CROSS Scenarios v2022-09

Modelling protocol

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1 Introduction

This modelling protocol summarizes the assumptions for the CROSS scenarios version **CROSS-v2022-09** (Marcucci et al., 2022). It includes:

1. The assumptions related to the scenario definition, i.e. CO_2 target (translated into electricity demand for models of the electricity sector) and import limits (Section 2);
2. and reference values and ranges for other variables that are relevant for the development of the future Swiss energy system (Section 3), including: population; gross domestic product (GDP); energy reference area (ERA); heating degree days (HDDs); energy services demands; availability of domestic resources; and prices of imported fuels.

2 Scenarios definition

The CROSS scenarios V2022-09 are defined along two dimensions: climate policy and energy market integration.

Climate policy dimension

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). Following the Swiss Climate Strategy (Swiss Federal Council, 2021), the net-zero target considers GHG emissions in all sectors, including agriculture and industry, which means that the energy sector should compensate for emissions difficult to avoid in other sectors. The net-zero target for the energy sector is, therefore, -5.7 $MtCO_2$[1] (see Marcucci et al. (2022) for the detailed estimation). The Swiss Climate Strategy (Swiss Federal Council, 2021) does not determine specific domestic and international shares for emission reductions. Hence, we consider two variants:

- 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 partial use of Internationally transferred mitigation outcomes (ITMOs), at most 5.7 $MtCO_2e$. 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 1 summarizes the values for each variant. In both variants, we assume that Switzerland has access to carbon storage abroad.

Energy market integration dimension

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, synthetic fuels and hydrogen (Table 1).

[1] Although, the Swiss Climate Strategy also includes the emissions from international aviation and shipping attributable to Switzerland, we do not include them in the CROSS-v2022-09 scenario definition.

Scenario overview

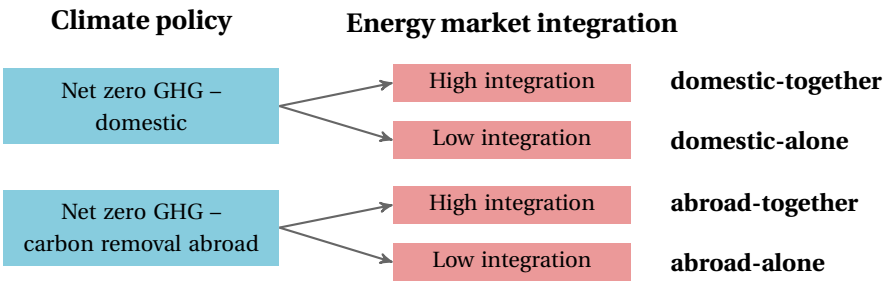

Figure 1: CROSS-v2022-09 scenarios overview

Figure 1 depicts the overview of the scenarios, resulting by combining the two dimensions previously described. Table 1 presents the values needed to implement the CROSS scenarios. This also includes the corresponding electricity demand for electricity sectoral models. These demands are based on the results from the first round of scenarios presented in January, 2023.

Table 1: CROSS scenarios v2022-09. All values are for the year 2050

Dimension and variables	**Variant**	
Climate change policy dimension		
	Net zero GHG – domestic	**Net zero GHG – carbon removal abroad**
Carbon removal domestic	-5.7 $MtCO_2$	0 $MtCO_2$ to -5.7 $MtCO_2$
Carbon removal abroad	0 $MtCO_2$	Up to -5.7 $MtCO_2$
Corresponding electricity demand	79 TWh	76 TWh
Energy market integration dimension		
	Low	**High**
Electricity	30% of NTC can be utilized	100% of NTC can be utilized
Biofuels and biomass	No imports at all	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	No imports at all	Upper limit on annual imports in 2050 of 64 PJ, Scenario Zero-C (BFE, 2020c)
Hydrogen	No imports at all	Upper limit on annual imports in 2050 of 40 PJ

3 Reference values for model input parameters

This section summarizes values for different input parameters of energy system models. The complete description of the estimation can be found in Marcucci et al. (2022).

3.1 Population, GDP and HDDs

Table 2: Population, GDP and HDDs

	2010	2020	2030	2040	2050	2010–2050	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)
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)
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)
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)
Heating degree days (HDDs)							
RCP2.6	3770	3351	3296	3248	3219	−0.39% p.a	Berger and Worlitschek (2019)
RCP4.5	3770	3350	3255	3166	3080	−0.50% p.a	Berger and Worlitschek (2019)
RCP8.5	3770	3353	3254	3141	2993	−0.57% p.a	Berger and Worlitschek (2019)

Data available at https://sweet-cross.ch/data/macroeconomic-drivers-cross/2022-09-30/ and https://sweet-cross.ch/data/heating-degree-days-cross/2022-09-30/

3.2 Building stock - Energy reference area (ERA)

The total ERA for the different sectors is shown in Table 3 and the ERA for the residential sector by age and building type in Table 4.

Table 3: ERA by sector (Mm2)

	2010	2020	2030	2040	2050	2020–2050
Residential (Mm2)						
Reference	461.7	487.2	535.5	573.9	600.5	0.70% p.a.
High	461.7	487.2	548.4	605.2	652.5	0.98% p.a.
Low	461.7	487.2	522.3	541.1	544.7	0.37% p.a.
Commercial (Mm2)						
Reference	219.8	230.4	244.3	257.3	266.2	0.48% p.a.
High	219.8	230.4	248.7	267.8	283.8	0.70% p.a.
Low	219.8	230.4	239.9	246.2	247.4	0.24% p.a.
Industry (Mm2)						
Reference	91.3	94.5	98.5	104.1	109.2	0.48% p.a.
High	91.3	94.5	99.1	106.0	112.3	0.58% p.a.
Low	91.3	94.5	98.1	102.4	106.1	0.39% p.a.

Data available at https://sweet-cross.ch/data/era-cross/2022-09-30/

Table 4: 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
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/2022-09-30/

3.3 Energy service demands

From the harmonized drivers in Table 2 and the ERA in Table 3, we calculate the future energy service demands in the different end-use sectors (see details of the estimation in Marcucci et al. (2022)). All the demands estimated in this section correspond to end-use energy demand (EUD).

Table 5: Space heating end-use demand before energy efficiency measures (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.
	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.

Table 5: Space heating end-use demand before energy efficiency measures (TWh) (continued)

	Climate	2010	2019	2025	2030	2040	2050	2010–2050
	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.
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.
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.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/2022-09-30/

Table 6: 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.
Commercial (TWh)							
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.
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.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/2022-09-30/

Table 7: 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.

Table 7: Process heat end-use demand (TWh) (continued)

	2010	2019	2025	2030	2040	2050	2010–2050
Low	0.47	0.52	0.54	0.56	0.61	0.67	0.89% p.a.
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.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/2022-09-30/

Table 8: 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.
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.
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.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/2022-09-30/

Table 9: Transport demand

	2010	2019	2025	2030	2040	2050	2010–2050
Passenger transport demand (Billion passenger-kilometer)							
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.
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.
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.
Freight transport demand (Billion ton-kilometer)							

Table 9: Transport demand (continued)

	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.
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.

Data available at https://sweet-cross.ch/data/end-use-energy-demand-cross/2022-09-30/

3.4 Resources

Table 10: 2050 potential of renewable resources

Resource	Variant			Reference
	Reference	High	Low	
Hydropower (TWh/a)	36.4	38.4	34.8	Boes et al. (2021)
Solar photovoltaics (TWh/a)				
Rooftop	40	50	30	High: BFE (2019), Low: Bauer et al. (2019)
Facades	4	8	0	High: Remund et al. (2019)
Mountains	3	30	0	Reference: Remund et al. (2019), High: Dujardin et al. (2021)
Total	47	88	30	
Wind (TWh/a)	4.3	15.0	1.7	Reference: BFE (2020c), High: Dujardin et al. (2021), Low: Cattin et al. (2012)
Biomass (PJ/a)				Guidati et al. (2021)
Wood				
Forest Wood				
Continued stock increase	26.0	26.0	26.0	
Moderate stock reduction	32.3	32.3	32.3	
Large stock reduction	39.4	39.4	39.4	
Wood from landscape	4.8	4.8	4.8	
Wood residues	7.7	7.7	7.7	
Waste wood	17.0	18.4	15.5	
Animal manure (dry)	26.3	26.3	26.3	
Green waste				
Collected organic waste	9.1	9.8	8.3	
Agricultural bioproducts	2.6	2.6	2.6	
Fresh sewage sludge (dry)	6.1	6.6	5.7	
Mixed fossil / organic waste (PJ/a)				Guidati et al. (2021)
Other waste fraction	42.1	45.7	38.6	
Municipal waste	31.7	34.4	29.0	
including green waste	*1.2*	*1.3*	*1.1*	

Data available at https://sweet-cross.ch/data/biomass-potentials-cross/2022-04-05/

3.5 Imports and exports

Table 11: Import price of energy carriers (CHF/GJ). Prices are based on the WEO 2021 (IEA, 2021) and are adjusted using recent developments. The table also includes the prices in the WEO 2021 and the BAU ans Zero basis scenarios in the EP2050+

	2017	2020	2030	2040	2050	2020–2050	Reference
Oil							
Stated policies		6.9	12.6		14.4	2.5 % p.a.	IEA (2021)
Reference		6.9	9.6	9.0	8.3	0.64% p.a.	CROSS
High		6.9	13.3	14.3	14.7	2.56% p.a.	CROSS
Low		6.9	6.1	4.9	4.1	−1.71% p.a.	CROSS
Net zero		6.9	5.9		3.9	−1.85% p.a.	IEA (2021)
Sustainable development		6.9	9.2		8.2	0.58% p.a.	IEA (2021)
Announced pledges		6.9	11.0		10.5	1.41% 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		4.0	5.0	4.9	4.9	0.7 % p.a.	CROSS
High		4.0	9.2	9.0	9.3	2.86% p.a.	CROSS
Low		4.0	4.6	4.2	3.9	−0.08% p.a.	CROSS
Net zero		4.0	3.7		3.4	−0.51% p.a.	IEA (2021)
Sustainable development		4.0	4.0		4.3	0.23% p.a.	IEA (2021)
Announced pledges		4.0	6.2		6.2	1.47% p.a.	IEA (2021)
Stated policies		4.0	7.3		7.9	2.3 % 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. (2021)
High	43.4	42.7	56.4	65.7	70.8	1.7 % p.a.	Marcucci et al. (2021)
Low	43.4	42.7	41.4	40.1	40.1	−0.22% p.a.	Marcucci et al. (2021)
Ethanol							
Reference	29.7	30.4	39.4	41.9	44.3	1.27% p.a.	Marcucci et al. (2021)
High	29.7	30.4	48.2	59.2	64.1	2.52% p.a.	Marcucci et al. (2021)
Low	29.7	30.4	30.6	24.6	24.6	−0.7 % p.a.	Marcucci et al. (2021)
Hydrogen							
Reference	0	26.9	40.1	42.7	44.7	1.7 % p.a.	Marcucci et al. (2021)
High	0	26.9	41.6	44.4	52.1	2.23% p.a.	Marcucci et al. (2021)
Low	0	26.9	38.5	41.1	37.3	1.09% p.a.	Marcucci et al. (2021)

Data available at https://sweet-cross.ch/data/import-prices-cross/2022-09-30/

Table 12: Annual net transfer capacities (GW) from ENTSO-E (2022a,b)

		TYNDP22 scenario					
		Distributed Energy			**Global Ambition**		
From-to	**2020**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Switzerland–Germnay	4.0	4.3	4.3	4.3	4.9	4.9	4.9
Switzerland–France	1.4	1.9	1.9	2.9	1.9	2.9	2.9
Switzerland–Italy	3.9	4.0	4.0	4.0	3.8	5.0	5.0
Switzerland–Austria	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Germany–Switzerland	2.7	3.6	3.6	3.6	3.9	3.9	3.9
France–Switzerland	3.7	5.2	5.2	6.2	5.2	6.2	6.2
Italy–Switzerland	1.9	1.9	1.9	1.9	1.7	2.9	2.9
Austria–Switzerland	1.2	1.2	1.2	1.2	1.2	1.2	1.2

Data available at https://sweet-cross.ch/data/net-transfer-capacities/2022-12-13/

3.6 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).

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Abbreviations

$BCHF_{2017}$	Billion Swiss Franc 2017
CCS	Carbon capture and storage
CHF	Swiss Franc
ERA	Energy reference area
EUD	End-use demand
GDP	Gross Domestic Product
HDD	Heating degree day
ITMO	Internationally transferred mitigation outcome
MFH	Multi family house
NET	Negative Emission Technology
RCP	Representative concentration pathway
SFH	Single family house