-2020. Technical Report. Bundesamt für Statistik. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/stand-entwicklung/haushalte.assetdetail.18845791.html.

BFS, 2021c. Transportleistungen im Güterverkehr, je-d-11.05.01.02. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/gueterverkehr.assetdetail.18864273.html.

BFS, 2021d. Verkehrsleistungen im Personenverkehr, je-d-11.04.01.02. URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/mobilitaet-verkehr/personenverkehr/leistungen.assetdetail.19904693.html.

BFS, 2022a. Demographic balance by canton, 1971–2021. Technical Report. Bundesamt für Statistik. URL: https://www.bfs.admin.ch/asset/de/px-x-0102020000_101.

BFS, 2022b. Employed persons (domestic concept) total number and in full-time equivalents by gender and nationality, gross and seasonally adjusted values. quarterly and yearly averages (1960–1974, 1975–2022). URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/arbeit-erwerb/erhebungen/ets.assetdetail.22985591.html.

BFS, 2022c. Gross domestic product: production approach (1995–2021). URL: https://www.bfs.admin.ch/bfs/de/home/statistiken/volkswirtschaft.assetdetail.23184098.html.

Boes, R., Burlando, P., Evers, F.M., Farinotti, D., Felix, D., Hohermuth, B., Schmid, M., Stähli, M., Münch-Alligné, C., Weigt, H., Avellan, F., Manso, P., 2021. Swiss Potential for Hydropower Generation and Storage. Synthesis Report. Technical Report. SCCER Supply of Electricity. Zurich. doi:`10.3929/ethz-b-000517823`.

Brunner, M.I., Björnsen Gurung, A., Zappa, M., Zekollari, H., Farinotti, D., Stähli, M., 2019. Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes. Science of The Total Environment 666, 1033 – 1047. URL: http://www.sciencedirect.com/science/article/pii/S0048969719306576, doi:`https://doi.org/10.1016/j.scitotenv.2019.02.169`.

Buffat, R., Grassi, S., Rauball, M., 2018. A scalable method for estimating rooftop solar irradiation potential over large regions. Applied Energy 216, 389–401. URL: https://doi.org/10.1016/j.apenergy.2018.02.008.

Cattin, R., Schaffner, B., Humar-Maegli, T., Albrecht, S., Remund, J., Klauser, D., Engel, J.J., 2012. Berechnung der Energiepotenziale für Wind- und Sonnenenergie. Technical Report. Meteotest - commissioned by Bundesamtes für Umwelt (BAFU).

CH2018, 2018. CH2018 – Climate Scenarios for Switzerland. Technical Report. National Centre for Climate Services.

Diamond, L., Herwegh, M., Holliger, K., Madonna, C., 2019. Deep underground heat reservoirs, Joint NRP70 project "Hydropower and geo-energy". Technical Report. Universität Bern, University of Lausanne and ETH Zurich. URL: https://nfp-energie.ch/en/projects/960/.

Dujardin, J., Kahl, A., Lehning, M., 2021. Synergistic optimization of renewable energy installations through evolution strategy. Environmental Research Letters 16, 064016. URL: https://doi.org/10.1088/1748-9326/abfc75, doi:`10.1088/1748-9326/abfc75`.

ENTSO-E, 2018. TYNDP 2018 Scenario Report. URL: https://tyndp.entsoe.eu/tyndp2018/.

FAO, 2019. OECD-FAO agricultural outlook. doi:`https://doi.org/10.1787/19991142`.

Guidati, G., Marcucci, A., Damartzis, T., Burg, V., Schildhauer, T., Giardini, D., Kröcher, O., 2021. Biomass and waste potentials and conversion pathways for energy use in Switzerland. Technical Report. JASM and WSL. doi:`10.3929/ethz-b-000540915`.

IEA, 2002. Potential for building integrated photovoltaics.

IEA, 2019. The future of hydrogen - seizing today's opportunities. URL: https://www.iea.org/reports/the-future-of-hydrogen.

IEA, 2021. World energy outlook. URL: https://www.iea.org/reports/world-energy-outlook-2021.

IOGP – International association of oil & gas producers, 2019. The potential for CCS and CCU in Europe. Report to the thirty second meeting of the European Gas Regulatory Forum 5-6 June 2019. URL: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.

Jakob, M., Catenazzi, G., Forster, R., Egli, T., Lemon, T.K., Looser, R., Melliger, M., Nägeli, C., Reiter, U., Soini, M., Sunarjo, B., 2019. Erweiterung des Gebäudeparkmodells gemäss SIA-Effizienzpfad Energie. Technical Report. TEP Energy – Bundesamt für Energie (BFE). URL: https://www.tep-energy.ch/docs/2016_GEPAMOD_GPM_SIA_Effizienzpfad_Schlussbericht.pdf.

Klauser, D., 2016. Solarpotentialanalyse für Sonnendach.ch. Technical Report. BFE. URL: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/geoinformation/geodaten/solar/solarenergie-eignung-hausdach.html.

Marcucci, A., Guidati, G., Giardini, D., 2021a. Swiss Hourly Energy Scope: Documentation. Technical Report. ETH Zurich - JASM. doi:`10.3929/ethz-b-000540917`.

Marcucci, A., Panos, E., Guidati, G., Lordan-Perret, R., Schlecht, I., Giardini, D., 2021b. JASM framework and drivers definition. Technical Report. ETH Zurich, Paul Scherrer Institute and U. Basel - JASM. doi:`10.3929/ethz-b-000540916`.

Müller, D.B., 2006. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. Ecological Economics 59, 142 – 156. URL: http://www.sciencedirect.com/science/article/pii/S092180090500460X, doi:`https://doi.org/10.1016/j.ecolecon.2005.09.025`.

Panos, E., Kober, T., Kannan, R., Hirschberg, S., 2021. Long-term energy transformation pathways - Integrated scenario analysis with the Swiss TIMES energy systems model. Technical Report. PSI - JASM. doi:`10.3929/ethz-b-000509023`.

Remund, J., Albrecht, S., Stickelberger, D., 2019. Schweizer PV-Potenzial basierend auf jedem einzelnen Gebäude. URL: https://www.swissolar.ch/fileadmin/user_upload/Tagungen/PV-Tagung_2019/Medien/190325Solarpotenzial_CH_JanRemund_lang.pdf.

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., Fujimori, S., Harmsen, M., Hasegawa, T., Krey, V., Luderer, G., Paroussos, L., Schaeffer, R., Weitzel, M., van der Zwaan, B., Vrontisi, Z., Longa, F.D., Després, J., Fosse, F., Fragkiadakis, K., Gusti, M., Humpenöder, F., Keramidas, K., Kishimoto, P., Kriegler, E., Meinshausen, M., Nogueira, L.P., Oshiro, K., Popp, A., Rochedo, P.R.R., Ünlü, G., van Ruijven, B., Takakura, J., Tavoni, M., van Vuuren, D., Zakeri, B., 2021. Cost and attainability of meeting stringent climate targets without overshoot. Nature Climate Change 11, 1063–1069. URL: https://doi.org/10.1038/s41558-021-01215-2, doi:`10.1038/s41558-021-01215-2`.

Sandberg, N.H., Sartori, I., Heidrich, O., Dawson, R., Dascalaki, E., Dimitriou, S., Vimm-r, T., Filippidou, F., Stegnar, G., Šijanec Zavrl, M., Brattebø, H., 2016. Dynamic building stock modelling: Application to 11 european countries to support the energy efficiency and retrofit ambitions of the eu. Energy and Buildings 132, 26–38. URL: http://www.sciencedirect.com/science/article/pii/S0378778816304893, doi:`10.1016/j.enbuild.2016.05.100`.

Sartori, I., Sandberg, N.H., Brattebø, H., 2016. Dynamic building stock modelling: General algorithm and exemplification for Norway. Energy and Buildings 132, 13 – 25. URL: http://www.sciencedirect.com/science/article/pii/S037877881630487X, doi:`https://doi.org/10.1016/j.enbuild.2016.05.098`.

Schlecht, I., Weigt, H., 2014. Swissmod - a model of the Swiss electricity market. WWZ Discussion Paper doi:`10.5451/unibas-ep34944`.

Schluck, T., Streicher, K.N., Mennel, S., 2019. Statistical modelling of the energy reference area based on the Swiss building stock. Journal of Physics: Conference Series 1343, 012031. doi:`10.1088/1742-6596/1343/1/012031`.

SECO, 2022. Szenarien zur BIP-Entwicklung der Schweiz, 2022-06-15. URL: https://www.seco.admin.ch/seco/de/home/wirtschaftslage---wirtschaftspolitik/wirtschaftspolitik/Wachstumpolitik/szenarien_bip-entwicklung_schweiz.html.

Streicher, K., Allan, J., Murray, P., Bollinger, A., Marcucci, A., 2020. Energy Efficiency from buildings retrofitting. Technical Report. U. Geneva, EMPA and ETH Zurich - JASM. doi:`10.3929/ethz-b-000540991`.

Suisse Eole, 2020. Windenergiestrategie: Winterstrom und Klimaschutz – Analyse und Aktualisierung des Potenzials der Windenergie in der Schweiz. Technical Report. Suisse Eole, EnergieSchweiz and BFE. URL: https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/wind-energy.html.

Swiss Federal Council, 2019. 2050 climate target. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/news-releases.msg-id-76206.html.

Swiss Federal Council, 2021. Switzerland's Long-Term Climate Strategy. URL: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target/climate-strategy-2050.html.

VBSA, 2020. Monitoring-Bericht zur CO2-Branchenvereinbarung für das Jahr 2020. Technical Report. Betreiber Schweizerischer Abfallverwertungsanlagen. URL: https://vbsa.ch/fakten/downloads/.

VSE, 2012. Wege in die neue Stromzukunft. Technical Report. Verband Schweizerischer Elektrizitätsunternehmen. URL: https://www.strom.ch/de/media/7496/download.

Walch, A., Castello, R., Mohajeri, N., Scartezzini, J.L., 2020. Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty. Applied Energy 262, 114404. URL: http://www.sciencedirect.com/science/article/pii/S0306261919320914, doi:`10.1016/j.apenergy.2019.114404`.

WEC, 2019. World Energy Scenarios 2019 – Exploring Innovation Pathways to 2040. Technical Report. World Energy Council. URL: https://www.worldenergy.org/publications/entry/world-energy-scenarios-2019-exploring-innovation-pathways-to-2040.

Wüest Partner, 2019. Entwicklung Energiebezugsflächen EBF 1990-2019, jährliches Update. URL: https://www.bfe.admin.ch/bfe/en/home/supply/statistics-and-geodata/energy-statistics/analysis-of-energy-consumption-by-specific-use.html.