ENERGY [R]EVOLUTION:
100% Renewable Energy for Switzerland

2020

UTS Institute for Sustainable Futures

ABOUT THE AUTHORS

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government, and the community to develop sustainable futures through research and consultancy. Our mission is to create change towards establishing sustainable futures that protect and enhance the environment, human well-being, and social equity. We use an inter-disciplinary approach to our work and engage our partner organizations in a collaborative process that emphasises strategic decision-making.

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CO-OPERATION PARTNER

This project has been conducted in co-operation with Georg Klingler Heiligtag, Leader of the Climate and Energy Unit at Greenpeace Switzerland.

ENERGY MODELS

The utility-scale solar photovoltaic and wind power potentials were mapped with [R]E-SPACE, a mapping tool developed by the Institute for Sustainable Futures of the University of Technology Sydney (ISF-UTS) based on QGIS (open source).

The long-term energy scenario software used for the long-term projections and economic parameters is based on the development of the German Aerospace Centre (DLR), Institute for Technical Thermodynamics, (Pfaffenwaldring 38-40, 70569 Stuttgart, Germany), and has been applied to over 100 energy scenario simulations for global, regional, and national energy analyses.

Regional *Power Analysis* calculated with [R]E 24/7 was developed by Dr. Sven Teske (PhD), with further developments by ISF-UTS.

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All conclusions and any errors that remain are the authors' own.

DISCLAIMER

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EXECUTIVE SUMMARY

Greenpeace Switzerland commissioned this report to examine how Switzerland could reach its commitments under the Paris Agreement to stay within a temperature rise of 1.5 °C globally and end the use of nuclear power. Three different scenarios are calculated: a REFERENCE scenario, based on current political goals to reach net zero green-house-gas emissions in 2050 (Prognos 2020, NET-ZERO scenario, published in '*The Energy Perspectives 2050+*'), and the two Energy [R]evolution scenarios, showing how the decarbonization goals can be reached earlier.

The socio-economic parameters used for all three scenarios are the same as those used in the energy scenarios of the Federal Office for Energy Uses, published in November 2020:

		2018	2020		2025	2030	2035	2040	2045	2050
			Reduced	Stable						
GDP	[billion CHF/a]	633	590	652	691	731	772	814	846	880
GDP/Person	[CHF/capita]	73,472	66,636	73,613	75,272	77,045	78,682	81,464	83,578	85,836
Population	[million]	8.6	8.7		9.2	9.5	9.8	10.0	10.1	10.3
			2020		2020–2025	2025–2030	2030–2035	2035–2040	2040–2045	2045–2050
Economic growth	[%/a]		−7.7%	+1.00%	1.15%	1.15%	1.10%	1.05%	0.78%	0.80%
Population growth	[%/a]		0.60%		0.70%	0.68%	0.68%	0.35%	0.27%	0.26%

Renewable energy potentials and restrictions

Switzerland has a largely untapped potential for renewable energy. Hydro power is utilized extensively and currently supplies more than half the country's electricity; bio-energy supplies about 14% of the heating demand, whereas solar and wind have the largest unutilized potentials.

<u>Solar photovoltaic:</u> If solar photovoltaic (PV) panels can be used in all areas, excluding slopes steeper than 30%—reduces this potential by the untapped potential is at minimum 54 GW. Where the land available for this purpose it is restricted by its proximity to power lines or the terrain slope, the solar potential will decrease by another 31% to 37 GW. Under this scenario, Switzerland has over 420 km^2 of land on which 16.9 GW of solar PV could potentially be harvested by utility-scale solar farms. There is also a huge unused potential for roof-top and facade installations in Switzerland: up to 485 km^2 could be used, which would translate into a total annual generation of 41 TWh/a (41 GW).

<u>Wind power:</u> Switzerland's total installed wind power capacity at the end of 2019 was 75 MW, with 39 turbines. Based on its terrain and the density of biodiversity and population hotspots, the maximum potential for wind power use in Switzerland is estimated by leading environmental organisations to involve a total of 400 machines. Large turbines of 6 MW capacity will provide an untapped potential of 2.4 GW.

The Energy [R]evolution scenario requires 354 turbines with a total installed capacity of 2.1 GW, whereas the ADVANCED scenario uses the entire 2.4 GW of potential.

Assumptions for both Energy [R]evolution scenarios

The Energy [R]evolution scenarios are designed to meet Switzerland's energy-related targets and to lead towards the use of over 90% renewable energy by 2040 and an entire fossil-fuel phase-out by 2050. This energy transition towards full decarbonization focuses on the power, residential building, and transport sectors. The replacement of fuels with electrification is at the core of the Energy [R]evolution concept, whereas the decarbonization of process heat for industry relies, to large extent, on bio-energy fuel co-generation and heating plants. The implementation of energy efficiency and renewable energy generation technologies will show ambitious growth rates during the first decade until 2030. Electric mobility will grow steadily over the entire modelling period, and the growth rates will increase significantly from 2025 onwards after an initial preparation phase. Switzerland's aging nuclear power capacity will be phase-out by 2030 and be replaced by a mix of energy efficiency and renewable power generation—mainly solar PV.

Assumptions for the ADVANCED Energy [R]evolution scenario

The ADVANCED Energy [R]evolution scenario builds on the Energy [R]evolution scenario, following similar technology pathways, but differs in three main sectors, as follows:

a. Transport—a shift in transport modes to accelerate oil phase-out. Whereas the implementation of electric mobility will follow the same pace as in the Energy [R]evolution scenario, cars with combustion engines will be replaced by a more ambitious reduction in individual transport. The use of cars will decrease by 1.5% per year between 2020 and 2025 and by 2% per year between 2025 and 2040. By 2040, more than one third of all passenger transport will be shifted away from cars towards public transport and (electric) bikes.

b. Buildings—oil heater exchange by 2030. The second major difference from the Energy [R]evolution scenario is an ambitious room-heating program, which will replace all the oil heaters used in Switzerland with a mix of efficiency gains (building insulation), heat pumps, and solar collectors, which will deliver about one quarter of the required heating energy in buildings by 2050.

c. Industry—accelerated phase-out of natural gas. Requirements for industrial process heat will be met by an increased share of hydrogen and synthetic fuels, produced with renewable electricity. The level of bio-energy will remain the same and will not increase between 2020 and 2050.

Development of Switzerland's final energy demand

Under the REFERENCE scenario, the total final energy demand will decrease by 29% from the current 700 PJ/a to 500 PJ/a in 2050. Under the Energy [R]evolution scenario, the final energy demand will decrease by 43% compared with current consumption and is expected to reach 400 PJ/a by 2050. The ADVANCED Energy [R]evolution scenario will result in some additional reductions due to a higher share of electric cars.

Under both Energy [R]evolution scenarios, the overall electricity demand is expected to increase with economic growth, increasing living standards, and the electrification of the transport sector, despite efficiency gains in all sectors (see Figure 12). The total electricity demand will increase from about 60 TWh/a to 72 TWh/a by 2050 under the Energy [R]evolution scenario. Additional efficiency measures in the industry, residential, and service sectors will avoid the generation of about 10 TWh/a compared with the REFERENCE scenario.

This reduction will be achieved, in particular, by introducing highly efficient electronic devices using the best available technology in all demand sectors. The transformation to a carbon-free energy system under the ADVANCED scenario will require the generation of 100 TWh annually by 2050. Electricity will become the major renewable 'primary' energy, not only for its direct use for various purposes but also for the generation of the synthetic fuels that will substitute for fossil fuels. Around 20 TWh will be used in 2050 for electric vehicles and rail transport under the ADVANCED Energy [R]evolution, and around 1.8 TWh for hydrogen for the transport sector.

Efficiency gains in the heating sector will be even larger than in the electricity sector. Under the Energy [R]evolution scenarios, consumption equivalent to about 10 PJ/a will be avoided through efficiency gains by 2050 compared with the REFERENCE scenario. With the energy-related renovation of the existing stock of residential buildings, the introduction of low-energy standards and 'passive climatization' for new buildings, and highly efficient air-conditioning systems, the same comfort and energy services will be accompanied by much lower energy demand in the future.

Development of electricity generation

The development of the electricity supply sector will be characterized by a dynamically growing renewable energy market and an increasing share of renewable electricity. This trend will more than compensate for the phasing out of nuclear power production under the Energy [R]evolution scenarios, and the continuous reduction of the number of fossil-fuel-fired power plants. By 2050, 100% of the electricity produced in Switzerland will come from renewable energy sources under the Energy [R]evolution scenario. 'New' renewables—mainly wind and solar PV electricity—will contribute 50% to the total electricity generated. The share of renewable electricity production will be 90% by 2025 and 100% by 2030. The installed capacity of renewables will reach about 31.6 GW in 2030 and 54.4 GW by 2050.

In GW		2018	2025	2030	2040	2050
Hydro	REF	13.372	13.572	13.914	14.588	14.226
	E[R]		13.538	13.606	13.674	13.746
	ADV E[R]		13.538	13.606	13.674	13.746
Biomass	REF	0.369	0.478	0.533	0.653	0.797
	E[R]		0.484	0.755	0.844	0.900
	ADV E[R]		0.472	0.735	0.905	1.015
Wind	REF	0.075	0.475	0.695	1.087	1.943
	E[R]		0.614	1.150	1.639	2.122
	ADV E[R]		0.626	1.893	2.334	2.400
Geothermal	REF	0.000	0.061	0.122	0.199	0.325
	E[R]		0.028	0.050	0.129	0.190
	ADV E[R]		0.003	0.005	0.009	0.018
PV	REF	2.090	3.119	4.520	14.828	25.356
	E[R]		12.044	16.042	31.173	38.179
	ADV E[R]		11.826	17.782	36.257	44.250
Total	REF	15.905	17.709	19.865	31.363	42.655
	E[R]		26.708	31.602	47.459	55.136
	ADV E[R]		26.465	34.021	53.179	61.433

Power sector analysis for Switzerland

Both Energy [R]evolution scenarios prioritize the use of regional hydro and solar power generation to rapidly decarbonize the electricity supply. Switzerland will increase its power demand under each scenario with the implementation of electric mobility and electric heating.

By 2030, variable power generation will reach over 45% in all regions, whereas the proportion of dispatchable renewables—bio-energy and hydro power—will remain over 40% in all regions, except in Wallis (29%) and the West sub-region (39%).

The current actual interconnection capacities between all regions seem sufficient under all three scenarios until 2030. The modelling results indicate that the planned upgrades of the transmission grids within Switzerland, published in *Strategic Grid 2025*[1], will be sufficient.

Switzerland operates a large fleet of run-of-river hydro power plants with and without water reservoir storage capacities and pumped hydro storage (PHS) facilities, and is therefore in a comfortable position to integrate large amounts of variable solar PV power generation. After the full utilization of the PHS capacity of 2,562MW—with an average annual throughput of 1,554 GWh for the integration of variable solar power generation—peak-shaving will still be required.

With peak-shaving, solar production spikes can be reduced with minor effect on the overall annual generation because there will be relatively few peak events. The assumed "economic curtailment rate" for all three scenarios with be up to 5%—for the annual generation (in GWh/a) of solar PV and onshore wind—until 2030, and 10% between 2031 and 2050. To build up the additional storage capacity required, we assume that a percentage of the solar PV capacity will be installed with battery storage. The suggested solar battery system should be able to store the entire peak capacity for 4 full-load hours.

The Energy [R]evolution scenario will require 20% of all PV systems to be equipped with the described battery technology by 2030, whereas under the ADVANCED Energy [R]evolution] scenario, it must be

[1] SwissGrid 2015, Bericht zum Strategischen Netz 2025, https://www.swissgrid.ch/dam/swissgrid/projects/strategic-grid/sg2025-technical-report-de.pdf

40%. In 2050, 35% of all PV installations under the Energy [R]evolution scenario and 50% under ADVANCED Energy [R]evolution must have batteries. The total investment costs in storage technologies required between 2035 and 2050 are calculated to be CHF 183 million under the REFERENCE scenario, CHF 2.7 billion for the Energy [R]evolution scenario, and CHF 4.0 billion under the ADVANCED Energy [R]evolution scenario.

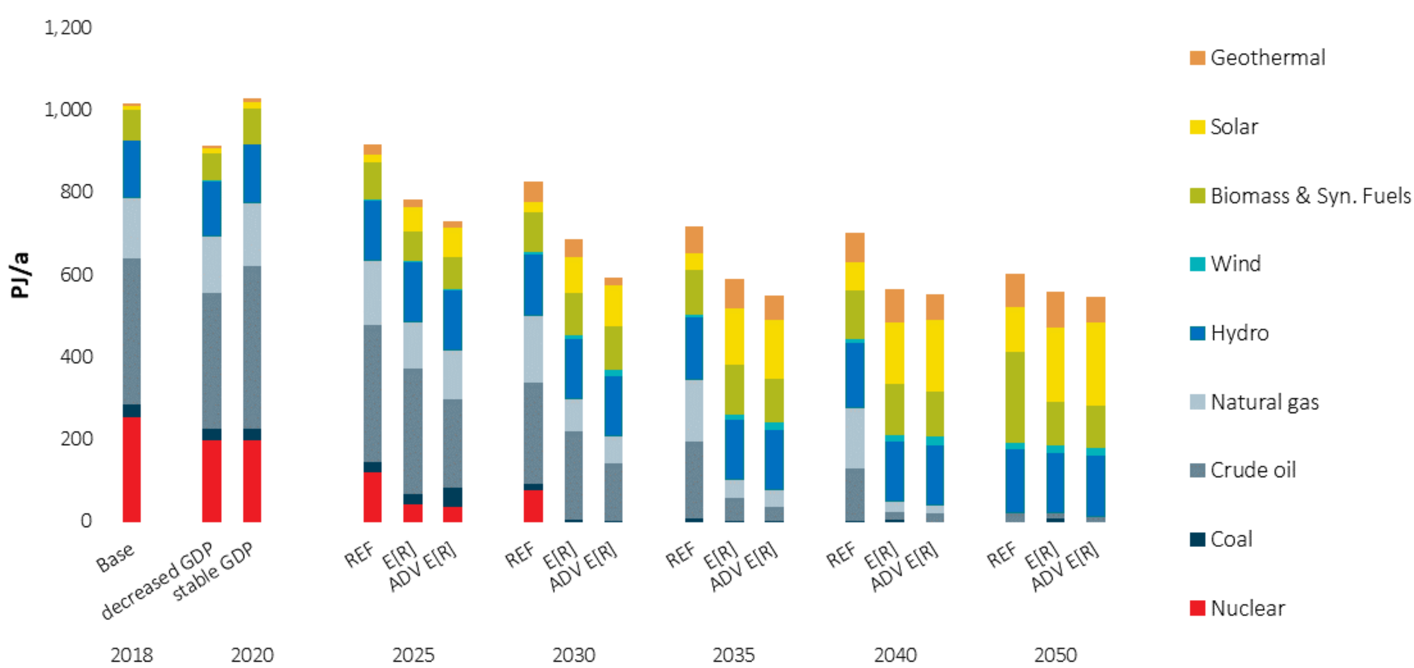
To conclude, a large solar PV power generation share of around 50% by 2050 is feasible for Switzerland under the documented assumptions.

Development of primary energy consumption

Under the Energy [R]evolution scenario, the primary energy demand will decrease by 45% from today's 1010 PJ/a to around 560 PJ/a in 2050. The overall primary energy demand will be reduced by 13% in 2050 under the Energy [R]evolution scenario compared with the REFERENCE scenario (around 40 PJ in 2050). The ADVANCED Energy [R]evolution scenario will result in a primary energy consumption of 549 PJ in 2050.

Both Energy [R]evolution scenarios aim to phase-out coal and oil as fast as is technically and economically possible through the expansion of renewable energies and the rapid introduction of very efficient vehicles in the transport sector to replace oil-based combustion engines. This will lead to an overall renewable primary energy share of 54% in 2030 and 100% in 2050 under the Energy [R]evolution scenario and of more than 100% in 2050 under the ADVANCED Energy [R]evolution scenario (including non-energy consumption).

Projection of total primary energy demand by energy carrier (including electricity import balance)



Development of carbon emissions

Based on the need for the global carbon budget to remain below a +1.5 °C increase in temperature and to achieve the Paris Climate Agreement goals—and Switzerland's share of the world's population—Greenpeace Switzerland calculated Switzerland's equity carbon budget until 2050 to be 0.120 Gt CO_2.

To achieve this target, a combination of a rapid decarbonization of the energy sector and the accounting of emission credits from outside Switzerland is required. The energy transition towards 100% renewable energy will requires significant changes and around 20 years—even under the most optimistic assumptions. Whereas the decarbonization of the electricity sector seems possible within one decade, the heating and transport sectors will require infrastructural changes that will take more time and therefore generate more CO_2 emissions.

All scenarios will lead to the phase-out of energy-related carbon emissions in Switzerland by 2050. However, the cumulative emissions between 2017 and 2050 will differ significantly under the different scenarios. The REFERENCE scenario will generate almost twice the emissions (0.85 Gt CO_2) as the ADVANCED Energy [R]evolution scenario.

Comparison of cumulative energy-related carbon dioxide emissions under the three scenarios

Switzerland	2019	2030	2050	SUM 2017–2030 [Gt CO_2]	Change relative to REF [Gt CO_2] (billion tones)	SUM 2015–2050 [Gt CO_2]	Change relative to REF [Gt CO_2] (billion tones)
Reference	40	29	0	0.499		0.804	
Energy [R]evolution	38	21	0	0.447	0.052	0.534	0.270
ADVANCED Energy [R]evolution	39	17	0	0.420	0.080	0.489	0.315

To achieve net zero carbon emissions by 2030, a compensation of 87 million tons of CO_2 (between 2030 and 2050) will be required under the Energy [R]evolution scenario and 69 million tons of CO_2 under the ADVANCED Energy [R]evolution scenario.

To remain within the equity carbon budget of 120 million tons of CO_2 between 2017 and 2050, a compensation of 684 million tons of CO_2 will be required under the REFERENCE scenario, 414 million tons of CO_2 under the Energy [R]evolution scenario, and 369 million tons of CO_2 under the ADVANCED scenario.

Nature-based carbon sinks will be required even when the global energy-related carbon emissions have been reduced in line with a global 1.5 °C energy pathway. However, implementing the required carbon removal pathways seems to be more challenging than the energy transition itself. To start the reversal of deforestation and the emission trends arising from land-use and to support sustainable agriculture and forest management, new programs must be commenced, especially in developing countries. Deforestation, especially of tropical rainforest, has accelerated in recent years, and new business models for forest management and reforestation programs are urgently required.

The implementation of the equity carbon budget for Switzerland is possible through a compensation scheme that focuses on forest management and reforestation. With a reliable and long-term carbon price, the protection of primeval forests and reforestation can bring more economic benefits than their destruction. For developing countries, it is fundamentally important that regional resources are used economically. Natural forests play a vital role in global climate protection and thus the preservation of the basis of life on the entire earth. The economic system must be adapted accordingly, so that the preservation of these ecosystems is economically more interesting than their short-term exploitation—which will inevitably leads to their destruction. Switzerland can play an important pioneering role here and establish bilateral agreements with developing countries.

1. METHODOLOGY AND ASSUMPTIONS

This report provides a technical and economic analysis of the long-term energy and power development plans for Switzerland, in the very centre of Europe.

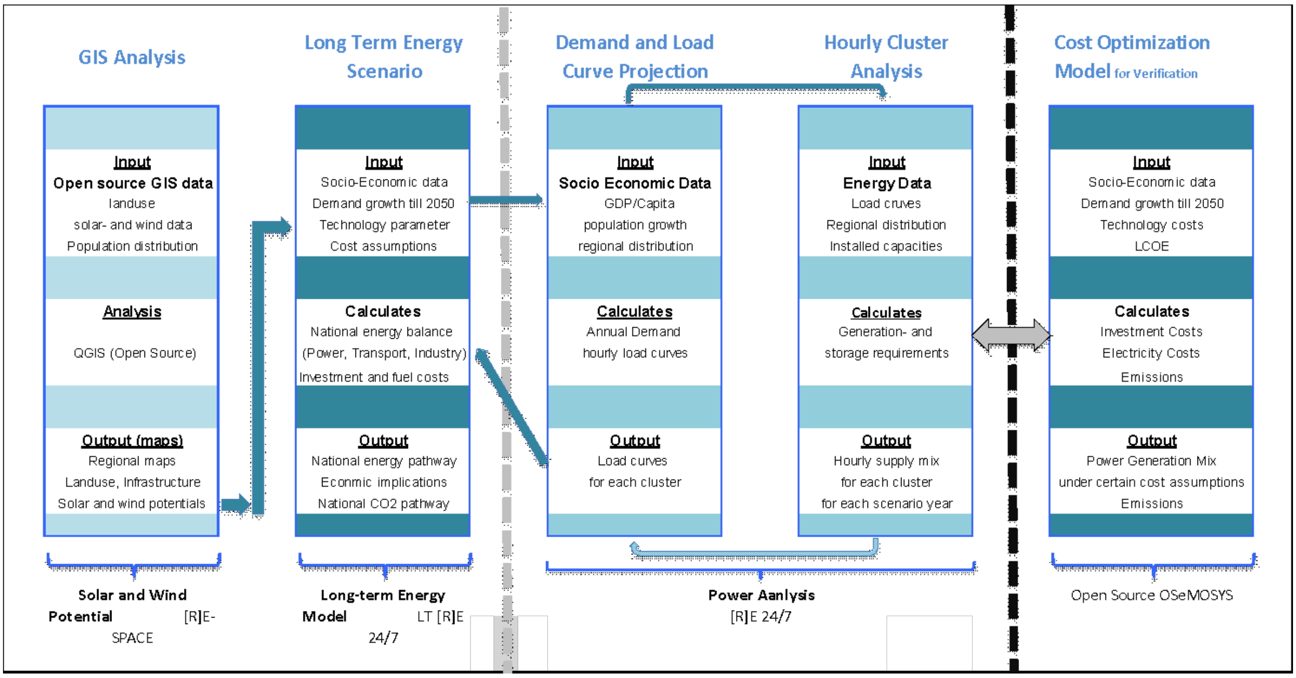
The analysis is based on the [R]E 24/7 energy access pathway methodology developed by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS) and on the long-term energy scenario model of the Institute for Thermodynamics of German Aero Space Centre (DLR), and energy models developed for various UTS-ISF surveys. The following section explains the methodology and provides an overview of the required input parameters, basic functions, and calculated outputs. The entire modelling process is based on four modules developed by UTS-ISF. The models are described below in their order of use.

For the mapping analysis, a global information system (GIS) was used for the regional analysis of Switzerland's population density and distribution, its solar and wind resources, and the currently existing energy infrastructure (transmission power lines and power plants with over 100 MW of installed capacity). This information has been used to define the cluster breakdown.

The long-term scenario LT [R]E 24/7 has been used to re-model the existing power development plan and to develop alternative national energy pathways for Switzerland. This model takes all sectors into account (power, heat, and transport) and includes costs and energy-related CO_2 calculations.

The [R]E 24/7 power sector analysis tool computes the annual demand for up to five different years (here 2020, 2030, 2040, and 2050) and the load curves for a full year (8760 h). The hourly load curves are required to simulate the demand and supply for each of the eight regions of Switzerland. The results are the development of loads, the generation mix, and the storage demand.

Figure 1: Overview—Modelling concept



1.1 [R]E 24/7—GIS Mapping tool

The primary purpose of GIS mapping is to ascertain the renewable energy resources (primarily solar and wind) available in Switzerland. It also contributes to the regional analysis of geographic and demographic parameters and the available infrastructure that can be leveraged in developing the scenarios.

Mapping was performed with the computer software QGIS, which analyses and edits spatial information and constructs and exports graphical maps. It has been used to allocate solar and wind resources and for the demand projections for each calculated region. Population density, access to electricity, and the distribution of wealth, or the economic development projections, are key input parameters in the region-specific analysis of Switzerland's future energy situation.

Open-source data and maps from various sources have been used to visualize the country and its regions and districts. Further demographic data related to population and poverty, as well as transmission networks and power plants, are also plotted on the maps. The main data sources and assumptions made for this mapping are summarized in the table below.

Table 1: [R]E 24/7—GIS-mapping—data sources

Data	Assumptions	Source
Land use/land cover	Land cover types of bare soil, annual cropland, perennial cropland, and grassland were included in the wind analysis. Only land cover types of bare soil, perennial cropland, and open bushland were included in the solar analysis.	World Bank: ESMAP
Elevation	For both wind and solar analyses, any land with a slope of more than 30% was ignored.	Open DEM
Population density	Estimates of numbers of people per pixel (ppp), with national totals adjusted to match UN population division estimates.	WorldPop
Power plants	The Global Power Plant Database is a comprehensive, open-source database of power plants around the world.	Global power plant database, World Resource Institute
Solar irradiance	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m^2 per year.	Solar GIS
Transmission lines and network	Only those sites within 10 km of an existing transmission line were included in the analysis.	EnergyData.info
Wind speed	Wind speeds above 6 m/s were considered at a height of 80 m	Global wind atlas

The areas of land available for potential solar and wind power generation were calculated at both the national and regional levels using the ellipsoidal area tool in the QGIS processing toolbox. Intersects were created between the transmission level layers and the solar/wind utility vector layers to break down the total land area available by cluster. A correction was made for sites that intersected the cluster boundaries and were part of the two transmission levels. This input was fed into the calculations for the [R]E 24/7 model, as described below.

1.2 Long-term Scenario Modelling

Historically, heating, electricity, and mobility have been separated in terms of their energy sources, requiring different infrastructures and therefore different planning: electricity for stationary power, petrol and diesel for mobility, and on-site heat for buildings and industrial processes. This will almost certainly change, with the increasing use of electricity for heating and mobility, such as in electric vehicles. This emerging '*sector coupling*' must be taken into account and requires an integrated approach across heat, mobility, and electricity/stationary power when developing future energy system scenarios, as is done in this model.

Three scenarios have been developed, a reference scenario and two alternative energy pathways. The assumptions for those scenarios are documented in section 3. The long-term (LT) modelling approach used in this research is based on the development of target-orientated scenarios. With this approach, a target is set and technical scenarios are developed to meet that target, and then compared with a reference scenario. The target can be set in terms of annual emissions and/or renewable energy shares. For Switzerland, an exogenous target of the complete decarbonization of the energy sector, with respect to the remaining CO_2 emissions budget (see section 4), has been considered for the two Energy [R]evolution scenarios. These scenarios are based on detailed input datasets that consider defined targets, renewable and fossil fuel energy potentials, and specific parameters for power, heat, and fuel generation in the energy systems. The datasets are then fed into LT-[R]E 247, which is based on a DLR model that uses the MESAP/PlaNet software, an accounting framework that calculates the complete energy system balance to 2050.

The LT-[R]E 24/7 model consists of two independent modules:

- a flow calculation module, which balances energy supply and demand annually; and
- a cost calculation module, which calculates the corresponding generation and fuel costs.

Note that this is not a dispatch model, such as the [R]E 24/7 power sector model used to calculate the future regional and hourly power, or a technical grid simulation (including frequency stability), such as DIgSILENT's PowerFactory, which is beyond the scope of this analysis.

The LT-[R]E 24/7 model is a bottom-up integrated energy balance model. Different modelling approaches each have their benefits and drawbacks. This model is particularly good at helping policy makers and analysts understand the relationships between different energy demand types in an economy—across all sectors and over a long time period, usually 30–40 years. In a simulation model, the user specifies the drivers of energy consumption, including the predicted population growth, GDP, and energy intensities.

Specific energy intensities are assumed for:

- electricity consumption per person;
- the ratios of industrial electricity and heat demand intensity to GDP;
- the demand intensities for energy services, such as useful heat;
- the energy intensities for different transport modes.

Electricity demand projections for the building and industry sectors are calculated with [R]E 24/7 (see section 4.4) as an input for the LT-[R]E 24/7 model of the alternative scenarios, but not for the REFERENCE scenario, for which they are taken from published scenarios for Switzerland (see Chapter 2 and Chapter 4).

The electricity demand for the transport sector has been calculated with the LT-[R]E 24/7 model. For both heat and electricity production, the model distinguishes between different technologies, which are characterized by their primary energy source, efficiency, and costs. Examples include biomass or gas burners, heat pumps, solar thermal, and geothermal technologies, and several power generation technologies, such as photovoltaics, wind, biomass, gas, coal, and combined heat and power (CHP). For each technology, the market share with respect to total heat or electricity production is specified based on a range of assumptions, including the renewable energy target, the potential costs, and societal, structural, and economic barriers.

The main outputs of the model are:

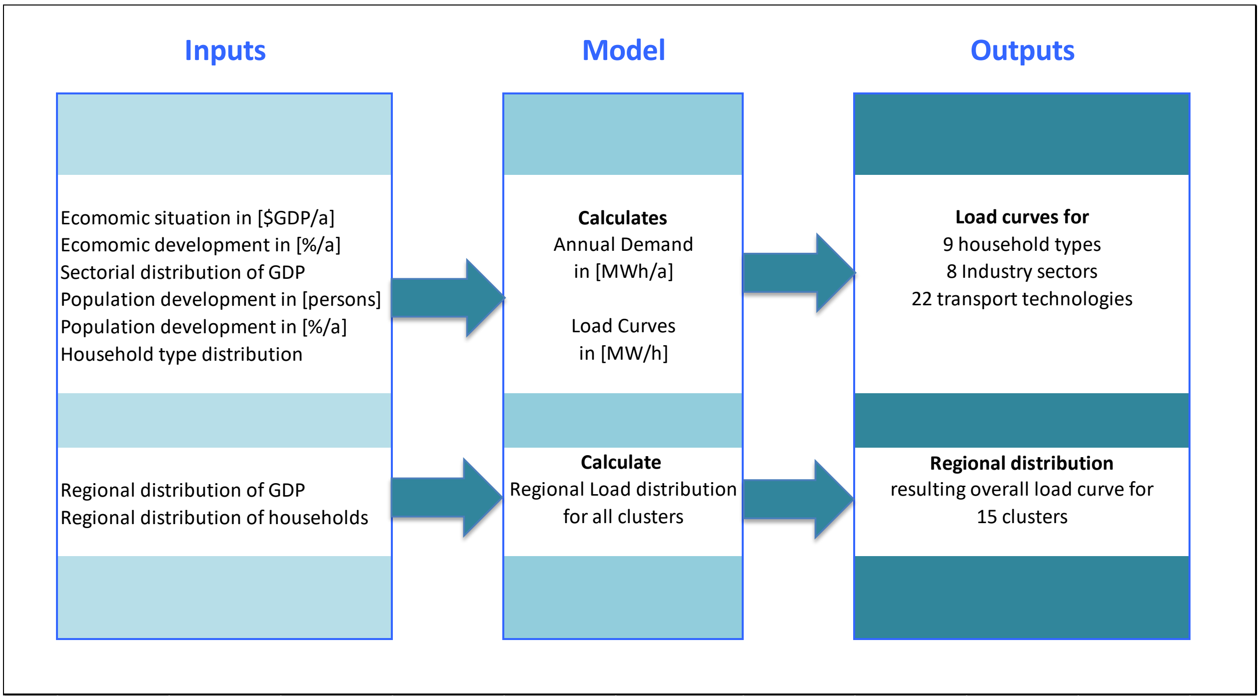
- the final and primary energy demands, broken down by fuel, technology, and sector of the economy, as defined by the International Energy Agency (IEA): industry, power generation, transport, or other (buildings, forestry, and fisheries)[2];
- the results broken down by the three main types of energy demand—electricity, heating, and mobility (transport); specifically, the energy required, technology deployment, and finance;
- the total energy budget, or the total cost of energy for the whole energy system;
- the energy-related greenhouse gas emissions over the projection period.

1.3 [R]E 24/7—POWER ANALYSIS

After the geographic analysis and the development of the long-term energy pathways for Switzerland, the power sector was analysed with the [R]E 24/7 module in a third step.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand based on the applications used, demand patterns, and household types allows a detailed forecast of the demand. Infrastructure needs, such as power grids combined with storage facilities, require an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis.

Figure 2: Overview—Energy demand and load curve calculation module



[2] Note these industry sectors correspond to IEA energy statistics input into the model.

1.3.1 Meteorological data

Variable power generation technologies are dependent on the local solar radiation and wind regimes. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database *renewable.ninja* (RE-N DB 2018)[3], which allows the simulation of the hourly power output from wind and solar power plants at specific geographic positions throughout the world. Weather data, such as temperature, precipitation, and snowfall, for the year 2014 were also available. To utilize climatization technologies for buildings (air-conditioning, electric heating), the demand curves for households and services were connected to the cluster-specific temperature time series. The demand for lighting was connected to the solar time series to accommodate the variability in lighting demand across the year, especially in northern and southern global regions, which have significantly longer daylight periods in summer and very short daylight periods in winter.

For every region included in the model, hourly output traces are utilized for onshore wind, utility solar, and roof-top solar photovoltaics. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future-generation systems, a representative site was selected for each of the five generation types.

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected from the database of Stefan Pfenninger (at ETH Zurich) and Iain Staffell (renewable.ninja; see above). The model methodology used by the renewable.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[4], and is based on weather data from global re-analysis models and satellite observations (Rienecker and Suarez 2011[5]; Müller and Pfeifroth, 2015[6]). It is assumed that the utility-scale solar sites will be optimized, and as such, the tilt angle was selected within a couple of degrees of the latitude of the representative site. For the roof-top solar calculations, this was left at the default of 35° because it is likely that the panels will match the roof tilt.

The wind outputs for onshore were calculated at an 80 m hub height because this reflects the wind datasets used in the mapping. Although onshore wind are likely be higher than this, 80 m was considered a reasonable approximation and made our model consistent with the mapping-based predictions. A turbine model of Vestas V90 2000 was used.

Limitations: The solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

[3] RE-N DB (2018) Renewables.ninja, online database of hourly time series of solar and wind data for a specific geographic position, data viewed and downloaded between May and July 2018, https://www.renewables.ninja/

[4] Pfenninger, S, Staffell, I. (2016a), Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251–1265. doi: 10.1016/j.energy.2016.08.060

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[5] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624–3648. doi: 10.1175/JCLI-D-11-00015.1

[6] Müller, R., Pfeifroth, U (2015), Müller, R., Pfeifroth, U., Träger-Chatterjee, C., Trentmann, J., Cremer, R. (2015). Digging the METEOSAT treasure—3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

1.4 Power Demand Projection and Load Curve Calculation

The [R]E 24/7 power analysis model calculates the development of the future power demand and the resulting possible load curves. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- households;
- industry and business; and
- transport.

Although each sector has its specific consumer groups and applications, the same set of parameters is used to calculate the load curves:

- electrical applications in use;
- demand pattern (24 h);
- meteorological data
  - sunrise and sunset, associated with the use of lighting appliances;
  - temperature and rainfall, associated with climatization requirements;
- efficiency progress (base year 2018 for 2020 until 2050, in 5-year steps
  - possibility that the electricity intensity data for each set of appliances will change, e.g., change from CFL light bulbs to LEDs as the main technology for lighting.

1.4.1 Methodology: Load curve calculations for households

The model differentiates nine household groups with various degrees of electrification and equipment:

- Rural – phase 1: Low-income household
- Rural – phase 2: Medium-income household
- Rural – phase 3: High-income household with electrical cooking, air-conditioning, and partly with electric vehicles (beyond 2030)
- Urban single: Household with minimal equipment
- Urban shared flat: 3–5 persons share one apartment in the centre of a large city, fully equipped medium-income household, but without vehicles
- Urban – family 1: 2 adults and 2–3 children, middle income
- Urban – family 2: 2 adults and > 3 children, and/or higher income
- Suburban 1: Average family, middle income, full equipment for high transport demand because of extensive commuting
- Suburban 2: High-income household, fully equipped, extremely high transport demand because of high-end vehicles and extensive commuting

The following electrical equipment and applications can be selected from a drop-down menu:

- Lighting: 4 different light bulb types
- Cooking: 10 different cooking stoves (2+4 burners, electricity, gas, firewood)
- Entertainment: 3 different computer, TV, and radio types
- White goods: 2 different efficiencies for washing machines, dryers, fridges, freezers
- Climatization: 2 different efficiency levels each for fan, air-conditioning
- Water heating: a selection of direct electric, heat pump, and solar

The Swiss Agency for Energy Efficiency has published a comprehensive survey of Swiss electricity demands by household and application (S.A.F.E. 2013)[7], shown in Table 2. The results were used to the develop nine household types.

Table 3 shows the assumed equipment of the different household types and the resulting annual electricity consumption. The average efficiency gain across all appliances is assumed to be 0.75% per year across the entire modelling period.

Table 2: Average annual demand of Swiss households

Standard Household [Switzerland]	Apartment			Separate house			
Category	2 Persons	Additional person	4 Persons	2 Persons	Any additional person	4 Persons	Calculated Urban Family 2
	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]	[kWh/a]
Cooking / baking including special equipment, e.g., coffee maker.	300	80	460	300	80	460	0
Dishwasher	250	25	300	250	25	300	
Refrigerator with or without freezer compartment	275	40	355	325	60	445	340
Separate freezer	275	25	325	350	25	400	
Lighting	350	90	530	450	125	700	198
Consumer electronics (TV, video, hi-fi, various players, etc.)	250	60	370	275	80	435	110
Home office (PC, printer, modem, comfort phone, etc.)	200	60	320	200	80	360	
Nursing and small appliances incl. humidifier	250	45	340	325	60	445	272
Washing machine	225	65	355	250	78	405	127
Laundry drying (about 2/3 of the laundry with tumbler)	250	85	420	275	88	450	
General (building services)	400		400+	900	150 *	1200 *	
Total	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**1047**
Climatization							1,013
Total, including climatization	**3025**	**575**	**4175**	**3900**	**850**	**5600**	**2060**

Source: SAFE, Swiss Energy Agency 2013

Table 3: Assumed appliances by household type

	Rural Phase 1	Rural Phase 2	Rural Phase 3	Urban – Single	Urban/ Shared Apartment.	Urban – Family 1	Urban – Family 2	Surburban 1	Surburban 2
Persons per household	5.0	3.7	3.7	1.0	2.4	3.7	3.7	3.7	3.7
Light bulbs	7.0	7.0	10.0	5.0	10.0	12.0	15.0	12.0	25.0
TV/radio	1.0	1.0	1.0	1.0	1.0	1.0	3.0	2.0	5.0
Computer	2.0	2.0	3.0	2.0	3.0	3.0	4.0	3.0	4.0
Cooking	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Washing machine	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Dryer	0.0	1.0	1.0	0.0	0.0	1.0	0.0	1.0	1.0
Fridge	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Freezer	0.0	0.0	1.0	0.0	0.0	0.0	1.0	1.0	1.0
Other appliances	1.0	1.0	1.0	0.0	0.0	0.0	1.0	1.0	1.0
Fan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air-conditioning	0.1	0.1	0.1	0.1	0.4	0.2	0.3	0.2	1.0
Water heating (technology neutral)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

[7] S.A.F.E 2013, Der typische Haushalt-Stromverbrauch, Jürg Nipkow, Schweizerische Agentur für Energieeffizienz S.A.F.E., Zürich, Dez. 2013

1.4.2 Load curve calculations for business and industry

The industrial sector is clustered into eight groups based on widely used statistical categories:

- Agriculture
- Manufacturer
- Mining
- Iron and steel
- Cement industry
- Construction industry
- Chemical industry
- Service and trade

For each sector, 2–6 different efficiency levels are available. The data are taken from international statistical publications (IEA [2016][8], IRENA [2016][9], DLR [2012][10]).

For the Switzerland modelling project, the business and industry load curve calculations were simplified by the limited data available and to make our calculations comparable to PROGNOS 2020. The demand and load curve calculations for industry and business are based on the following three economic sectors:

- Agriculture
- Industry and construction
- Service and trade

Thus, the industry-specific projections for *manufacturing*, *mining*, *iron and steel*, *cement industry*, *construction industry*, and the *chemical industry* are summed into one demand and one resulting load curve. For industry, the base load is assumed, whereas for agriculture and service & trade, core working hours from 6 am to 8 pm are assumed.

8 IEA (2016), World Energy Balances, 2016

9 Report citation IRENA (2016), REmap: Roadmap for a Renewable Energy Future, 2016 Edition. International Renewable Energy Agency (IRENA), Abu Dhabi, www.irena.org/remap

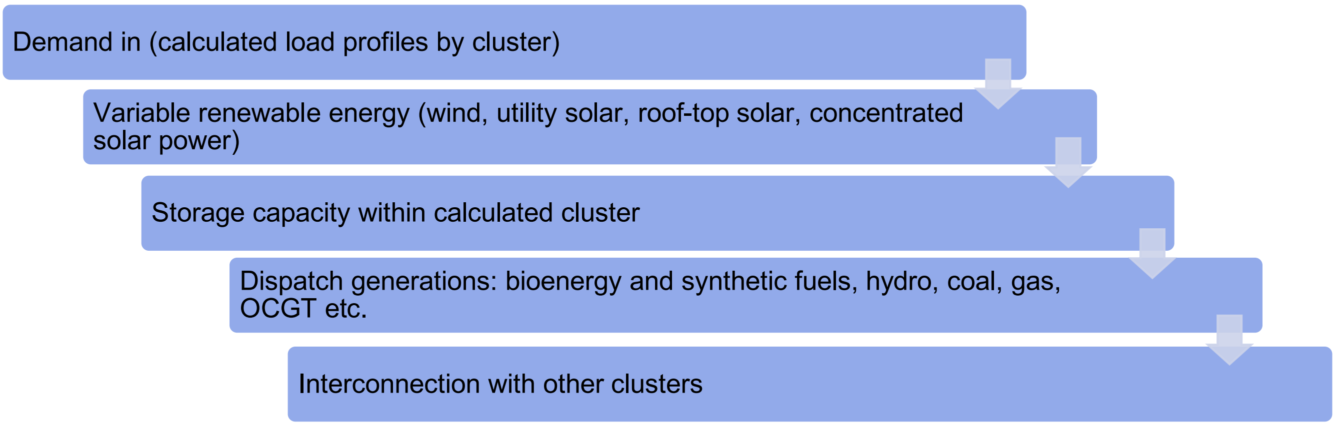
10 DLR et. al. (2012) Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global Schlussbericht BMU - FKZ 03MAP146 (DLR), (IWES), (IFNE), 29 March 2012

1.5 The [R]E 24/7 Dispatch Module

The [R]E 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first-generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can be either moved to storage, moved to other regions, or—if neither option is available—curtailed. Non-variable renewable sources will reduce output. In the case of an undersupply, electricity will be supplied either from available storage capacities, from neighbouring clusters, or from dispatch power plants. The key objective of the modelling is to calculate the load development by region, modifying the residual loads (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. The theoretical storage requirement is provided as "storage requirement to avoid curtailment". The economic battery capacity is a function of the storage and curtailment costs, as well as the availability of dispatch power plants and costs. This analysis focuses on the technical storage requirements.

Figure 3 provides an overview of the dispatch calculation process. The dispatch order can be changed in terms of the order of renewables and the dispatch power plant, as well as in the order of the generation categories: variable, dispatch generation, and storage. The following key parameters are used as input: generation capacity by type, the demand projection and load curve for each cluster, interconnection with other clusters, and meteorological data, from which solar and wind power generation are calculated with hourly resolution. The installed capacities are derived from the long-term projections described in section 4.4, and the resulting annual generation in megawatt hours is calculated on the basis of meteorological data (in the cases of solar and wind power) or dispatch requirements.

Figure 3: Dispatch order within one cluster



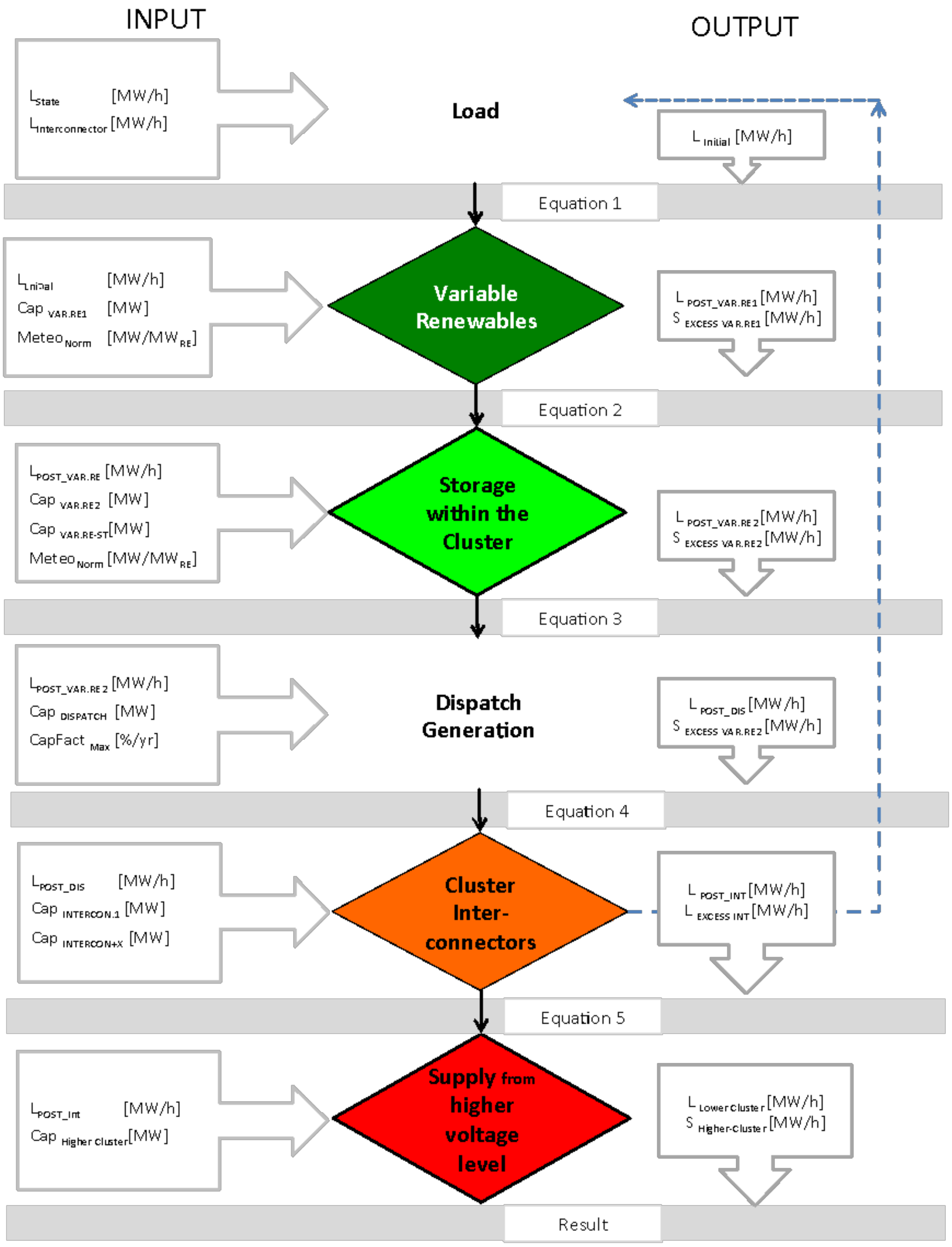
Overview: input and output—[R]E 24/7 energy dispatch model

Figure 4 gives an overview of the input and output parameters and the dispatch order. Although the model allows changes in the dispatch order, a 100% renewable energy analysis always follows the same dispatch logic. The model identifies excess renewable production, which is defined as the potential wind or solar photovoltaic (PV) generation that exceeds the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be stored with some form of electrical storage technology or exported to a different cluster. Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge the storage within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as 'potential curtailment' (pre-storage). It is assumed that a certain number of behind-the-meter consumer batteries will be installed, independently of the system requirements.

Limitations

The calculated loads are not optimized with regard to local storage, the self-consumption of decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may be well below the calculated values.

Figure 4: Overview—Input, output, and dispatch order



2. LONG-TERM SCENARIO: SWITZERLAND

The long-term scenarios for Switzerland are documented here. The results of the long-term energy scenario developments are used for the more detailed power system analysis documented in Chapter 5.

2.1 Switzerland: Scenario Assumptions

Switzerland is located in the centre of Europe and is an important market place for electricity. Therefore, Switzerland has an extraordinarily high amount of imported and exported electricity, as well as electricity transfer, for example, from France to Italy, which does not contribute to the supply of electricity but affects the power grid infrastructure. The assumptions of the REFERENCE scenario are based on the latest scenario research of PROGNOS AG, INFRAS AG, and TEP Energy and Ecoplan AG for the Swiss Ministry of Energy, November 2020[11].

2.1.1 Switzerland: Socio-economic parameters

Socio-economic data

In 2019, Switzerland had a population of 8.5 million[12] and a population density of 219 persons per square kilometre[13]. Between 1960 and 2019, the population increased steadily at a growth rate of around 1% per year from 5.3 million to 8.5 million, with the exception of the period 1963–1978, in which the annual growth rate decreased from 2% to −0.3% per year. According to the projection of Population Pyramid[14], the population of Switzerland will continue to increase steadily until the end of the projection period in 2100 to 11 million people, with an annual average increase of 1.6%. For this analysis, we considered the development until 2050 (see Table 4).

Economic development

Switzerland's economic development over the past decade was characterized by steady growth since 1970, at 2.8% per annum on average. Economic recessions occurred in 1975 (−7.5%), 1982 (−1.3%), 1991 (−0.9%), and during the Global Financial Crisis (GFC) in 2009 (−2.2%)[15]. Switzerland has a robust economy with one of the highest per capita GDP, at around CHF 75,000—almost twice as high as the World Bank's classification of a 'high-income country' (CHF 45,000).

Table 4: Switzerland—Population and GDP projections

		2018	2020		2025	2030	2035	2040	2045	2050
			Reduced	Stable						
GDP	[billion CHF/a]	633	590	652	691	731	772	814	846	880
GDP/Person	[CHF/capita]	73,472	66,636	73,613	75,272	77,045	78,682	81,464	83,578	85,836
Population	[million]	8.6	8.7		9.2	9.5	9.8	10.0	10.1	10.3
			2020		2020–2025	2025–2030	2030–2035	2035–2040	2040–2045	2045–2050
Economic growth	[%/a]		−7.7%	+1.00%	1.15%	1.15%	1.10%	1.05%	0.78%	0.80%
Population growth	[%/a]		0.60%		0.70%	0.68%	0.68%	0.35%	0.27%	0.26%

The OECD World Economic Outlook expects a drop in Switzerland's GDP of −7.7% in 2020, due to the COVID-19 pandemic[16]. However, for this research, we assumed that the economy will restart successfully and the average GDP growth will be back on the trajectory projected in PROGNOS 2020[11]. Furthermore, a constant trajectory of medium GDP development of around 1% per year is assumed—below the average growth rate of the past 50 years. The resulting economic activity per capita—in Swiss francs (CHF) per capita—will increase further. Our assumption for the energy decarbonization trajectory is therefore conservative, and allows a fully renewable energy supply, even under the higher energy demand. The projections of population and economic growth are important factors in the development of energy

[11] PROGNOS 2020, Energieperspektiven 2050+Kurzbericht
[12] Worldbank database, viewed July 2020, https://data.worldbank.org/country/switzerland?view=chart
[13] Worldometers, viewed July 2020, https://www.worldometers.info/world-population/switzerland-population/
[14] Population Pyramid provides projections of future population developments for all world regions and countries on the basis of United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2019 Revision. (Medium variant) and other regional sources: https://www.populationpyramid.net/switzerland/2019/ viewed July 2020
[15] Worldbank database, viewed July 2020, https://data.worldbank.org/country/switzerland
[16] OECD Economic Outlook, June 2020, http://www.oecd.org/economic-outlook/june-2020/ viewed July 2020

scenarios because they affect the size and composition of the energy demand, both directly and through their impact on economic growth and development.

2.1.2 Switzerland: Electricity demand development projections

The electricity demand projections were calculated for the residential and business sectors with the [R]E 24/7 model in a bottom-up process. The further electricity demand entailed by transport (especially under the two alternative scenarios, with increased electric mobility and heat pumps), by the internal electricity demand of power plants ("own consumption"), and by the distribution losses were calculated with the long-term model (see Chapter 1, Methodology, and Chapter 2, Long-term Scenario) and added to the calculated demand projections. However, the [R]E 24/7 power analysis only takes into account the additional electricity demand for distribution losses and the electricity for hydro pump storage because the power plant consumption does not influence the storage or grid requirements.

2.1.3 Switzerland: Demand projections for the industry and business sectors

The industry and business demand development is based on the GDP. The breakdown of GDP by industry sector and province (canton) in 2018 is shown in Table 5. The data are taken from the Swiss Bureau of Statistic (BfS 2020)[17].

Table 5: Switzerland: Development of GDP shares by industry sector and province (*canton*) (2018)

Cluster Name	Canton	GDP 2017 [Million CHF]	Landwirtschaft, Forstwirtscha, und Fischerei		Bergbau und Gewinnung von Steinen und Erden, Herstellung von Waren, Bau		Gesundheitswesen, Finanzdienstleistungen, Kunst, Kultur, Oeffentliche Verwaltung, Private Haushalte als Hersteller	
			Agriculture	Agriculture [%]	Industry	Industry [%]	Service	Service [%]
West	Freiburg	18,154	293	1.6%	5,230	29%	12,632	70%
West	Waadt	52,207	552	1.1%	9,730	19%	41,925	80%
West	Neuenburg	14,993	88	0.6%	7,060	47%	7,844	52%
West	Genf	47,970	122	0.3%	6,619	14%	41,230	86%
Wallis (South West)	Wallis	17,907	262	1.5%	4,444	25%	13,201	74%
Bern-Basel (Centre West)	Bern	75,920	657	0.9%	16,752	22%	58,511	77%
Bern-Basel (Centre West)	Solothurn	17,223	80	0.5%	4,917	29%	12,227	71%
Bern-Basel (Centre West)	Basel-Stadt	34,584	4	0.0%	17,094	49%	17,486	51%
Bern-Basel (Centre West)	Basel-Landschaft	19,808	70	0.4%	4,613	23%	15,124	76%
Bern-Basel (Centre West)	Jura	4,509	57	1.3%	1,998	44%	2,454	54%
Centre North	Luzern	26,153	407	1.6%	7,423	28%	18,323	70%
Centre North	Uri	1,861	6	0.3%	605	33%	1,250	67%
Centre North	Schwyz	9,150	51	0.6%	2,446	27%	6,654	73%
Centre North	Obwalden	2,434	29	1.2%	1,003	41%	1,402	58%
Centre North	Nidwalden	2,952	18	0.6%	1,127	38%	1,806	61%
Centre North	Zug	18,160	44	0.2%	4,651	26%	13,466	74%
Centre North	Aargau	40,316	303	0.8%	10,702	27%	29,312	73%
Tessin (South)	Tessin	27,614	80	0.3%	6,872	25%	20,662	75%
Graubünden (South)	Graubünden	13,589	85	0.6%	3,137	23%	10,366	76%
Zürich & Centre North East	Zürich	138,168	392	0.3%	18,888	14%	118,888	86%
Zürich & Centre North East	Glarus	2,681	12	0.5%	1,033	39%	1,635	61%
Zürich & Centre North East	Schaffhausen	6,723	62	0.9%	2,822	42%	3,839	57%
Zürich & Centre North East	Appenzell I. Rh.	960	21	2.2%	341	35%	598	62%
Zürich & Centre North East	Appenzell A. Rh.	3,010	33	1.1%	1,113	37%	1,864	62%
Zürich & Centre North East	St. Gallen	35,676	274	0.8%	12,364	35%	23,038	65%
Zürich & Centre North East	Thurgau	15,901	389	2.4%	5,585	35%	9,927	62%

The 26 provinces[18] are grouped into seven sub-regions or clusters. The accumulated GDP and sectorial breakdown are show in Table 6. The GDP distribution by region is based on 2018 (BfS 2020) data and is assumed to remain the same for the entire modelling period, until 2050. In the industry sector, an efficiency gain of 0.5% per year has been calculated between 2020 and 2030 and of 0.75% per year between 2031 and 2050. In the service and agricultural sectors, an efficiency development of 0.5% per year until 2030 has been calculated, with 0.25% for the rest of the modelling period (Teske et al. 2019)[19].

[17] BFS 2020, Bundesamt fuer Statistik, Bruttowertschoepfung (BWS) pro Kanton und Aktivitaet
[18] There are 26 provinces (Swiss: Kanton), there are two different types of Kanton's: 20 *Voll-Kantone* and 6 *Half-Kantone* that has to do the voting system and is based on historical developments. In this analyses Kantons are all handled equally only based on electricity demand & supply.
[19] Teske (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5˚C and +2.0˚C, Chapter 5 – Assumptions, Thomas Pregger et. al. ISBN 978-3-030-05842-5, Springer, Switzerland 2019

Table 6: Switzerland: Development of GDP shares by region

Country/Sub-region	GDP	Agriculture		Industry		Service	
	[million CHF]	[million CHF]	[%]	[million CHF]	[%]	[million CHF]	[%]
Schweiz	648,624	4,391	0.7%	158,568	24.4%	485,665	74.9%
West	133,324	1,055	0.8%	28,639	21.5%	103,631	77.7%
South West (Wallis)	17,907	262	1.5%	4,444	24.8%	13,201	73.7%
Centre-West (Bern–Basel)	152,045	869	0.6%	45,373	29.8%	105,803	69.6%
Centre North	101,027	857	0.8%	27,957	27.7%	72,213	71.5%
Tessin	27,614	80	0.3%	6,872	24.9%	20,662	74.8%
Graubuenden	13,589	85	0.6%	3,137	23.1%	10,366	76.3%
Centre North East (Zürich)	203,118	1,183	0.6%	42,146	20.7%	159,789	78.7%

2.1.4 Switzerland: Electricity demand projections—households

The analysis of the current and future development of the electricity demand for Switzerland's households is based on the information presented in section 1.4.1. The annual electricity demand for all household types and their social classification are shown in Table 7. The average assumed efficiency gain across all appliances is assumed to be 0.75% per year across the entire modelling period.

Table 7: Switzerland: Household types used in all scenarios and their assumed annual electricity demands

Household Type			2020 [kWh/a]
Rural - Phase 1	-	Low-income rural household	1,900
Rural - Phase 2	-	Lower-middle-income rural household	3,000
Rural - Phase 3	-	Upper-middle-income rural household	3,000
Urban – Single	-	Very-low-income urban household	1,250
Urban/Shared App.	-	Lower-middle-income urban household	2,400
Urban - Family 1	-	Middle-income-household (urban and rural)	3,200
Urban - Family 2	-	Upper-middle-income urban household	2,250
Suburban 1	-	High-income rural household	4,450
Suburban 2	-	High-income urban household	3,150

The estimated development of the country-wide electricity shares for the various household types is presented in Table 8. It is assumed that households will increasingly use electricity for heating and to charge electric vehicles, so the overall demand will also increase on the household level.

Table 8: Switzerland: Household types—changes in electricity shares country-wide

Household Type	Country-wide Share [%] (rounded)			
	2020	2030	2040	2050
Rural – Phase 1	17.5%	15.0%	10.0%	7.5%
Rural – Phase 2	22.5%	25.0%	27.5%	25.0%
Rural – Phase 3	5.0%	5.0%	7.5%	12.5%
Urban – Single	10.0%	7.5%	5.0%	2.5%
Urban/Shared App.	10.0%	12.5%	12.5%	15.0%
Urban – Family 1	10.0%	7.5%	10.0%	7.5%
Urban – Family 2	5.0%	7.5%	7.5%	10.0%
Suburban 1	10.0%	7.5%	5.0%	2.5%
Suburban 2	10.0%	12.5%	15.0%	17.5%
Total	100%	100.0%	100%	100%

The distributions of electricity shares across the household categories can vary regionally. All shares have been rounded and calibrated to the current regional electricity demand. The authors of this report have deliberately chosen a high standard for Switzerland's households. The projected development of the electricity demand for Switzerland's households could be lower if all electrical appliances are of the best technical standard available and if electrical heating is reduced and building insulation standards increased, which would reduce the overall heating demand. However, the entire efficiency demand is a theoretical benchmark only and could not be implemented entirely.

2.2 Technology and Fuel Cost Projections

The parameterization of the model requires that many assumptions be made about the development of the characteristic technologies, such as the specific investments required and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

2.2.1 Background: Fuel price projections

The speed of an energy system transition depends, to some extent, on overcoming economic barriers. These largely relate to the relationships between the costs of renewable technologies and those of their fossil counterparts. For our scenarios, the projection of these costs is vital, allowing valid comparisons of energy systems to be made. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs. Moreover, efficiency measures also generate costs, which are usually difficult to determine, and depend on the technical, structural, and economic boundary conditions.

During the last decade, fossil fuel prices have seen huge fluctuations. Figure 5 shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices have shown similar development (IEA 2017)[20]. Consequently, fossil fuel price projections have also seen considerable variation (IEA 2017[74]; IEA 2013[21]), and have markedly influenced the scenario results ever since, especially those scenarios that are based on cost optimization algorithms.

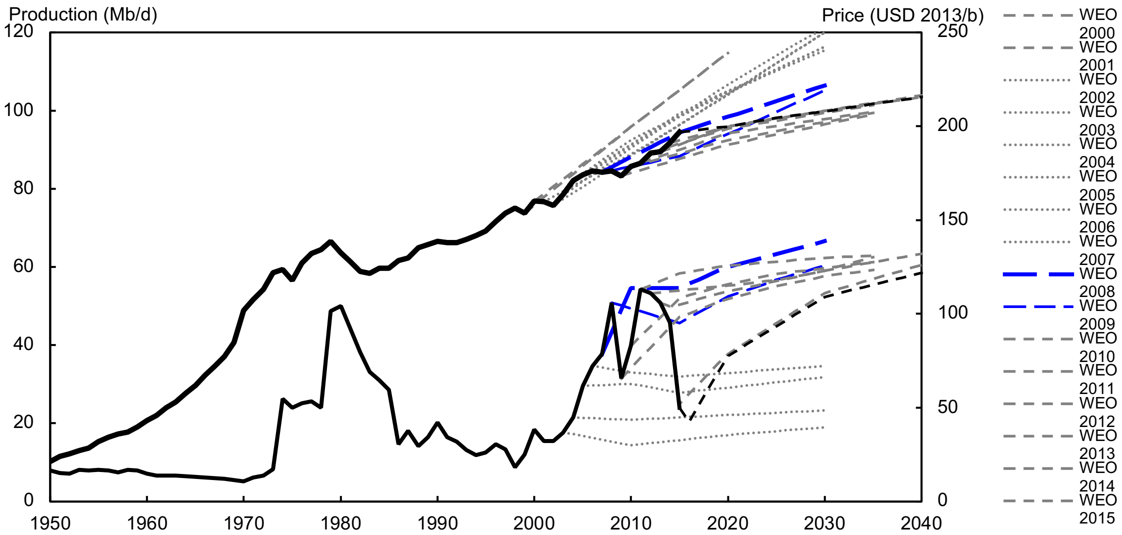
Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the International Energy Agency (IEA) leading the way in 2018 (Roland Berger 2018)[22]. An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[23] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections have shown errors of 40%–60%, even when made for only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from €70 to €140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation, the IEA provides a comprehensive set of price projections. Therefore, we based our scenario assumptions on these projections, as described below.

Because most renewable energy technologies provide energy with no fuel costs, the projections of investment costs become more important than the fuel cost projections, which limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. Today, these costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials, to comparatively expensive energy crops.

[20] IEA (2017): IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris
[21] IEA 2013: IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris
[22] Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. https://www.rolandberger.com/en/Publications/pub_oil_price_forecast_2015.html. Accessed 10.9.2018 2018
[23] Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138-153. doi:https://doi.org/10.1016/j.apenergy.2018.03.013

Figure 5: Historic development and projections of oil prices

by IEA according to Wachtmeister et al. (2018)



The projection of investment costs also poses challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most commonly used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[24]; Rubin et al. 2015[25]). Therefore, the reliability of cost projections largely depends on the uncertainty of future markets and the availability of historical data. Fossil fuel technologies provide a large cost dataset, featuring well-established markets and large annual installations. They are also mature technologies, where many potential cost reductions have already been exploited.

For renewable technologies, the picture is more mixed. For example, hydro power is (like fossil fuels) well established and provides reliable data on investment costs. Other technologies, such as solar photovoltaic (PV) and wind, are currently experiencing tremendous advances in installation and cost reductions. Photovoltaic and wind power are the foci of cost monitoring, and considerable data are already available on existing projects. However, their future markets are not easily predicted, as can be seen from the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA 2007, IEA 2014, and IEA 2017). For PV and wind energy, small differences in cost assumptions will lead to large deviations in the overall costs, so cost assumptions must be made with especial care.

Furthermore, many technologies feature only relatively small markets, such as geothermal and modern bio-energy applications, for which costs are still high and for which future markets are insecure. The cost reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technological options in the long term after 2035, but their cost reduction potential cannot be assessed with any certainty today.

Therefore, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not calculated internally, we have assumed the same progressive cost developments for all scenarios. In the next section, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment and fuel costs and the potential CO_2 costs, in the various scenarios.

[24] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255-261. doi:https://doi.org/10.1016/S0301-4215(00)00122-1
[25] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198-218. doi:https://doi.org/10.1016/j.enpol.2015.06.011

2.2.2 Power and combined heat and power (CHP) technologies

The focus of the cost calculations in our scenario modelling is the power sector. We compared the specific investment costs estimated in previous studies (Teske et al. 2019[26] and Teske et al. 2015[27]), which were based on a variety of studies, including investment cost projections by the IEA (IEA 2014) and current cost assumptions by IRENA[28] and IEA (IEA 2016c). We found that the investment costs generally converged, except for the cost of solar PV, which was higher than average.

The cost projections for power plant and co-generation technologies are taken from Teske et al. (2019)[26]. To achieve results comparable to those of PROGNOS (2020) for the baseline scenario, fuel costs have been taken from PROGNOS (2020). The technology costs (overnight costs and escalation costs due to the interest rates during construction) are given in Table 9. A discount rate of 10% was used for the cost of capital. This discount rate was used to calculate investment annuities and the levelized costs of electricity over the technical lifetime of a power plant.

Several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are extensively deployed. Fuel cells are expected to outpace other CHP technologies, with a cost reduction potential of more than 75% (from currently high costs). Hydro power and biomass will remain stable in terms of costs. Tremendous cost reductions are still expected for solar energy and offshore wind, even though they have experienced significant reductions already. However, PV costs could drop to 35% of today's costs. Offshore wind has experienced significant cost reductions over the past decade and could decrease by a further 30% over the next decade, whereas the cost reduction potential for onshore wind seems to have been exploited already to a large extent.

The investment costs provided in the table below are only the technology costs, and exclude the costs for operation and maintenance and the land fuel costs.

[26] Teske (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5C and +2.0C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019

[27] Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T, Schmid S, Özdemir ED, Pagenkopf J, Kleiner F, Rutovitz J, Dominish E, Downes J, Ackermann T, Brown T, Boxer S, Baitelo R, Rodrigues LA (2015) Energy [R]evolution - A sustainable world energy outlook 2015. Greenpeace International

[28] IRENA (2020), Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi, ISBN 978-92-9260-244-4

Table 9: Investment cost assumptions for power generation plants (in CHF/kW) until 2050

Assumed Investment Costs for Power Generation Plants						
		2017	**2020**	**2030**	**2040**	**2050**
CHP Coal	CHF/kW	2650	2650	2650	2650	2650
CHP Gas	CHF/kW	1060	1060	1060	1060	1060
CHP Lignite	CHF/kW	2650	2650	2650	2650	2650
CHP Oil	CHF/kW	1389	1367	1314	1251	1198
Coal power plant	CHF/kW	2120	2120	2120	2120	2120
Diesel generator	CHF/kW	954	954	954	954	954
Gas power plant	CHF/kW	638	530	530	530	710
Lignite power plant	CHF/kW	2332	2332	2332	2332	2332
Nuclear power plants	CHF/kW	6996	6360	5406	4770	4770
Oil power plant	CHF/kW	1007	986	943	912	869
Renewables						
CHP Biomass***	CHF/kW	2703	2650	2597	2491	2385
CHP Fuel cell	CHF/kW	5300	5300	2650	2650	1187
CHP Geothermal	CHF/kW	13992	11861	9423	7908	6848
Biomass power plant	CHF/kW	2544	2491	2438	2332	2237
Geothermal power plant****	CHF/kW	7004	6867	6297	5726	5156
Hydro power plant**	CHF/kW	2809	2809	2809	2809	2809
Ocean energy power plant	CHF/kW	7367	7049	4664	3286	2237
PV power plant	CHF/kW	1378	1039	774	594	498
CSP power plant*	CHF/kW	6042	5300	3922	3233	2904
Wind turbine offshore	CHF/kW	4240	3911	3381	3000	2767
Wind turbine onshore	CHF/kW	1738	1675	1601	1537	1484
Hydrogen production	CHF/kW	1463	1293	975	742	604

*Costs for a system with a solar multiple of two and thermal storage for 8 h of turbine operation

**Values apply to both run-of-the-river and reservoir hydro power

*** In this research, bio-energy and synthetic fuels are considered to be interchangeable fuels for power plants, combined heat and power plants (CHP), and heating plants. Synthetic fuels produced by renewable electricity—mainly solar and wind power—will either be added to bio-energy supply or replace it.

*** IRENA (2017), Geothermal Power: Technology Brief, International Renewable Energy Agency, Abu Dhabi, page 13, CAPEX for binary plants—low projection

2.2.3 Heating technologies

Assessing the costs in Switzerland's industrial heating sector is more ambitious than assessing those in the power sector. The costs of new installations will differ significantly between regions and will be linked to construction costs and industry processes, which are not addressed in this study. Moreover, no data are available to allow the comprehensive calculation of the costs of existing heating appliances in Switzerland. Therefore, we concentrate on the additional costs that will result from the application of new renewable resources in the heating sector. Our cost assumptions for heat generation are based on a previous survey of renewable heating technologies across Europe, which focused on solar collectors, geothermal, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies, which can provide higher shares of the heat demand from renewable sources, are still under development and rather expensive. Market barriers will slow the further implementation and cost reduction of renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in our high-renewables scenarios. Table 10 presents the investment cost assumptions for heating technologies in Europe, disaggregated by sector (Teske et al. 2019)[7].

Table 10: Specific investment cost assumptions (in Swiss francs) for heating technologies in the scenarios until 2050

Investment costs for heat generation plants							
			2017	**2020**	**2030**	**2040**	**2050**
Geothermal		CHF/kW	2533	2406	2152	1908	1685
Heat pumps		CHF/kW	1897	1844	1738	1632	1537
Biomass heat plants		CHF/kW	636	615	583	541	509
Residential biomass stoves, ovens	Industrialized countries	CHF/kW	890	859	806	763	721
Solar collectors	Industry	CHF/kW	901	869	774	689	583
	In heat grids	CHF/kW	1028	1028	1028	1028	1028
	Residential	CHF/kW	1124	1071	965	848	721

Heat pumps typically provide hot water or space heat for heating systems with relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently vary widely and are expected to decrease by only 20%, to around CHF1,550 per kilowatt-thermal, by 2050 (Teske et al. 2019)[7]. For biomass and solar collectors, we assume the appropriate differences between the sectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single-room stoves to heating or CHP plants on a megawatt scale.

Investment costs show similar variations: simple log-wood stoves can cost from CHF 100 per kilowatt-thermal, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive. Log-wood or pellet boilers range from CHF550/$kW_{thermal}$ to CHF1500/$kW_{thermal}$. Large biomass heating systems are assumed to reach their cheapest in 2050 at around CHF 500 per installed kilowatt-thermal for industry.

For all sectors, we assume a cost reduction of 20% by 2050. In contrast, solar collectors for households are comparatively simple and will become cheap, at around CHF 700 per kilowatt -thermal, by 2050. The cost of simple solar collectors for swimming pools might have been optimized already, whereas their integration into large systems is neither technologically nor economically mature. The collectors for larger applications, especially in heat grid systems, are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be cost reduction potential until 2050 (Teske et al. 2019)[7]. Quantification of the possible cost reduction was not possible.

2.3 Fuel Cost Projections

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions on IEA[29]. Although these price projections are highly speculative, but they provide a set of prices consistent with our investment assumptions. Bio-energy costs will increase as utilization increases and importation might be required after 2025 (Teske et al. 2019).

Table 11: Development projections for fuel prices

Development projections for fuel prices						
All Scenarios		**2017**	**2020**	**2030**	**2040**	**2050**
Biomass	$/GJ	7.70	13.65	20.00	26.00	30.00
Synthetic Fuels	$/GJ	-	-	20.00	26.00	30.00
Oil	$/GJ	8.5	12.3	21.5	24.2	35.1
Gas	$/GJ	2.5	3.3	5.5	6.2	8.9
Coal	$/GJ	2.9	3.3	4.2	4.4	5.3

2.4 Switzerland: Geographic Information

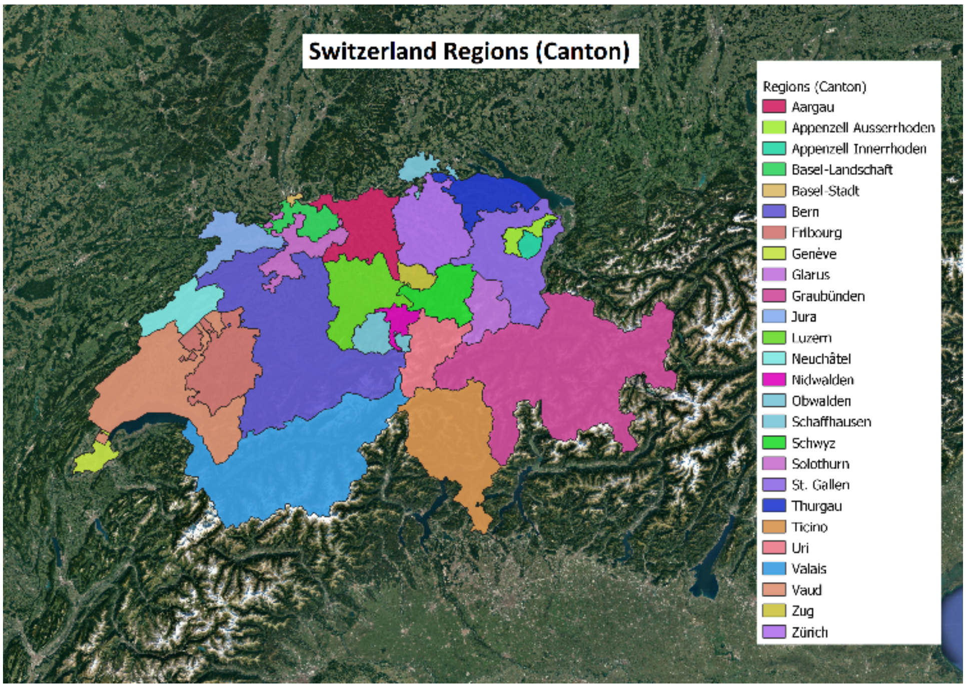
Switzerland has 26 cantons (*Kantone*) or member states, which form the Swiss Confederation. For the power sector analysis (see Chapter 4), we identified seven regions (Figure 7), some of which are actual cantons, such as region 2 (Valais), and some of which combine five or more cantons. This breakdown reflects the demand and supply centres of Switzerland.

Table 12: Overview—Regions of Switzerland

Scenario Region	Abbreviation	Canton	Capital	Population	Area [km^2]	Population density
1	FR	Freiburg	Freiburg	318,714	1,671	191
1	VD	Waadt	Lausanne	799,145	3,212	249
1	NE	Neuenburg	Neuenburg	176,850	803	220
1	GE	Genf	Genf	499,480	282	1,771
2	VS	Wallis	Sitten	343,955	5,224	66
3	BE	Bern	Bern	1,034,977	5,959	174
3	SO	Solothurn	Solothurn	273,194	791	345
3	BS	Basel-Stadt	Basel	194,766	37	5,264
3	BL	Basel-Landschaft	Liestal	288,132	518	556
3	JU	Jura	Delsberg	73,419	838	88
4	LU	Luzern	Luzern	409,557	1,493	274
4	UR	Uri	Altdorf	36,433	1,077	34
4	SZ	Schwyz	Schwyz	159,165	908	175
4	OW	Obwalden	Sarnen	37,841	491	77
4	NW	Nidwalden	Stans	43,223	276	157
4	ZG	Zug	Zug	126,837	239	531
4	AG	Aargau	Aarau	685,424	1,404	488
5	TI	Tessin	Bellinzona	353,343	2,812	126
6	GR	Graubünden	Chur	198,379	7'105	28
7	ZH	Zürich	Zürich	1,520,968	1,729	880
7	GL	Glarus	Glarus	40,403	685	59
7	SH	Schaffhausen	Schaffhausen	81,991	298	275
7	AR	Appenzell Ausserrhoden	Herisau, Trogen5	55,234	243	227
7	AI	Appenzell Innerrhoden	Appenzell	16,145	173	93
7	SG	St. Gallen	St. Gallen	507,697	2,026	251
7	TG	Thurgau	Frauenfeld	276,472	991	279

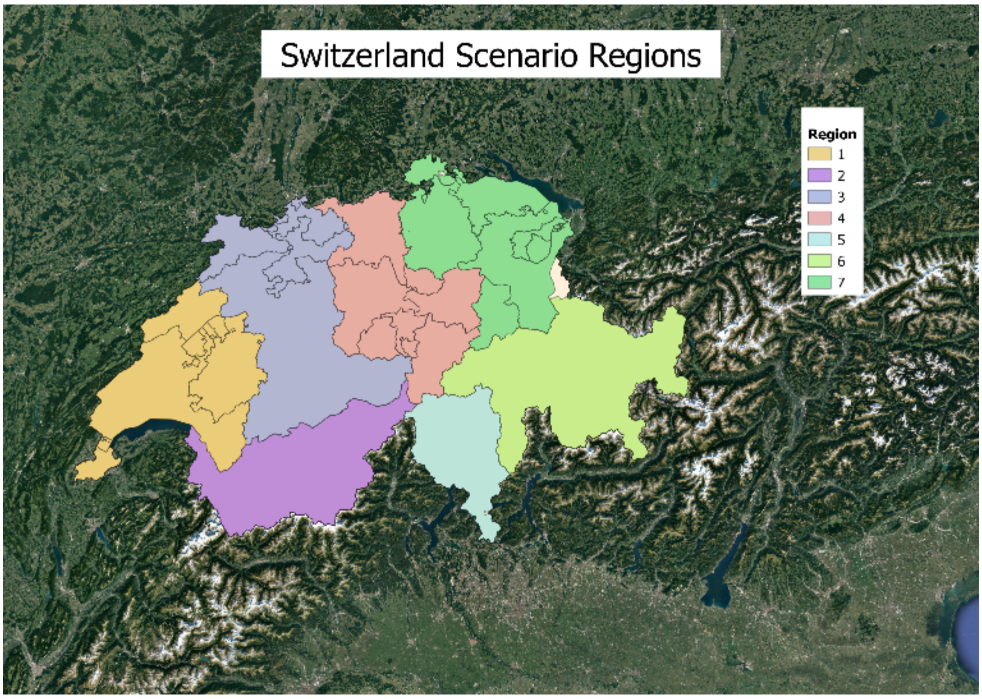
[29]Teske (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5□C and +2.0□C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019

Figure 6: Switzerland: 26 cantons–member states of the Swiss Confederation



Source: ISF mapping, June 2020

Figure 7: Switzerland: Seven modelling regions for the Switzerland power sector analysis

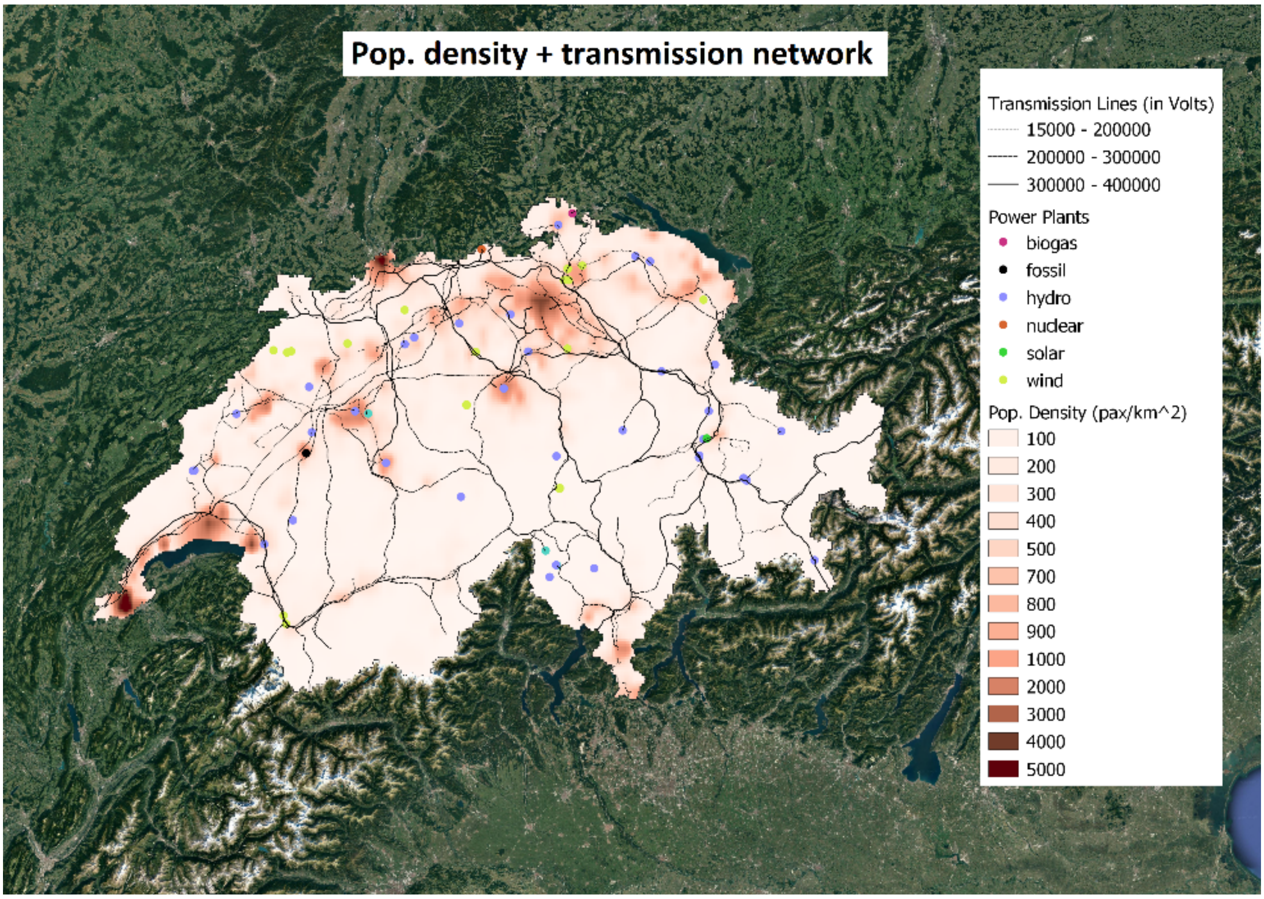


Source: ISF mapping, June 2020

2.4.1 Switzerland: Electricity infrastructure

For this analysis, the power sector of Switzerland is divided in seven regions. The regional distribution of the population and the availability of energy infrastructure correlate with the socio-economic situation in all regions. The following map provides an overview of the locations of power lines and power plants, a regional breakdown of energy pathways, and a power sector analysis (section 5.9).

Figure 8: Distribution of population and the existing electricity infrastructure in Switzerland



Source: ISF mapping, June 2020

Figure 8 shows the population density of Switzerland. The highest population concentrations are in dark red and the lowest in white. The map clearly shows the metropolitan areas of Genève in the southwest, Zürich in centre north, and Basel in the north, towards the German border. The existing electricity infrastructure (power lines and power plants over 50 MW), with the different types of grids, are shown as lines, and the differently coloured dots mark grid-connected power plants—each colour stands for a specific technology, identified in the legend. The lines represent power transmission power lines with different voltage levels. The majority of decentralized solar and wind power plants are not shown on the map because all the installations are under 50 MW capacity, and to ensure the clarity of the map. However, the map shows utility-scale installations. The intention of the figure is to visualize the distribution of the grid, power plants, and population density, and it does not claim to be complete.

2.5 Renewable Energy Potential

Switzerland has a largely untapped potential for renewable energy. Hydro power is utilized extensively and currently supplies more than half the country's electricity, and bio-energy supplies about 14% of the heating demand. However, solar and wind have large unutilized potentials.

Solar energy is abundant, with a high unused potential for roof-top generators in urban areas and utility-scale photovoltaic (PV) power stations, particularly in rural areas. Wind resources have been assessed by various organizations and there is medium potential for wind power generation. However, mainly because restrictions protect landscape areas, only a maximum of 400 wind turbines will be installed in total by 2050 according to a political agreement, which does not reflect the actual wind potential of Switzerland.

2.5.1 Switzerland: Solar potential analysis by UTS-ISF

The average annual solar radiation level in Switzerland is 3.2–3.8 kWh/m^2 per day (SolarGIS 2020)[30]. The higher end of that range is in the southwest of the country, mainly in the canton of Valais. According to the association SwissSolar, Switzerland had an installed solar capacity of 2.5 GW, including roof-top PV, at the end of December 2019 (SwissSolar 2020)[31]. There are currently only a few utility-scale solar PV power plants, and solar PV installations are mainly small roof-top systems of < 20 kW$_{peak}$. However, tenders for utility-scale solar PV projects are currently planned (PV MAGAZINE 2019)[32].

Switzerland's solar potential has been mapped under the three different scenarios.

1. Available land—restricted by nature conservation, and agricultural, commercial, or urban use (LU).
2. See 1, with two additional restrictions: (i): maximum of 10 km from existing transmission lines (PT); and (ii) contiguous areas (CA)—fractured areas of less than 1 km^2 are excluded.
3. See 1 and 2, with an additional restriction: (iii) slope > 30% (mountain areas) (S30).

The available land–when the power line restriction is excluded—would provide a total potential for utility-scale solar PV capacity of 171 GW, and excluding all areas with a slope steeper than 30%–which are unrealistic to include in an alpine region–reduces this potential by 54 GW.

When the land area is restricted by its proximity to power lines and the terrain slope, the solar potential decreases by another 31%. Under this scenario, Switzerland has over 420 km^2 of land on which 16.9 GW of solar PV can potentially be harvested by utility-scale solar farms. This would cover 44% of the total installed solar capacity in 2050 under the Energy [R]evolution scenario and 35% of that under the more ambitious ADVANCED Energy [R]evolution.

To avoid conflicts with national parks and other competing land uses, only perennial cropland and open bushland land-cover types were included in the analysis. Only utility-scale solar energy has been included in the analysis, and no further breakdown by technology has been undertaken.

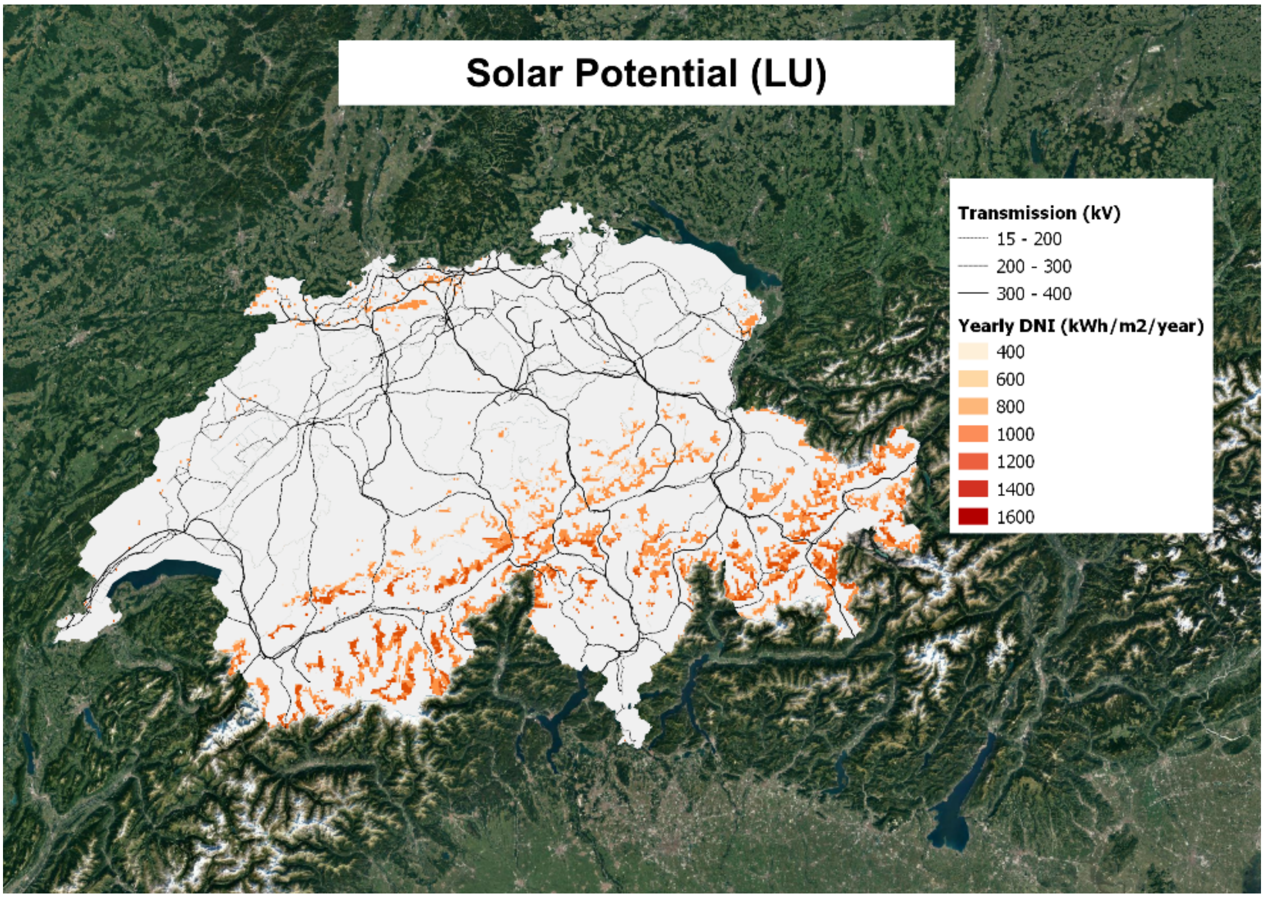
Switzerland has additional roof-top solar PV potential, but its assessment was beyond the scope of this research. According to Walch et al. (2020)[33], Switzerland has a roof-top potential of 251–485 km^2, which translates to total annual generation of 15–41 TWh/a (15–41 GW). Walch et al. (2020) estimate an average of 24.5 ± 9 TWh/a, or around 25 GW.

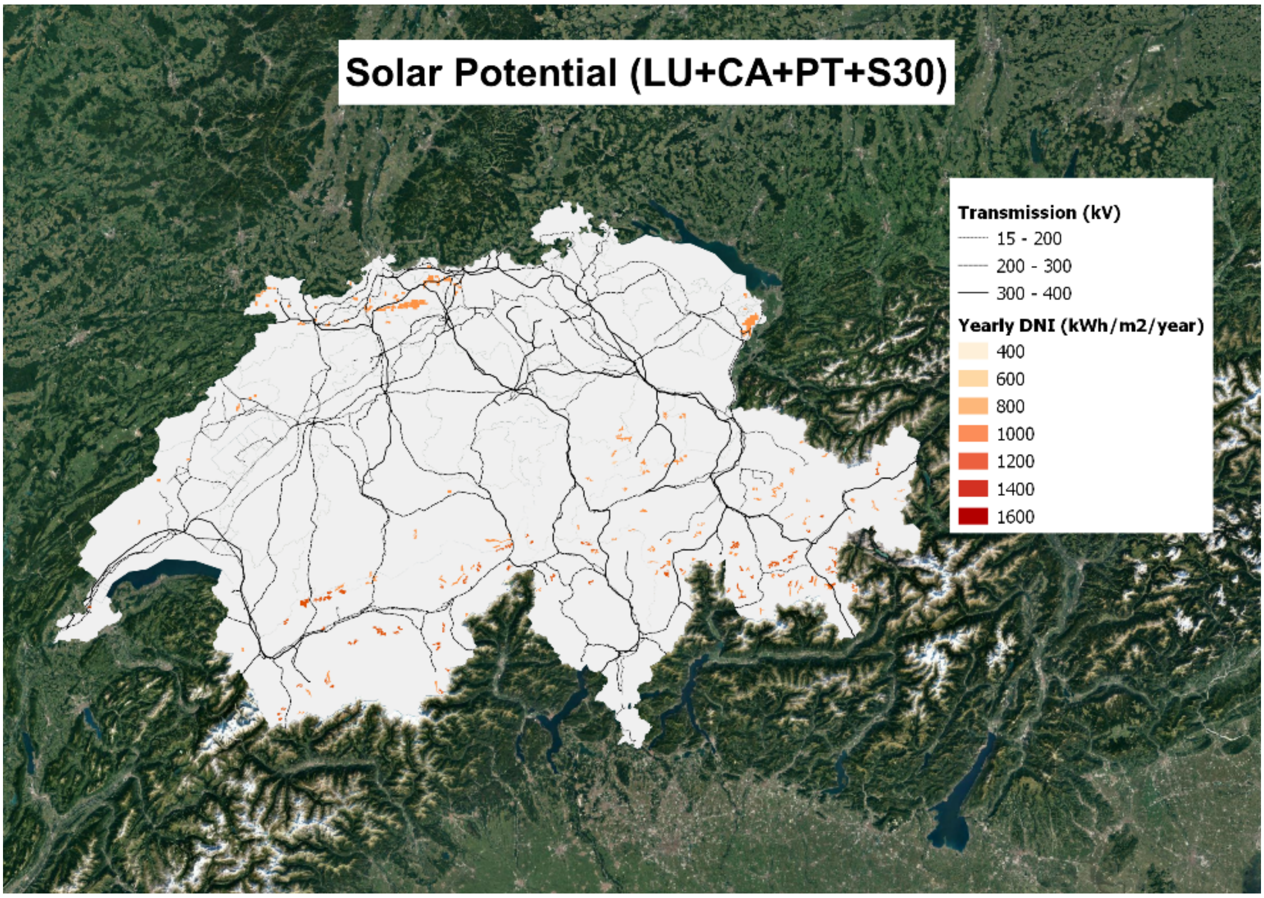
Figure 9 shows the land available for utility-scale solar PV under the LU restriction, and under all other restrictions, such as proximity to transmission lines and topographic slope.

The basic Energy [R]evolution scenario requires the utilization of around 30 GW of roof-top solar PV and the ADVANCED scenario requires close to 35 GW, above the average roof-top estimate, but still well below the 41 GW published in the literature. The utility-scale solar PV potential with all land-use restrictions is 9.3 GW (see Table 13).

[30] SolarGIS – online database, viewed July 2020; Global horizontal irradiation, https://solargis.com/maps-and-gis-data/download/switzerland
[31] SwissSolar (2019) – Markterhebung Sonnenenergie 2019, https://www.swissolar.ch/services/medien/news/detail/n-n/25-gigawatt-installierte-solarleistung-wir-brauchen-20-mal-mehr/
[32] PV MAGAZINE (2019), https://www.pv-magazine.com/2019/09/30/switzerland-plans-large-scale-solar-auctions/
[33] Big data mining for the estimation of hourly rooftop photovoltaic potential and its uncertainty, Alina Walch et. al. 2020, ELSEVIER,, March 2020, https://doi.org/10.1016/j.apenergy.2019.114404 https://www.sciencedirect.com/science/article/pii/S0306261919320914

Figure 9: Potential for utility-scale solar energy generation in Switzerland under two different restriction scenarios





Source: ISF mapping, January 2021

Scenario Regions	LU		LU+PT+CA		LU+PT+CA+S30	
	Solar Area in km^2	Solar Potential in GW	Solar Area in km^2	Solar Potential in GW	Solar Area in km^2	Solar Potential in GW
Region 1	24.6	0.6	14.0	0.4	9.5	0.2
Fribourg	0.5	0.0	0.0	0.0	0.0	0.0
Vaud	13.6	0.3	8.0	0.2	3.6	0.1
Neuchâtel	7.4	0.2	5.0	0.1	4.9	0.1
Genève	3.1	0.1	1.0	0.0	1.0	0.0
Region 2	958.5	24.0	635.0	15.9	64.1	1.6
Valais	958.5	24.0	635.0	15.9	64.1	1.6
Region 3	438.2	11.0	328.0	8.2	95.3	2.4
Bern	326.7	8.2	241.0	6.0	21.4	0.5
Solothurn	29.2	0.7	27.0	0.7	21.3	0.5
Basel-Stadt	0.0	0.0	0.0	0.0	0.0	0.0
Basel-Landschaft	42.3	1.1	34.0	0.9	31.6	0.8
Jura	40.0	1.0	26.0	0.7	21.0	0.5
Region 4	219.7	5.5	164.0	4.1	34.0	0.9
Luzern	1.4	0.0	0.0	0.0	0.0	0.0
Uri	153.3	3.8	119.0	3.0	6.2	0.2
Schwyz	17.7	0.4	15.0	0.4	0.4	0.0
Obwalden	6.6	0.2	2.0	0.1	0.0	0.0
Nidwalden	1.8	0.0	0.0	0.0	0.0	0.0
Zug	0.0	0.0	0.0	0.0	0.0	0.0
Aargau	39.0	1.0	28.0	0.7	27.4	0.7
Region 5	204.4	5.1	167.0	4.2	10.5	0.3
Ticino	204.4	5.1	167.0	4.2	10.5	0.3
Region 6	1651.2	41.3	1383.0	34.6	118.8	3.0
Graubünden	1651.2	41.3	1383.0	34.6	118.8	3.0
Region 7	126.6	3.2	103.0	2.6	39.9	1.0
Zürich	0.0	0.0	0.0	0.0	0.0	0.0
Glarus	47.1	1.2	37.0	0.9	4.6	0.1
Schaffhausen	0.0	0.0	0.0	0.0	0.0	0.0
Appenzell Ausserrhoden	3.7	0.1	1.0	0.0	1.0	0.0
Appenzell Innerrhoden	1.7	0.0	1.0	0.0	0.0	0.0
St. Gallen	74.1	1.9	64.0	1.6	34.2	0.9
Thurgau	0.0	0.0	0.0	0.0	0.0	0.0
Total	3623.2	90.6	2794.0	69.9	372.1	9.3

Table 13: Utility-scale solar potential for Switzerland under different restrictions

2.5.2 Switzerland: Wind potential analysis by UTS-ISF

Switzerland: Wind Energy

Switzerland's total installed wind power capacity for onshore wind farms at the end of 2019 was 75 MW, with 39 turbines[34]. There is obviously no offshore wind potential for land-locked Switzerland.

Switzerland: Onshore Wind

The overall wind resources on land are moderate to low in Switzerland and the average annual wind speeds in most suitable land areas range between 4.5 and 5.5 m/s. In this analysis, we have included only areas with an average annual wind speed of ≥ 5 m/s. Switzerland's wind potential has been mapped under four different scenarios.

1. Available land—restricted by nature conservation, and agricultural, commercial, or urban use (LU).
2. See 1, with the additional restriction: (i): maximum of 10 km from transmission lines (PT).
3. See 1 and 2, with the additional restriction: (ii) contiguous areas (CA).
4. See 1, 2, and 3, with the additional restriction: (iii) slope > 30% (mountain areas) and additional land use restrictions (S30).

The main reduction in the total theoretical potential is the restriction that excludes all regions further than 10 km from a transmission power line, which reduces the potential by 44%, whereas the slope restriction−removing all regions with a slope of more than 30%−reduces the total wind potential by 18%.

Restrictions	km^2	GW	% remaining of LU potential	Reduction of LU potential
Slope—reduction of potential	955.7	3.8	81.8%	18.2%
Reduction—powerline proximity	2309.8	9.2	56.0%	44.0%
LU+S30—no grid restrictions	4290.6	17.2	18.2%	

Table 14: Onshore wind potential for Switzerland and the impact of different restrictions

The overall UTS/ISF wind potential calculations confirm the results of the Swiss wind energy strategy published in June 2020, and the regional distribution of wind farms calculated in the power sector analysis in Chapter 5 is also similar (Suisse Eole 2020)[35].

[34] Suisse eole – Statistik, viewed July 2020, https://www.suisse-eole.ch/de/windenergie/statistik/
[35] SUISSE EOLE 2020, WINDENERGIESTRATEGIE: WINTERSTROM & KLIMASCHUTZ
Analyse und Aktualisierung des Potenzials der Windenergie in der Schweiz, Version Nr. 3 vom 12. Juni 2020; https://www.are.admin.ch/are/de/home/raumentwicklung-und-raumplanung/strategie-und-planung/konzepte-und-sachplaene/konzepte/konzept-windenergie.html

Figure 10: Potential for wind power in Switzerland under two different restriction scenarios

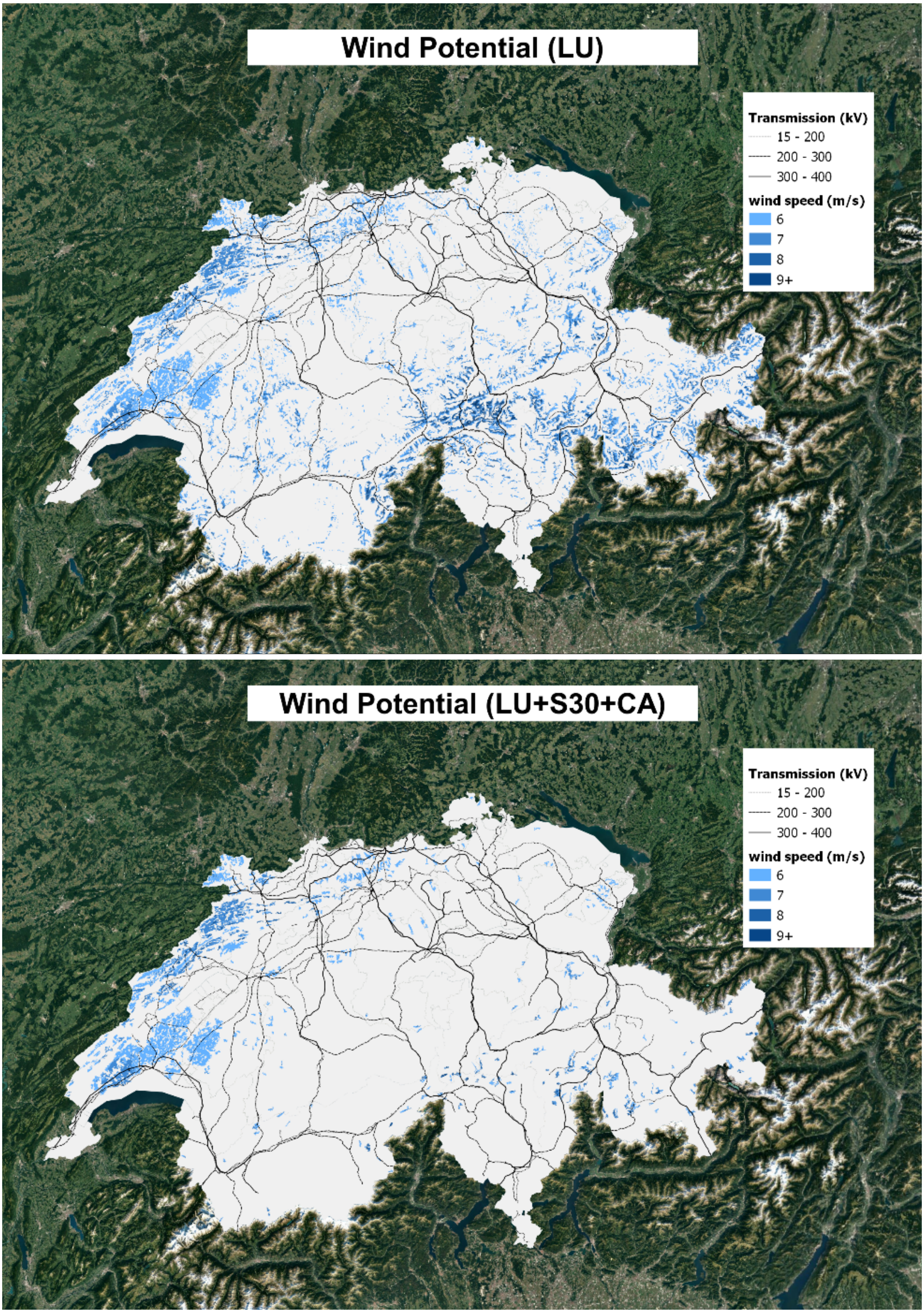


Table 15 shows that the total wind potential under all restrictions would lead to an overall wind potential of 7.7 GW. The Energy [R]evolution scenario projects a total capacity of 2.1 GW. This potential assumes the utilization of only large turbines of 6 MW, and will therefore require 354 machines, whereas the installed wind capacity under the ADVANCED scenario will increase to 2.4 GW, the maximum possible under the 400 turbines restriction.

Scenario Regions	LU		LU+PT+CA		LU+PT+CA+S30	
	Wind Area in km^2	Wind Potential in GW	Wind Area in km^2	Wind Potential in GW	Wind Area in km^2	Wind Potential in GW
Region 1 - West	1185.3	4.7	1115.3	4.5	1028.3	4.1
Fribourg	104.1	0.4	81.0	0.3	195.4	0.8
Vaud	886.3	3.5	847.9	3.4	627.6	2.5
Neuchâtel	193.9	0.8	184.7	0.7	205.3	0.8
Genève	1.1	0.0	1.7	0.0	0.0	0.0
Region 2 - South West (Wallis)	435.9	1.7	118.6	0.5	40.2	0.2
Valais	435.9	1.7	118.6	0.5	40.2	0.2
Region 3 - Centre-West (Bern-Basel)	926.2	3.7	691.8	2.8	475.4	1.9
Bern	606.4	2.4	408.6	1.6	186.1	0.7
Solothurn	85.3	0.3	76.6	0.3	35.9	0.1
Basel-Stadt	0.0	0.0	0.0	0.0	0.0	0.0
Basel-Landschaft	63.0	0.3	51.0	0.2	50.9	0.2
Jura	171.4	0.7	155.6	0.6	202.4	0.8
Region 4 - Centre North	400.0	1.6	187.2	0.7	85.4	0.3
Luzern	44.2	0.2	33.5	0.1	17.3	0.1
Uri	201.6	0.8	42.9	0.2	11.5	0.0
Schwyz	28.5	0.1	9.9	0.0	3.8	0.0
Obwalden	30.4	0.1	10.9	0.0	3.2	0.0
Nidwalden	4.3	0.0	0.9	0.0	0.0	0.0
Zug	1.1	0.0	0.9	0.0	0.0	0.0
Aargau	89.9	0.4	88.2	0.4	49.6	0.2
Region 5 - Tessin	264.4	1.1	68.5	0.3	25.2	0.1
Ticino	264.4	1.1	68.5	0.3	25.2	0.1
Region 6 - Graubünden	1305.7	5.2	430.1	1.7	191.9	0.8
Graubünden	1305.7	5.2	430.1	1.7	191.9	0.8
Region 7 - Centre North East (Zürich)	319.0	1.3	175.9	0.7	68.5	0.3
Zürich	42.0	0.2	41.5	0.2	10.4	0.0
Glarus	39.9	0.2	10.2	0.0	2.7	0.0
Schaffhausen	9.1	0.0	8.7	0.0	4.7	0.0
Appenzell Ausserrhoden	32.7	0.1	29.4	0.1	13.9	0.1
Appenzell Innerrhoden	20.7	0.1	12.7	0.1	13.1	0.1
St. Gallen	162.6	0.7	60.2	0.2	18.0	0.1
Thurgau	12.1	0.0	13.1	0.1	5.6	0.0
Total	4836.6	19.3	2787.3	11.1	1914.9	7.7

Table 15: Onshore wind potential for Switzerland under different restrictions

3. SWITZERLAND: NARRATIVES

With the reductions in the prices for solar photovoltaics and onshore wind that have occurred in recent years, renewables have become an economic alternative to building new gas power plants. Consequently, renewables have achieved a global market share of over 60% of all newly built power plants since 2014. Switzerland has significant solar resources and some additional potential for onshore wind. In 2019, the installed capacity of renewable power generation grew by more than 200 GW (mostly solar photovoltaic [PV]) (REN21 GSR 2020)[36]–10 times Switzerland's current power plant capacity–the largest global increase ever.

The cost of renewable power generation is generally lower in situations with greater solar radiation and higher wind speeds. However, constantly shifting policy frameworks often lead to high investment risks, and therefore to higher project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building process for all scenarios includes assumptions about policy stability, the roles of future energy utilities, centralized fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that all of Switzerland will establish a secure and stable framework for the deployment of renewable power generation. In essence, financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement, which ensures a relatively stable price for a specific quantity of electricity, is required to finance the project. Daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions about any kind of power plant with a technical lifetime of 20 years or longer. In short, the better the investment certainty, the lower the cost of capital.
- **Strengthened energy efficiency policies:** Existing policy settings (i.e., the energy efficiency standards for electrical applications, buildings, and vehicles) must be strengthened to maximize the cost-efficient use of renewable energy and to achieve high energy productivity in 2030 and beyond.
- **Role of future energy utilities:** Because the 'grid parity' of roof-top solar PV is below most current retail tariffs, this modelling assumes that energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** The REFERENCE scenario, the Energy [R]evolution scenario, and the ADVANCED Energy [R]evolution scenario are based on the same population and GDP assumptions. The projections of population growth and the GDP projections are based on government projections (see Table 4 and Table 5).
- **Cost assumptions:** The same cost assumptions are used across all three scenarios. Because technology costs decline as the scale of deployment increases rather than with time, the renewable energy cost reduction potential under both Energy [R]evolution scenarios may be even larger than under the REFERENCE scenario because the market sizes are larger. Furthermore, all scenarios are calculated with the same fossil fuel price projections. The cost assumptions are documented in section 5.3.

3.1 Switzerland: REFERENCE Scenario

The present energy policy debate in Switzerland is largely focused on the security of supply and decarbonization strategies to achieve net-zero green-house-gas emissions by 2050. Under the Paris Climate Agreement, all countries must submit National Determined Contributions (NDC) to comply with the treaty's rules. Therefore, the objective of the present report is to review Switzerland's targets under the accelerated decarbonization strategy required to achieve a maximum temperature rise of 1.5 °C globally.

The reference case is based on PROGNOS 2020[37] NET-ZERO scenario, published in 'The energy perspectives 2050+' analysis, which aimed to develop an energy system that is compatible with the long-term climate target of net zero greenhouse gas emissions by 2050 and at the same time ensures a secure energy supply. Several variants of this scenario are examined, which are characterized by different mixes of technologies. The technology paths are called the basic variant (ZERO Basis) and variants A, B, and C (ZERO A, ZERO B, and ZERO C). Further variants are also being investigated for the electricity system, which are based on different assumptions for the expansion of renewable energies within the electricity sector.

[36] REN21 GSR 2020—Global Status Report, Renewables 2020, page 17; https://www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf
[37] PROGNOS 2020, Energieperspektiven 2050+, Prognos AG, INFRAS AG
TEP Energy GmbH, Ecoplan AG; Im Auftrag des Bundesamt für Energie BFE; 9. November 2020

ZERO Basis is the variant that appears to be most advantageous from today's perspective in terms of the highest possible cost efficiency, high social acceptance, certain aspects of energy supply security, and the robustness of target achievement. However, there is a certain amount of leeway in achieving this goal. This is indicated by variants A, B and C. In ZERO A, more electrification takes place; in ZERO B, more synthetic gases are used; and in ZERO C, electricity-based liquid energy carriers and heating networks are given more weight than in the Basis variant. The range of scenarios examined is supplemented by the scenario '*Weiter wie bisher*' (WWB; business as usual), which depicts the continuation of the existing energy and climate policy measures. The REREFENCE scenario in this report is based on ZERO Basis. Because the methodologies differ, the scenario is not identical to ZERO Basis and has some variations in the demand and supply structure.

3.1.1 Switzerland: Assumptions for both Energy [R]evolution scenarios

Both Energy [R]evolution scenarios are built on a framework of targets and assumptions that strongly influence the development of individual technological and structural pathways for each sector. The main assumptions made in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures undertaken to reduce CO_2 emissions include strong improvements in energy efficiency, resulting in an increase in energy productivity of 33% between 2020 and 2030, and the dynamic expansion of renewable energy across all sectors.
- **Renewables industry growth:** The dynamic growth of new capacities for renewable heat and power generation is assumed, based on current knowledge of potentials, costs, and recent trends in renewable energy deployment (see energy potentials, discussed in section 2.5). Communities will play a significant role in the expansion of renewables, particularly in terms of project development, the inclusion of local populations, and the operation of regional and/or community-owned renewable power projects.
- **Future power supply:** The capacity of bio-energy facilities will grow within their economic and ecological potentials. The supply from all bio-energy facilities supported by sustainable biofuels and synthetic fuels is a key issue. Solar energy–especially solar PV power–and the existing hydro power plant capacities are expected to be the main pillars of the future power supply, complemented by contributions from bio-energy and wind energy. The solar PV figures combine both roof-top and utility-scale PV plants. The economic potential for onshore wind is limited and is used entirely to reduce storage requirements for solar-PV-driven production peaks.
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in each of the scenarios are designed to target the firm capacity. The firm capacity is the "proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed."[38] Firm capacity is important to ensure a reliable and secure energy system. Note that variable renewables also have a firm capacity rating, and the combination of technology options increases the firm capacity of a portfolio of options. Storage will add to the firm capacity as the share of variable power generation increases.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. This includes storage technologies. Power generation from biomass or hydro power, and a share of syngas-fired back-up capacity and storage, are considered important for the security of supply in a future energy system and are related to the output of firm capacity discussed above.
- **Electrification of transport**: Efficiency savings in the transport sector will result from fleet penetration by new highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The renewable energy scenarios assume a limited use of biofuels for transportation, given the limited supply of sustainable biofuels.

  Hydrogen and synthetic fuels: Hydrogen and synthetic fuels, generated by electrolysis using renewable electricity, are introduced as a third renewable fuel in the transportation sector, complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses. However, the limited potential of biofuels to supply the demand for industrial processes means it will be necessary to have a third renewable option. In the industry sector, hydrogen will be an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes whenever the direct use of renewable electricity is not possible. Alternatively, renewable hydrogen can be converted into synthetic methane and liquid fuels, to replace fossil fuel and to continue using the existing infrastructure, such as gas pipelines, to avoid stranded assets. Hydrogen and synthetic fuels can be produced locally or imported. In this analysis, synthetic fuels are introduced after 2030 as a replacement for natural gas.

[38] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf

3.1.2 Assumptions for both Energy [R]evolution scenarios

The Energy [R]evolution scenario is designed to meet Switzerland's energy-related targets and to lead towards a pathway of over 90% renewable energy by 2040 and an entire fossil fuel phase-out by 2050. The focus for this energy transition towards full decarbonization is on the power, residential building, and transport sectors. Electrification to replace fuels is at the core of the Energy [R]evolution concept, whereas the decarbonization of process heat for industry relies, to a large extent, on bio-energy fuel co-generation and heating plants.

The implementation of energy efficiency and renewable energy generation technologies will follow ambitious growth rates during the first decade until 2030. Electric mobility will grow steadily over the entire modelling period, and growth rates will increase significantly after an initial preparation phase from 2025 onwards. Switzerland's aging nuclear power capacity will be phase-out by 2030 and will be replaced by a mix of energy efficiency and renewable power generation−mainly solar PV.

3.1.3 Assumptions for the ADVANCED Energy [R]evolution scenario

The ADVANCED Energy [R]evolution scenario builds on the Energy [R]evolution scenario, following similar technology pathways but differing in the three main sectors, as follows:

d. Transport−a shift of transport modes to accelerate oil phase-out. Whereas the implementation of electric mobility follows the same pace as in the Energy [R]evolution scenario, cars with combustion engines will be replaced by a more ambitious reduction of individual transport. The use of cars will decrease by 1.5% per year between 2020 and 2025 and by 2% per year between 2025 and 2040. By 2040, more than one third of all passenger transport will have shifted away from cars towards public transport and (electric) bikes.

e. Buildings−oil heater exchange by 2030. The second major difference from the Energy [R]evolution scenario is an ambitious room-heating program that replaces all oil heaters used in Switzerland with a mix of efficiency improvements (building insulation), heat pumps, and solar collectors, which will deliver about one quarter of the required heating energy in buildings by 2050.

f. Industry−accelerated phase-out of natural gas. Industrial process heat requirements will be met by an increased share of hydrogen and synthetic fuels produced with renewable electricity. The level of bio-energy will remain the same and will not increase between 2020 and 2050.

The decarbonization of the power, heating, and transport sectors will be achieved by 2040 under both Energy [R]evolution scenarios. The ADVANCED Energy [R]evolution scenario will lead to less cumulative energy-related carbon emissions, but will require the increased importation of renewable electricity for hydrogen production−or the import of renewable hydrogen−because Switzerland does not have enough potential for large-scale solar PV to produce the entire amount of hydrogen required.

Table 16: Cumulative energy-related carbon emissions in 2017–2050 under the three different scenarios

	Cumulative Carbon Emissions in 2017–2050 [Mt CO_2]			Total CO_2 Reduction (2017–2050) compared with REFERENCE	
	REFERENCE	Energy [R]evolution	ADVANCED Energy [R]evolution	Energy [R]evolution	ADVANCED Energy [R]evolution
Switzerland:	804	527	483	34%	40%

4. KEY RESULTS FOR SWITZERLAND: LONG-TERM ENERGY SCENARIO

In this section, we outline the key results across a range of areas, in terms of both the impacts and the costs of the different scenarios. First, we consider stationary energy, focusing on electricity generation, capacity, and their breakdown by technology. We then examine the energy supply for heating, focusing on the industrial heat supply. This is followed by a discussion of the impacts and costs of the different scenarios on transport and the development of CO_2 emissions. The chapter ends with an examination of the final costs and an outline of the required energy budget.

The scenarios describe a holistic approach to the entire energy sector—power, heat, process heat, and transport. Increased electrical mobility and the electrification of heating processes will lead to '*sector coupling*' or the interconnection of historically rather separate energy sectors. As a result, the electricity demand will increase, even under ambitious electricity efficiency assumptions. Therefore, the following chapter, Chapter 5—Power Sector Analysis—focuses entirely on the electricity sector.

4.1 Switzerland's Final Energy Demand

We combine the projections for population development, GDP growth, and energy intensity to establish the future development pathways for Switzerland's final energy demand. These are shown in Figure 11 for the REFERENCE and Energy [R]evolution scenarios. Under the REFERENCE scenario, the total final energy demand will decrease by 29%, from the current 700 PJ/a to 500 PJ/a in 2050. Under the Energy [R]evolution scenario, the final energy demand will decrease by 43% compared with current consumption and is expected to reach 400 PJ/a by 2050. The ADVANCED Energy [R]evolution scenario will result in some additional reductions due to the higher share of electric cars.

Under both Energy [R]evolution scenarios, the overall electricity demand is expected to increase in response to economic growth, increasing living standards, and the electrification of the transport sector, despite efficiency gains in all sectors (see Figure 12). The total electricity demand will increase from about 60 TWh/a to 70 TWh/a in 2050 under the Energy [R]evolution scenario. Compared with the REFERENCE scenario, additional efficiency measures in the industry, residential, and service sectors will avoid the generation of about 10 TWh/a. This reduction will be achieved, in particular, by introducing highly efficient electronic devices using the best available technology in all demand sectors.

The transformation to a carbon-free energy system under the ADVANCED scenario will require the generation of 100 TWh annually by 2050. Electricity will become the major renewable 'primary' energy, not only for direct use for various purposes but also for the generation of synthetic fuels to substitute for fossil fuels. Around 20 TWh will be used for electric vehicles and rail transport in 2050 under the ADVANCED Energy [R]evolution scenario, with around 1.8 TWh for hydrogen for the transport sector (excluding bunkers; see Figure 13).

Efficiency gains will be even larger in the heating sector than in the electricity sector. Under the Energy [R]evolution scenarios, consumption equivalent to about 10 PJ/a will be avoided through efficiency gains by 2050 compared with the REFERENCE scenario. The same level of comfort and energy services will be accompanied by a much lower future energy demand as the result of energy-related renovation of the existing stock of residential buildings, the introduction of low energy standards, and 'passive climatization' in new buildings, as well as highly efficient air-conditioning systems.

The COVID-19 pandemic had a significant impact on the global economy during the first half of 2020 and it is almost certain that the GDP will contract in all countries. The possible economic impact on the Swiss economy is estimated to be −7.7% for 2020.

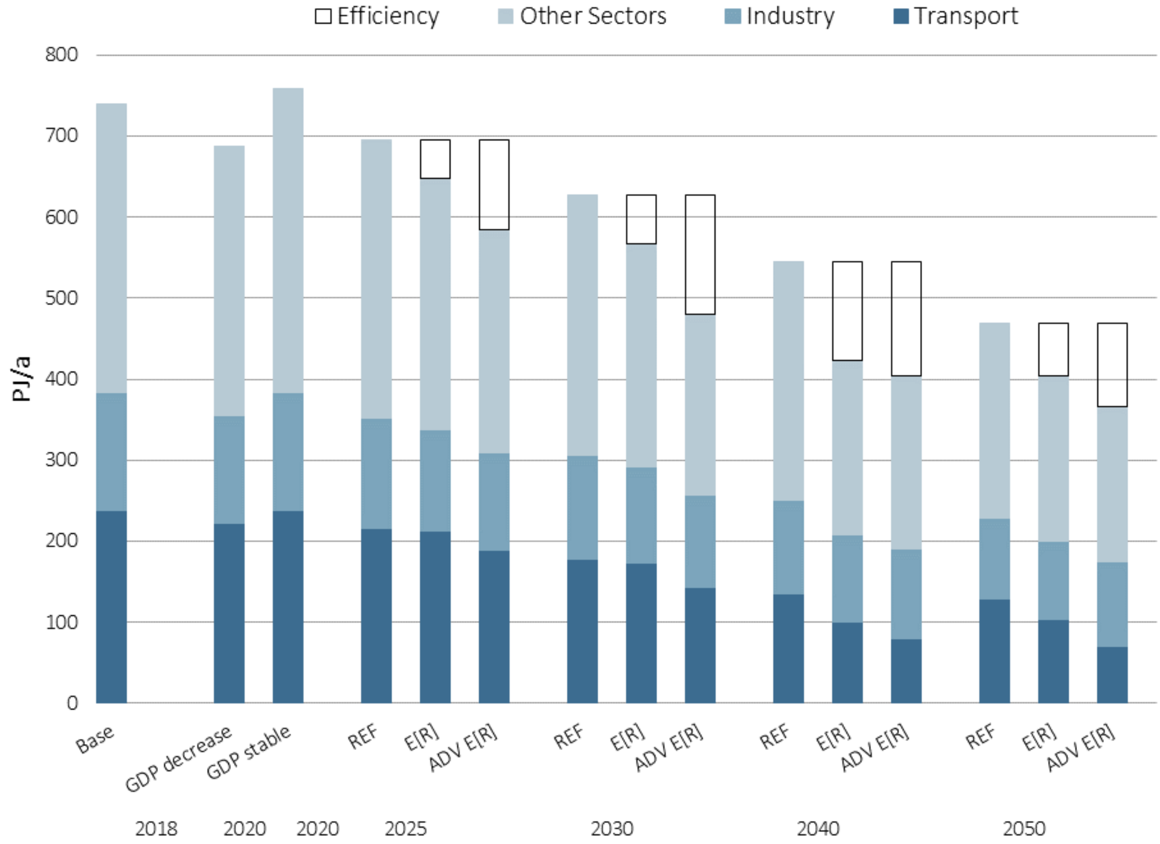
To take the unprecedented economic impact of the pandemic into account, two different GDP projections for 2020 have been calculated:

- 2020 in which GDP decreased by −7.7%
- 2020 in which GDP was stable, based on projections published prior to the pandemic of +1%

It is assumed that the economy will recover by 2025, so the following years, 2025–2050, are calculated with the long-term GDP projections (prior to the pandemic).

Switzerland's final energy demand could fall by up to 11% in 2020 if a decline in GDP of −7.7% actually occurs.

Figure 11: Projections of total final energy demand by sector (excluding non-energy use and heat from CHP autoproducers)



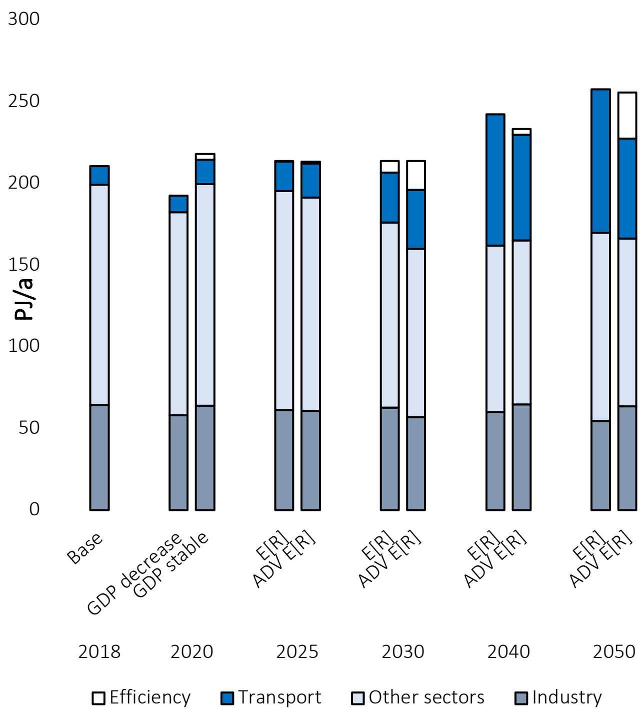


Figure 12: Development of the electricity demand by sector under both Energy [R]evolution scenarios

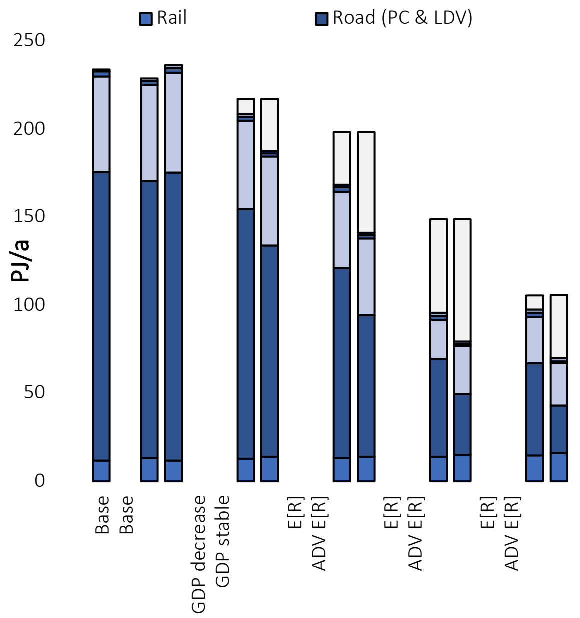


Figure 13: Development of the final energy demand for transport by sector under the Energy [R]evolution and ADV Energy [R]evolution] scenarios

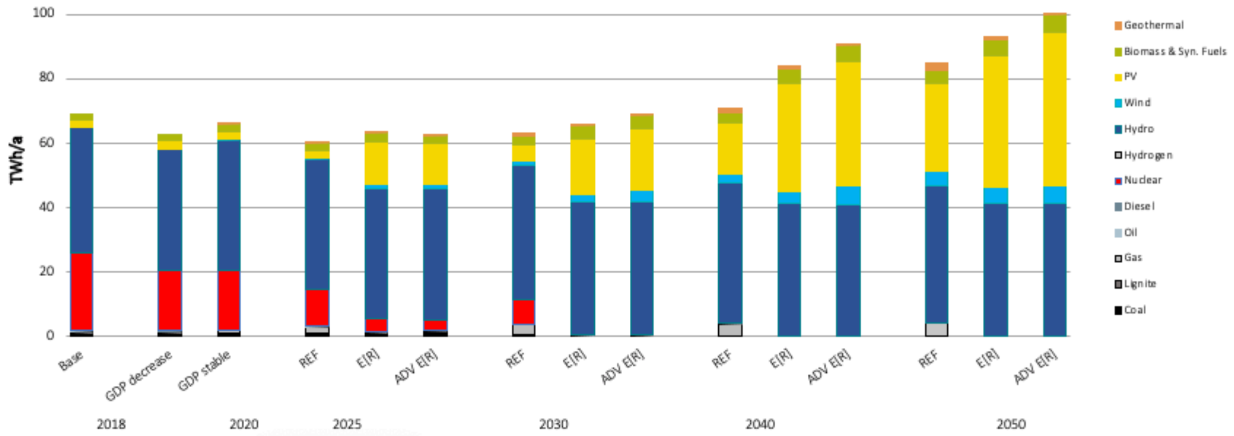
4.2 Switzerland: Electricity Generation

The development of the electricity supply sector is characterized by a dynamically growing renewable energy market and an increasing share of renewable electricity. This trend will more than compensate for the phasing-out of nuclear power production under the Energy [R]evolution scenarios, together with a continuous reduction in the number of fossil-fuel-fired power plants. By 2050, 100% of the electricity produced in Switzerland will come from renewable energy sources under the Energy [R]evolution scenario. 'New' renewables—mainly wind and solar PV electricity—will contribute 50% to the total electricity generation. The share of renewable electricity production will be 90% by 2025 and 100% by 2030. The installed capacity of renewables will reach about 31.6 GW in 2030 and 55.1 GW by 2050.

Table 17: Projections of renewable electricity generation capacities

In GW		2018	2025	2030	2040	2050
Hydro	REF	13.372	13.572	13.914	14.588	14.226
	E[R]		13.538	13.606	13.674	13.746
	ADV E[R]		13.538	13.606	13.674	13.746
Biomass	REF	0.369	0.478	0.533	0.653	0.797
	E[R]		0.484	0.755	0.844	0.900
	ADV E[R]		0.472	0.735	0.905	1.015
Wind	REF	0.075	0.528	0.810	1.448	2.590
	E[R]		0.614	1.150	1.639	2.122
	ADV E[R]		0.626	1.893	2.334	2.400
Geothermal	REF	0.000	0.061	0.122	0.199	0.325
	E[R]		0.028	0.050	0.129	0.190
	ADV E[R]		0.003	0.005	0.009	0.018
PV	REF	2.090	3.119	4.520	14.828	25.356
	E[R]		12.044	16.042	31.173	38.179
	ADV E[R]		11.826	17.782	36.257	44.250
Total	REF	15.905	17.762	19.903	31.724	43.301
	E[R]		26.708	31.602	47.459	55.136
	ADV E[R]		26.465	34.021	53.179	61.433

Figure 14: Breakdown of electricity generation by technology



The 100% electricity supply from renewable energy resources under the ADVANCED Energy [R]evolution scenario will lead to an installed generation capacity of just over 61 GW in 2050.

Table 17 shows the comparative evolution of the different renewable technologies in Switzerland over time. Until 2040, hydro will remain the main renewable power source. PV will just overtake biomass as the second largest contributor to the growing renewable market. After 2025, the continuing growth of wind and solar PV will be complemented by electricity from bio-energy and some additional geothermal energy. Both Energy [R]evolution scenarios will lead to a high share of variable power generation sources (PV and wind) of 22% by 2025 and around 45% by 2050. Therefore, smart grids, demand-side management, energy storage capacities, and other options must be expanded to increase the flexibility of the power system for grid integration, load balancing, and a secure supply of electricity.

Both alternative scenarios will use the onshore wind potential with the highest restrictions (described in section 2.5.2) until 2030. The wind expansion plan is consistent with the Swiss national wind plan under the Energy [R]evolution scenario and slightly higher under the ADVANCED Energy [R]evolution scenario.

4.3 Switzerland: Energy Supply for Heating and Industrial Process Heat

Today, renewables meet around 22% of Switzerland's energy demand for heating, and the main contribution is from biomass. Dedicated support instruments are required to ensure dynamic development, particularly in renewable technologies for buildings and renewable process heat production. In the Energy [R]evolution scenario, renewables will already provide 60% of Switzerland's total heat demand in 2030 and 100% in 2050.

- Energy efficiency measures will help to reduce the currently growing energy demand for heating by 7% in 2050 (relative to the REFERENCE scenario), despite improved living standards and economic growth.
- In the industry sector, solar collectors, geothermal energy (including heat pumps), as well as electricity and hydrogen from renewable sources will increasingly substitute for fossil-fuel-fired systems.
- A shift from natural gas to bio-energy and hydrogen/synthetic fuels in the remaining conventional applications will lead to a further reduction in CO_2 emissions.

The calculated reduction in the heat demand in the *reduced GDP* case for 2020 is based on the assumption that less economic activity will lead to a reduction in demand for industrial process heat and for the climatization of commercial buildings, such as offices and shops.

Figure 15: Switzerland—Projection of heat supply by energy carrier (REF, E[R], and ADV E[R])

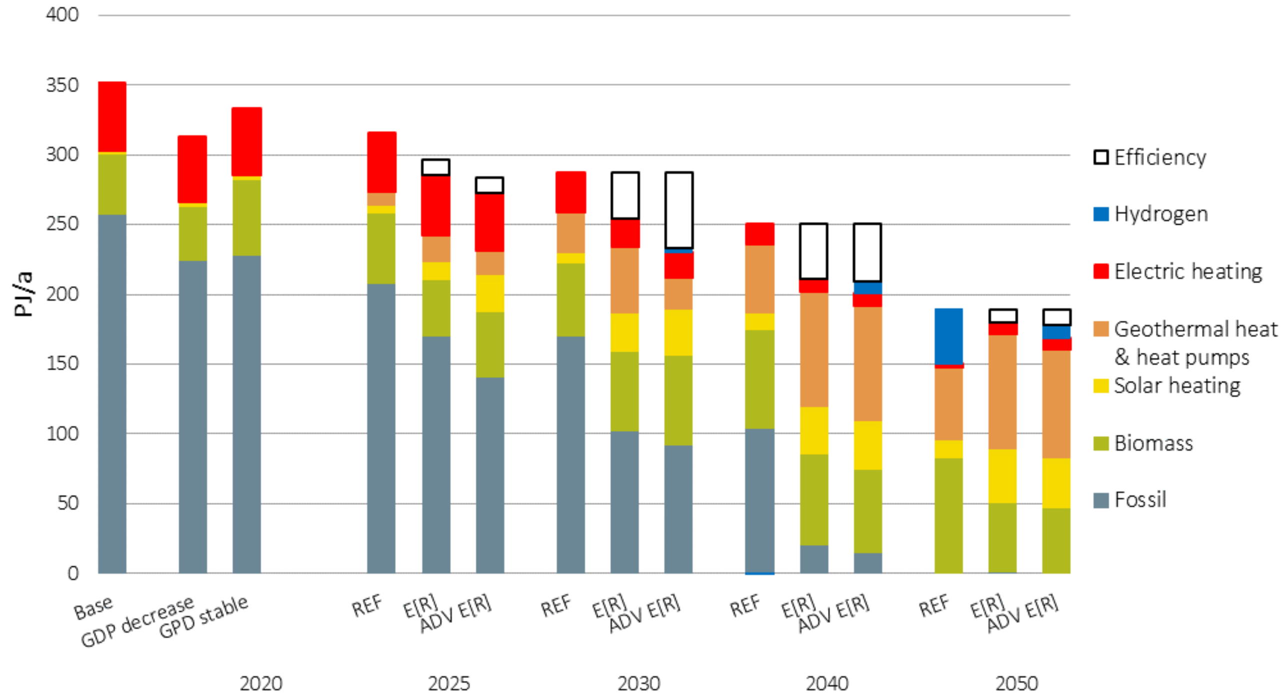


Table 18: Switzerland—Projections of renewable heat supply

in PJ/a		2018	2020	2020	2025	2030	2040	2050
			Reduced GDP	Stable GDP				
Biomass	REF	43	45	54	50	52	71	83
	E[R]				40	57	65	50
	ADV E[R]				47	64	59	48
Solar heating	REF	3	2	3	5	8	12	12
	E[R]				14	27	34	38
	ADV E[R]				26	33	35	35
Geothermal heat & heat pumps	REF	3	3	3	10	29	49	52
	E[R]				18	47	82	82
	ADV E[R]				18	23	82	78
Hydrogen	REF	0	0	0	0	0	0	39
	E[R]				0	0	0	0
	ADV E[R]				0	3	8	9
Total	REF	49	50	60	65	89	132	186
	E[R]				72	132	181	171
	ADV E[R]				91	123	185	170

Table 18 shows the development of different renewable technologies for heating in Switzerland over time. Biomass will remain the main contributor, with increasing investments in highly efficient modern biomass technology. After 2030, a massive growth in solar collectors and a growing share of geothermal and environmental heat, as well as heat from renewable hydrogen, will further reduce the dependence on fossil fuels. The ADVANCED Energy [R]evolution scenario will result in the complete substitution of the remaining gas consumption by hydrogen generated from renewable electricity.

Table 19: Switzerland—Installed capacities for renewable heat generation

in GW		2018	2020	2025	2030	2040	2050
			Stable GDP				
Biomass	REF	7	7	6.8	6.7	6.7	7.6
	E[R]			4.7	5.3	5.3	5.2
	ADV E[R]			6.6	7.1	7.1	4.9
Geothermal	REF	0	0	0.0	0.0	0.0	0.0
	E[R]			0.0	0.0	0.0	0.0
	ADV E[R]			0.0	0.0	0.0	0.0
Solar heating	REF	2.5	2.7	1.6	2.4	2.4	3.7
	E[R]			3.2	6.3	6.3	9.2
	ADV E[R]			7.2	8.0	8.0	10.1
Heat pumps	REF	2.2	2.4	2.5	7.1	7.1	12.2
	E[R]			4.1	9.5	9.5	17.2
	ADV E[R]			3.9	5.0	5.0	17.1
Total 1)	REF	10.2	10.4	10.9	16.3	16.3	23.5
	E[R]			11.9	21.1	21.1	31.7
	ADV E[R]			17.7	20.1	24.0	29.3

4.4 Switzerland: Transport

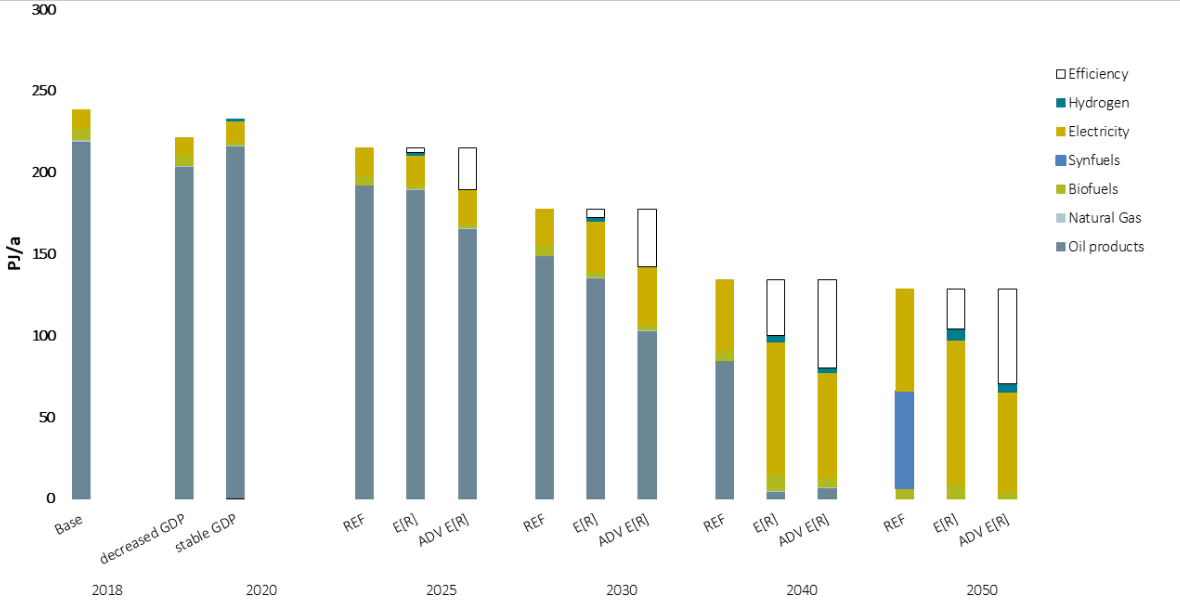
A key target in Switzerland is to introduce incentives for people to drive smaller cars and to buy new, more-efficient vehicles. It is also vital to shift transport use to efficient modes such as rail, light rail, and buses, especially in the expanding large metropolitan areas. Together with rising prices for fossil fuels, these changes will reduce the further growth of car sales projected under the REFERENCE scenario. Despite an increase in population, GDP growth, and higher living standards, the energy demand from the transport sector is expected to decrease under the REFERENCE scenario by around 46% to 130 PJ/a in 2050. Under the Energy [R]evolution scenario, efficiency measures and modal shifts will save 19% (10 PJ/a) in 2050 compared with the REFERENCE scenario.

Additional modal shifts and technology switches will lead to even higher energy savings under the ADVANCED Energy [R]evolution scenario of 45% (60 PJ/a) in 2050 compared with the REFERENCE scenario. Highly efficient propulsion technology with hybrid, plug-in hybrid, and battery-electric-powered trains will bring about large efficiency gains. By 2030, electricity will provide 18% of the transport sector's total energy demand under the Energy [R]evolution scenario, whereas in 2050, the share will be 84% (87% under the ADVANCED Energy [R]evolution scenario). Hydrogen and other synthetic fuels generated with renewable electricity will be complementary options to further increase the renewables share in the transport sector. In 2050, up to 5 PJ/a of hydrogen will be used in the transport sector under the ADVANCED Energy [R]evolution scenario.

Table 20: Switzerland—Projection of the transport energy demand by mode (excluding pipeline transport)

in PJ/a		2017	2020		2025	2030	2040	2050
			Reduced GDP	Stable GDP				
Rail	REF	12	11	12	13	14	15	16
	E[R]				13	13	14	15
	ADV E[R]				14	14	15	16
Road	REF	222	206	222	200	180	129	85
	E[R]				192	151	78	79
	ADV E[R]				171	124	62	51
Domestic Aviation	REF	3	3	3	3	3	3	3
	E[R]				2	2	2	3
	ADV E[R]				2	2	1	1
Domestic Navigation	REF	2	1	2	2	2	2	2
	E[R]				2	2	2	2
	ADV E[R]				1	1	1	2
Total	REF	238	221	238	217	198	148	105
	E[R]				209	168	96	98
	ADV E[R]				188	143	84	82

Figure 16: Switzerland—Final energy consumption by transport under the scenarios

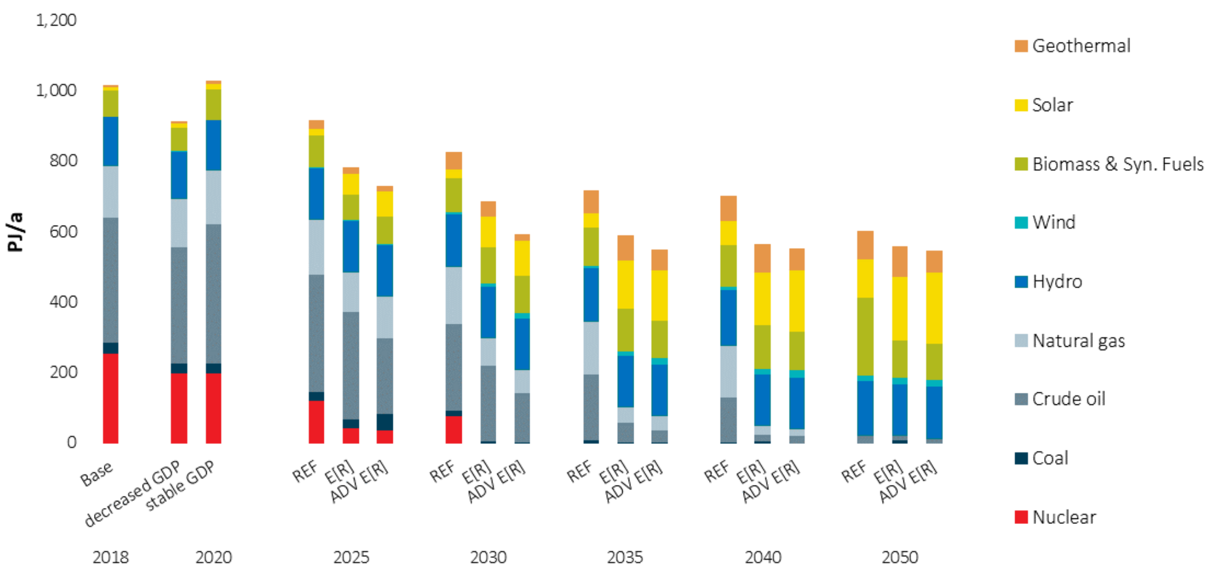


4.5 Switzerland: Primary Energy Consumption

The primary energy consumption under the Energy [R]evolution scenarios after the assumptions discussed above are taken into account is shown in Figure 17. Under the Energy [R]evolution scenario, the primary energy demand will decrease by 45% from today's 1010 PJ/a to around 560 PJ/a. Compared with the REFERENCE scenario (around 40 PJ in 2050), the overall primary energy demand will decrease by 13% in 2050 under the Energy [R]evolution. The ADVANCED Energy [R]evolution scenario will result in a primary energy consumption of 549 PJ in 2050.

The Energy [R]evolution scenarios aim to phase-out coal and oil as fast as is technically and economically possible by the expansion of renewable energies and the rapid introduction of very efficient vehicle concepts in the transport sector to replace oil-based combustion engines. This will lead to overall renewable primary energy shares of 54% in 2030 and 100% in 2050 under the Energy [R]evolution scenario and of more than 100% in 2050 under the ADVANCED Energy [R]evolution scenario (including non-energy consumption).

Figure 17: Projection of total primary energy demand by energy carrier (including electricity import balance)

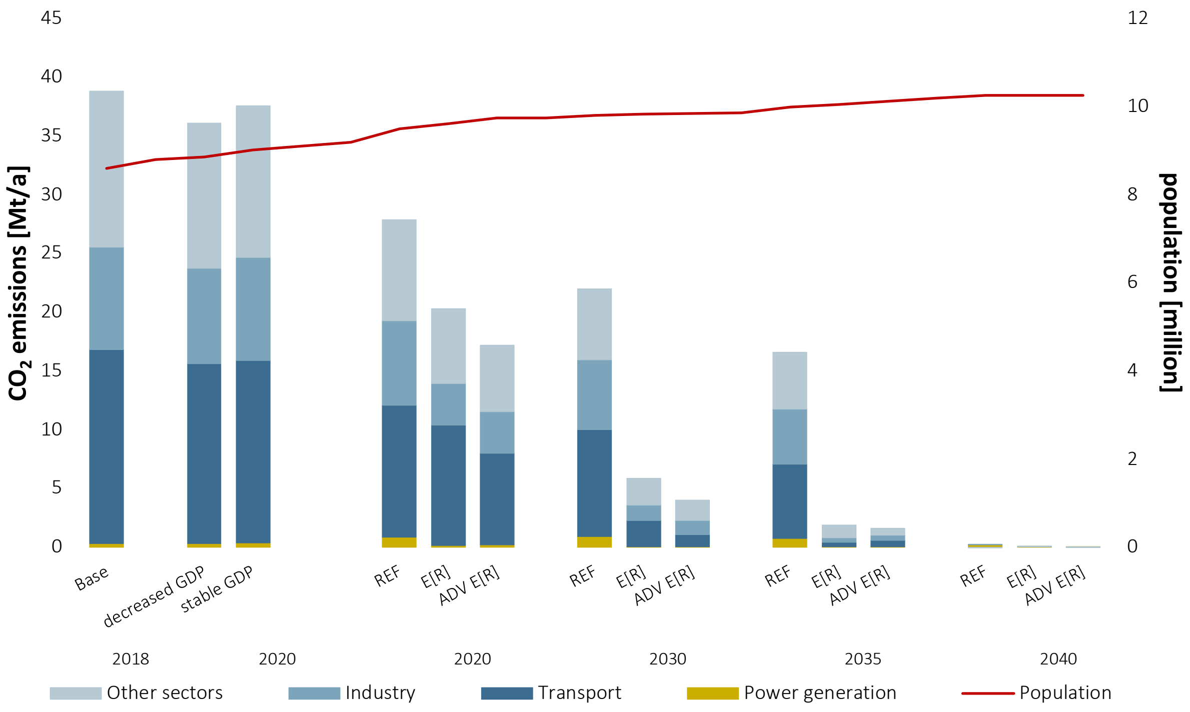


4.6 CO_2 Emissions Trajectories

Both Energy [R]evolution scenarios will decarbonize the power sector by 2030, the industry sector by 2040, and the transport sector by 2040. The REFERENCE scenario will also decarbonize the entire energy system by 2050. The main differences are that the REFERENCE scenario will replace remaining fossil fuels after 2040 with hydrogen and synthetic fuels—mainly imported, whereas both Energy [R]evolution scenarios will increase direct electrification to replace fuels—including synthetic fuels. The ADVANCED Energy [R]evolution will replace biomass with higher rates of electric mobility, and cars with combustion engines will be phased-out and not entirely replaced with electric vehicles, but with an increase in public transport and the use of bicycles and/or walking. Furthermore, oil heating systems—which are very common in Switzerland—will be replaced with electrical and renewable heating systems until 2030.

The greatest annual CO_2 emissions under the Energy [R]evolution scenario will come from the transport sector, with around 14 million tons in 2025 and 11 million tons in 2030. Between 2020 and 2050, the ADVANCED Energy [R]evolution scenario will result in cumulative energy-related CO_2 emissions of 489 million tons, whereas the basic Energy [R]evolution scenario will result in 534 million tons in the same time period. The reduction under the ADVANCED Energy [R]evolution scenario is due to the rapid phase-out of combustion engines in the transport sector and of oil heating systems. The REFERENCE scenario will lead to accumulated energy-related CO_2 emissions of 804 million tons until 2050—39% higher than the ADVANCED Energy [R]evolution case.

Figure 18: Switzerland—Development of CO_2 emissions by sector



4.7 Switzerland: Cost Analysis—Long-term Energy Scenario

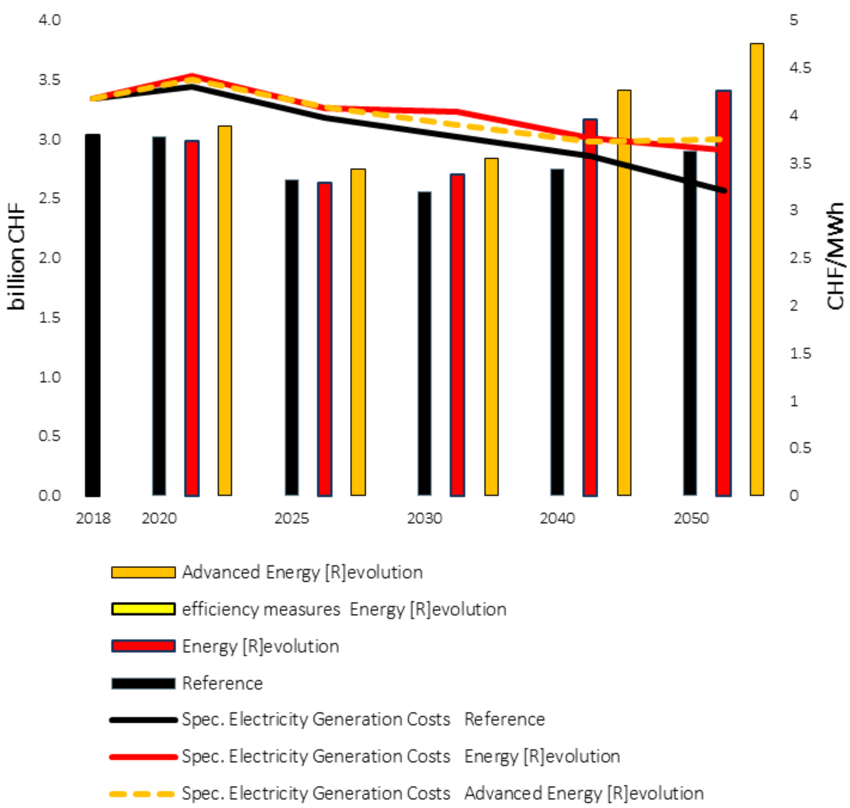
4.7.1 Future costs of electricity generation

The costs provided in this section include all the construction costs for new power plants, the average standard operation and maintenance costs for each technology, and fuel costs.

Figure 19 shows that the introduction of renewable technologies under both Energy [R]evolution scenarios will increase the future cost of electricity generation compared with the REFERENCE scenario until 2030, without any additional cost for carbon. This difference in the full cost of generation will be less than 0.3 CHF/MWh under the Energy [R]evolution scenario and about 0.2 CHF/MWh under the ADVANCED Energy [R]evolution scenario, when the integration costs for storage or other load-balancing measures are not taken into account. Because the prices of conventional fuels will increase and the CO_2 intensity of electricity generation will decrease, electricity generation costs will become economically favourable after 2040 under the Energy [R]evolution scenario. However, differences in the electricity generation costs between both Energy [R]evolution scenarios and the REFERENCE scenario will be minor until 2050, at around 0.5 CHF/MWh, and within the margin of error for the long-term projection beyond 30 years.

Under the assumption of a high carbon tax of CHF100 per ton CO_2 in 2025, and a further increase of CHF50 every 5 years to CHF350, the ADVANCED Energy [R]evolution will be the most economic scenario (Figure 20).

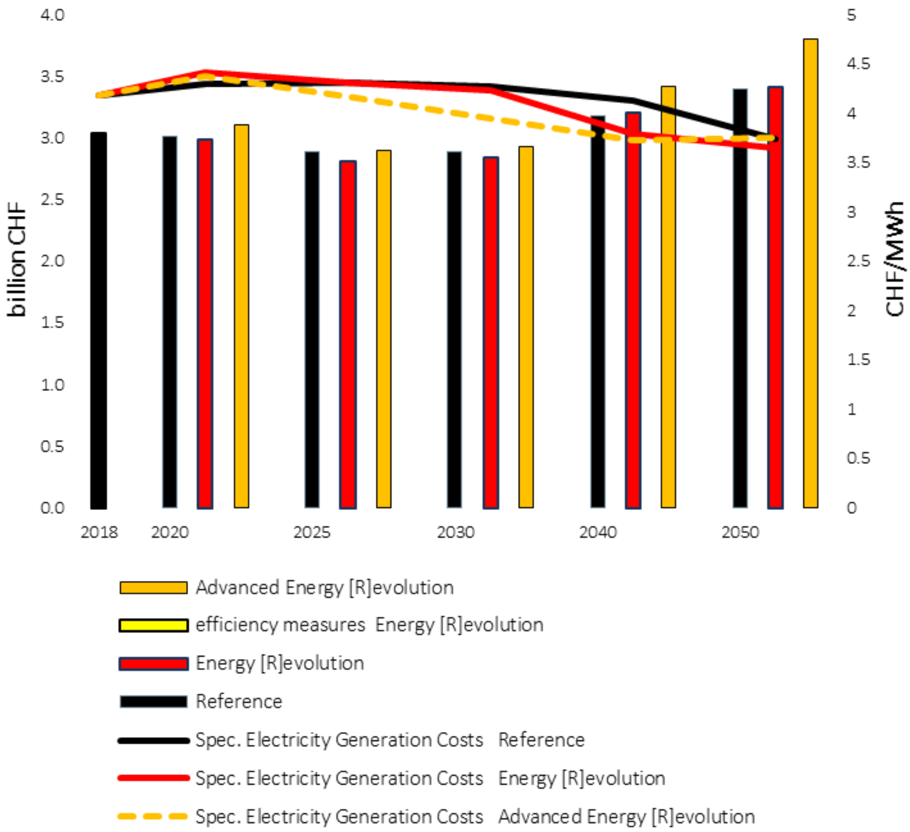
Figure 19: Switzerland—Development of total electricity supply costs and specific electricity generation costs in the scenarios—with no carbon costs



Under the REFERENCE scenario, the total calculated electricity supply costs, excluding any carbon costs, will decrease slightly from today's CHF3 billion per year to CHF 2.6 billion in 2025 and increase again to CHF 2.9 billion by 2050. The overall electricity supply costs under the Energy [R]evolution scenarios will follow the REFERENCE development, with similar costs in 2025, increasing to CHF 3.4 billion by 2050. The ADVANCED scenario will have the highest overall electricity supply costs because it will have the highest electrification rate. However, both Energy [R]evolution scenarios use higher volumes of electricity to replace fossil fuel in the transport and heating sectors.

The total electricity supply costs, including the assumed carbon costs, will lead to almost identical electricity supply costs in the REFERENCE scenario and Energy [R]evolution scenario, whereas the ADVANCED Energy [R]evolution scenario will have the highest overall supply costs. However, it will have the lowest specific electricity generation costs and will therefore be the most economic scenario if carbon costs are included.

Figure 20: Switzerland—Development of total electricity supply costs and specific electricity generation costs in the scenarios—with carbon costs (2025, 100 CHF/ton CO_2; 2030, 150 CHF/ton CO_2; 2050, 350 CHF/ton CO_2)



4.7.2 Future investments in the power sector

Around CHF 70 billion is required in investment for the Energy [R]evolution scenario to become a reality (including investments in the replacement of plants after their economic lifetimes)—or approximately CHF 2 billion per year, CHF 20 billion more than in the REFERENCE scenario (CHF 50 billion). Investments under the Energy [R]evolution and ADVANCED Energy [R]evolution scenarios will sum to CHF 60 billion and CHF 70 billion, respectively, or CHF 3 billion per year on average. All scenarios will focus on investment in the renewables sectors, with no new capacities for fossil-fuel power plants.

Because renewable energy involves no fuel costs, the fuel cost savings in both Energy [R]evolution scenarios will reach around CHF10 billion in total up to 2050, or CHF 0.33 billion per year. Therefore, the total fuel cost savings will be equivalent to 50% of the total additional investments required under the REFERENCE scenario. Renewable energy sources will then go on to produce electricity without any further fuel costs beyond 2050, whereas the cost of imported synthetic fuels will remain under the REFERENCE scenario.

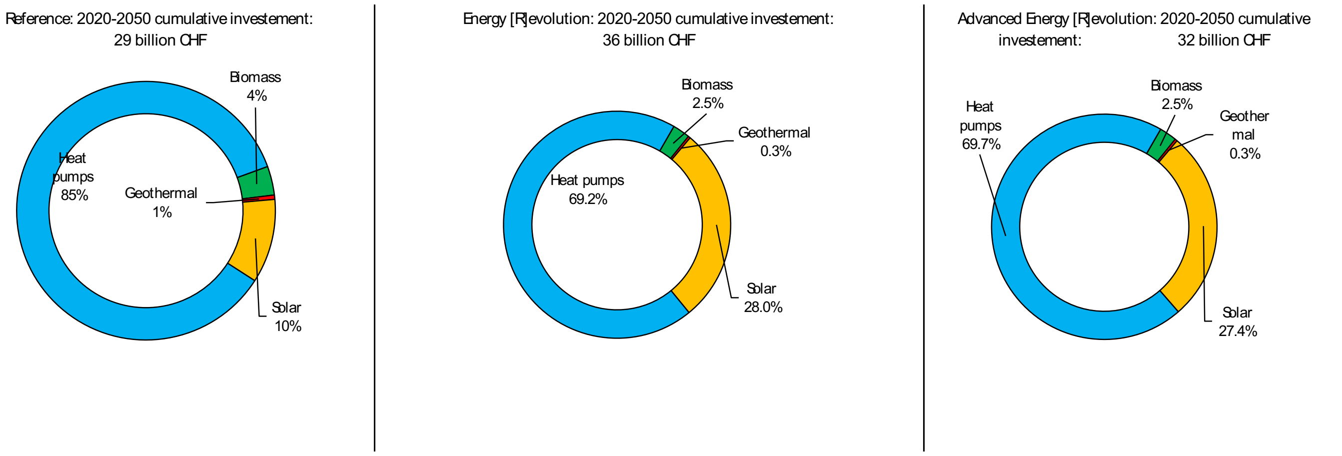
4.7.3 Future investments in the heating sector

Similarly, in the heating sector, the Energy [R]evolution scenarios will require a major revision of the current investment strategies for heating technologies. In particular, solar thermal, geothermal, and heat pump technologies will require enormous increases in installations if these potentials are to be tapped for the heating sector. The use of biomass for heating purposes will shift from the traditional biomass common today to modern, efficient, and environmentally friendly heating technologies under the Energy [R]evolution scenarios.

Renewable heating technologies are extremely variable, from low-tech biomass stoves and unglazed solar collectors to very sophisticated enhanced geothermal and solar systems. Therefore, a necessarily rough estimate is that the Energy [R]evolution scenario will require a total of around CHF 35.5 billion investment in renewable heating technologies up to 2050 (including investments in the replacement of plants after their economic lifetimes), or approximately CHF 1.2 billion per year. The ADVANCED Energy [R]evolution scenario assumes an equally ambitious expansion of renewable technologies, resulting in an average investment of around CHF 1.06 billion per year, although the main strategy in this scenario is the substitution of the remaining natural gas consumption with electricity and bio-energy.

The REFERENCE scenario will increase the use of heat pumps, similar to both Energy [R]evolution scenarios. However, both Energy [R]evolution scenarios will use more solar collectors for space heating and less bio-energy than the REFERENCE scenario. The overall investment in new renewable heating systems under that scenario is calculated to be CHF 28.9 billion.

Figure 21: Switzerland—Cumulative investments in *renewable* heat generation in 2020–2050



4.7.4 Investment and fuel cost savings in the power sector

Compared with the REFERENCE scenario, the additional investments under the Energy [R]evolution scenario between 2020 and 2030 are estimated to be CHF 9.8 billion, or just under CHF 1 billion per year. Over the entire modelling period until 2050, the overall additional investments under the Energy [R]evolution scenario will accumulate to CHF 15.9 billion, and the fuel costs in the power sector alone will account for 38% of these (CHF 6.1 billion), because additional fuel costs will arise in the transport and heating sectors due to the high electrification rates.

Table 21: Cumulative investment costs for electricity generation and fuel cost savings under Energy [R]evolution

CUMULATIVE INVESTMENT COSTS Difference: REFERENCE minus Energy [R]evolution		2020–2030	2020–2030 average per year	2031–2040	2041–2050	2020–2050	2020–2050 average per year
Conventional (fossil + nuclear)	billion CHF	0.1	0.0	0.0	0.1	0.2	−0.1
Renewables (including CHP)	billion CHF	−9.9	−1.0	−1.5	−4.8	−16.2	−0.5
Total	**billion CHF**	**−9.8**	**−1.0**	**−1.5**	**-4.7**	**−15.9**	**−0.6**
CUMULATIVE FUEL COST SAVINGS							
Savings: Cumulative Energy [R]evolution versus REFERENCE							
Fuel oil	billion CHF	0.0	0.0	0.0	−0.1	0.0	0.0
Gas	billion CHF	0.9	0.1	2.6	1.7	5.2	0.2
Hard coal	billion CHF	0.1	0.0	0.0	−0.2	0.1	0.0
Lignite	billion CHF	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear energy	billion CHF	0.6	0.1	0.2	0.0	0.8	0.0
Total	**billion CHF**	**1.7**	**0.2**	**2.8**	**1.6**	**6.1**	**0.2**

Under the ADVANCED Energy [R]evolution scenario, the additional investment between 2020 and 2030 is estimated to be around CHF 12.1 billion compared with the REFERENCE scenario. Between 2021 and 2050, the fuel cost savings will add up to CHF 6.0 billion, similar to those under the Energy [R]evolution scenario, and additional investments in renewables will add up to CHF 21.5 during the same time period. Fuel cost savings in the transport sector arising from increased electrification are not included.

Table 22: Cumulative investment costs for electricity generation and fuel cost savings under ADVANCED Energy [R]evolution

CUMULATIVE INVESTMENT COSTS Difference: REFERENCE minus ADVANCED Energy [R]evolution		2020–2030	2020–2030 average per year	2031–2040	2041–2050	2020–2050	2020–2050 average per year
Conventional (fossil + nuclear)	billion CHF	0.1	0.0	0.0	−0.1	0.2	0.0
Renewables (incl. CHP)	billion CHF	−12.3	−1.2	−3.2	−6.3	−21.8	−0.7
Total	**billion CHF**	**−12.1**	**−1.2**	**−3.2**	**−6.2**	**−21.5**	**−0.7**
CUMULATIVE FUEL COST SAVINGS							
Savings: Cumulative ADVANCED Energy [R]evolution versus REFERENCE							
Fuel oil	billion CHF	0.0	0.0	0.0	0.0	0.1	0.0
Gas	billion CHF	1.0	0.1	2.6	1.7	5.2	0.2
Hard coal	billion CHF	0.1	0.0	0.1	−0.2	0.1	0.0
Lignite	billion CHF	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear energy	billion CHF	0.6	0.1	0.2	0.0	0.8	0.0
Total	**billion CHF**	**1.7**	**0.2**	**2.9**	**1.5**	**6.2**	**0.2**

5. SWITZERLAND: POWER SECTOR ANALYSIS

In this chapter, we summarize the results of the hourly simulations of the long-term scenarios (Chapter 4). The [R]E 24/7 model calculates the demand and supply by cluster. The electricity market in Switzerland has been partly liberalized since 2009. With an annual demand over 100,000 kWh, consumers can choose their electricity supplier. The Swiss Government decided in April 2020 to further open up the electricity market for households and small businesses[39]. Because of its geographic position, the Swiss electricity market includes large shares of imported and exported electricity, which are traded on stock markets.

This analysis is based on various consultations with local experts and took the key points of the published Switzerland's *Strategic Grid 2025*[40] strategy as a central foundation for the development of both Energy [R]evolution scenarios. Moreover, it extends this strategy further in terms of the deployment of renewable and sustainable local resources. The new scenarios aim to reduce energy-related carbon emissions even faster, so the shares of variable renewable electricity—mainly solar, because wind resources are insufficient—will grow rapidly between 2020 and 2030. We also simulated the REFERENCE scenario based on PROGNOS 2020 with the [R]E24/7 model (see section 03.1). We compared our results for the future projected loads with the results of the *Strategic Grid 2025* publication.

5.1 Switzerland: Development of Power Plant Capacities

Switzerland has legislated for a staged nuclear phase-out by 2035. The development of other fossil-fuelled power generation—mainly natural gas power plants—is discussed within the various energy scenarios. However, the overall consensus in the Swiss energy debate is to decarbonize the power sector, although the speed of transition and the choice of technologies have not been decided. This analysis aims to contribute to the debate.

In terms of the renewable electricity potential, the vast majority of future generation will be solar photovoltaic (PV). Wind resources are limited and the land-locked country has no access to any offshore renewable energy resources. Hydro power plants have already been the backbone of the Swiss power sector for decades and the sustainable biomass resources are limited. There is a small geothermal energy potential for electricity generation, whereas the potential for geothermal heating systems (heat pumps) for low-temperature heating is significant.

Therefore, the capacity for solar PV installations will increase substantially under both Energy [R]evolution scenarios. The average market until 2025 will range around 130 MW per year under the REFERENCE scenario, whereas the Energy [R]evolution scenarios will require the annual installation of around 1,900 MW.

Under the ADVANCED Energy [R]evolution scenario, Switzerland will increase its wind power capacity by close to 650 MW by 2025 and 1,900 MW by 2030. This will exhaust the calculated potential of wind power under the NGO consensus of a maximum of 400 wind turbines (see also section 2.5.2). The rapid transition towards a fully decarbonized electricity sector by 2035 will lead to an almost unchanged power generation mix between 2035 and 2050, with only solar PV installations increasing slightly. However, there will be a rapid increase in the electricity demand due to the high electrification rates in the transport and heating sectors. The majority of the Swiss solar market after 2035 will be replacement capacities for installations older than 20–25 years. In both Energy [R]evolution scenarios, solar PV and hydro power will provide the backbone of the Swiss electricity supply.

The lack of support for wind power and the relative low wind power potential of around 9 TWh per year means that the requirements for seasonal storage capacities or electricity imports are greater than in countries with sufficient wind resources.

[39] Schweizerische Eidgenossenscjhaft, Departement fuer Umwelt, Verkehr und Kommunikation (UVEK), https://www.uvek.admin.ch/uvek/de/home/energie/oeffnung-strommarkt.html
[40] SwissGrid 2015, Bericht zum Strategischen Netz 2025, https://www.swissgrid.ch/dam/swissgrid/projects/strategic-grid/sg2025-technical-report-de.pdf

Table 23: Switzerland—Average annual changes in installed power plant capacity (main technologies)

Power Generation: average annual change of installed capacity [MW/a] renewables versus nuclear	2021–2025			2026–2030			2030–2050		
	REF	E[R]	ADV E[R]	REF	E[R]	ADV E[R]	REF	E[R]	ADV E[R]
Nuclear	−245	−512.0	−512.0	−145	−144.0	−144.0	−65	0.00	0.00
Biomass (including CHP)	7.0	22.7	21.2	11.0	54.1	52.5	13.2	7.3	14.0
Hydro	33.7	27.0	27.0	68.5	13.6	13.6	15.6	7.0	7.0
Wind (onshore)	78.0	105.0	108.0	44.0	107.0	253.0	62.5	49.0	25.6
Photovoltaic (roof-top)	96.3	1432.3	1,400	210.1	600.0	893.4	781.3	801.4	992.5.8
Photovoltaic (utility-scale)	32.1	477.4	466.5	70.0	200.0	297.8	260.4	267.1	330.8

5.2 Switzerland: Utilization of Power Generation Capacities

Table 24 and Table 25 show the installed capacities for solar PV and wind for the Energy [R]evolution scenario in 2030 and for the more ambitious ADVANCED Energy [R]evolution scenario in 2050, respectively. The distributions are based on the regional solar and wind potentials and the regional demands, with the aim of generating electricity where the demand is located. Whereas solar PV power generation is modular and can be installed close to the consumer or even integrated into buildings, onshore wind must be kept at a distance of several hundred meters from settlements. Therefore, onshore wind must be clustered into wind farms with double digit megawatt capacities, on average. The best wind resources are in the West region (Fribourg, Vaud, Neuchâtel, Genève), South West region (Wallis), and Graubuenden.

Table 24: Switzerland—Installed photovoltaic and wind capacities by region—Energy [R]evolution (2030)

Energy [R]evolution 2030	West	South West (Wallis)	Centre-West (Bern-Basel)	Centre North	Tessin	Graubuenden	Centre North East (Zürich)
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
Photovoltaic (roof-top)	2,268	526	2,5509	2,392	603	391	4,103
Photovoltaic (utility-scale)	567	131	638	598	151	98	1,026
Onshore wind	383	383	96	96		288	96

Table 25: Switzerland—Installed photovoltaic and wind capacities by region—ADV. Energy [R]evolution (2050)

ADVANCED Energy [R]ev olution 2050	West	South West (Wallis)	Centre-West (Bern-Basel)	Centre North	Tessin	Graubuenden	Centre North East (Zürich)
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
Photovoltaic (roof-top)	6,167	1,656	6,948	6,350	1,607	1,221	9,411
Photovoltaic (utility-scale)	1,542	414	1,737	1,588	402	305	2,353
Onshore wind	686	686	171	171	0	514	171

Both Energy [R]evolution scenarios aim for an even distribution of variable power plant capacities across all regions by distributing the roof-top and utility-scale solar PV and onshore wind power generation facilities accordingly. In this analysis, we assumed that 80% of the solar PV installations are roof-top and 20% are utility-scale power plants. The distribution is based on the population in each of the sub-regions. Compared with the vast solar potential, wind generation will be limited and will not compensate for differences in seasonal generation. However, to reduce energy-related carbon emissions as fast as possible and to diversify the generation mix to reduce the seasonal storage requirements, the wind resources of Switzerland should be used to the highest possible degree.

By 2030, variable power generation will exceed 45% in all regions, whereas the proportion of dispatchable renewables—bio-energy and hydro power—will remain above 40% in all regions, except Wallis (29%) and the West sub-region (39%).

Table 26: **Switzerland—Power system shares by technology group**

Power Generation Structure in percentage of annual supply [GWh/a]		REFERENCE			Energy [R]evolution			ADVANCED Energy [R]evolution		
Switzerland		Variable Renewable	Dispatch Renewable	Dispatch Fossil	Variable Renewable	Dispatch Renewable	Dispatch Fossil	Variable Renewable	Dispatch Renewable	Dispatch Fossil
West	2020	6%	87%	7%						
	2030	13%	81%	5%	32%	66%	2%	38%	60%	2%
	2050	48%	49%	3%	54%	46%	0%	61%	39%	0%
South West (Wallis)	2020	6%	94%	0%						
	2030	16%	84%	0%	44%	56%	0%	51%	49%	0%
	2050	53%	47%	0%	62%	38%	0%	71%	29%	0%
Centre West (Bern-Basel)	2020	5%	17%	78%						
	2030	10%	84%	6%	34%	65%	1%	38%	61%	1%
	2050	38%	56%	7%	50%	50%	0%	52%	48%	0%
Centre North	2020	5%	6%	89%						
	2030	10%	79%	11%	36%	63%	1%	41%	59%	1%
	2050	41%	57%	2%	53%	47%	0%	56%	44%	0%
Tessin	2020	5%	95%	0%						
	2030	11%	89%	0%	37%	63%	0%	41%	59%	0%
	2050	44%	56%	0%	54%	46%	0%	54%	46%	0%
Graubuenden	2020	6%	94%	0%						
	2030	17%	82%	0%	46%	54%	0%	55%	45%	0%
	2050	60%	40%	0%	68%	32%	0%	77%	23%	0%
Centre North East (Zürich)	2020	7%	88%	5%						
	2030	10%	84%	6%	35%	63%	1%	40%	59%	1%
	2050	40%	54%	6%	53%	47%	0%	55%	45%	0%

The significant regional differences in the power system shares—the ratio between dispatchable and non-dispatchable variable power generation—will require a combination of increased interchange, storage facilities, and demand-side management incentives. Over time, the proportion of variable power generation will increase (Table 27) under all scenarios.

Table 27: System-relevant generation types

Generation type	Fuel	Technology
Limited dispatchable	Fossil, uranium	Coal, brown coal/lignite, (including co-generation)
	Renewable	Hydro power, bio-energy and synthetic fuels, geothermal, concentrated solar power (including co-generation)
Dispatchable	Fossil	Gas, oil, diesel (including co-generation)
		Storage systems: batteries, pumped hydro power plants, hydrogen- and synthetic-fuelled power and co-generation plants
	Renewable	Bio-energy, hydro, hydrogen- and synthetic-fuelled power and co-generation plants
Variable	Renewable	Solar photovoltaic, Onshore wind

Table 27 shows the system-relevant technical characteristics of the various generation types. Future power systems must be structured according to the generation characteristics of each technology in order to maximize their synergy. Power utilities can encourage sector coupling—between industry, transport, and heating—in order to utilize various demand-side management possibilities and to maximize the cross-benefits. The integration of large shares of variable power generation will require a more flexible market framework. Those power plants requiring high capacity factors because of their technical limitations regarding flexibility ("base-load power plants") might not be desirable to future power system operators. Therefore, capacity factors will become more of a technical characteristic than an economic necessity. Flexibility is a commodity that increases in value over time.

5.3 Switzerland: Development of Load, Generation, and Residual Load

Table 28 shows the current annual demand, maximum and minimum loads, and the calculated average load by region. The data have been downloaded from the website of Swiss Grid[41] and show the measured values for the year 2019. The original data are broken down by province (canton) and combined according to the seven sub-regions defined above. The regional load varies significantly. The three main load centres are *West* (Freiburg, Waadt, Neuenburg, and Genf), *Centre West* (Bern, Solothurn, Basel Stadt & Land, Jura), and *Centre North East* (greater Zürich area).

Table 28: Switzerland—Load, generation, and residual load in 2019

Real load (rounded)—measured by grid operators in 2018	Annual Demand [GWh/a]	Max. Load [MW]	Min. Load [MW]	Average Load [MW]
West	10,954	1,875	716	1,251
South West (Wallis)	3,507	600	239	400
Centre West (Bern-Basel)	13,245	2,092	915	1,512
Centre North	10,822	1,820	686	1,236
Tessin	2,949	532	176	337
Graubuenden	2,422	562	128	277
Centre North East (Zürich)	15,812	2,628	993	1,805
Switzerland Total	61,464	9,831	4,185	7,017

Table 29 shows that the average load is calculated to decrease over the next decade by approximately 10%–15% under all scenarios and across all the regions analysed, except region *WEST, where the load is calculated to increase by 7%* within the next 10 years until 2030. Under all scenarios, the load will remain at today's level until 2030. Between 2030 and 2050, the load will increase by around 30% on average across Switzerland under the ADVANCED Energy [R]evolution scenario and by around 15% under the REFERENCE and Energy [R]evolution scenarios. The higher load increase under the ADVANCED Energy [R]evolution scenario will be due to the higher electrification rate in both the transport and heating sectors. Electricity will also replace a proportion of biofuels. The use of synthetic fuels will be lower under both Energy [R]evolution scenarios than under the REFERNCE scenario, and they will be mainly imported under the REFERENCE scenario.

Although there will be significant regional differences, the calculated peak generation under the REFERENCE and Energy [R]evolution scenarios will be almost identical until 2030. In 2050, generation under both Energy [R]evolution scenarios will be higher than under the REFERENCE scenario due to the higher electrification rates in the transport sector. The residual load—the load remaining after supply with local generation—will increase, especially in urban areas, where the demand for electricity for transport will increase more than in rural areas, and where local generation will be limited. This is an indication that energy efficiency must be introduced in parallel with the implementation of electric mobility to limit the required investment in upgrading the power grid infrastructure.

[41] Swiss Grid 2020, downloaded in June 2020, https://www.swissgrid.ch/de/home/operation/grid-data/generation.html

Table 29: Switzerland—Projection of load, generation, and residual load until 2050

Switzerland		REFERENCE				Energy [R]evolution				Advanved Energy [R]evolution			
Development of load and generation		Max. Demand	Max. Generati on	Max. Residual Load	Peak Load Increase	Max. Demand	Max. Generati on	Max. Residual Load	Peak Load Increase	Max. Demand	Max. Generati on	Max. Residual Load	Peak Load Increase
		[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]
West	2020	2.4	1.5	1.3	100%								
	2030	2.6	2.1	1.2	107%	3.2	3.1	1.9	127%	3.3	3.2	2.0	136%
	2050	3.0	4.5	1.4	125%	3.8	5.9	2.5	151%	4.2	7.6	3.0	175%
South West (Wallis)	2020	0.6	4.5	0.0	100%								
	2030	0.5	4.7	0.0	87%	0.5	4.6	0.0	84%	0.6	4.7	0.0	89%
	2050	0.6	5.0	0.0	102%	0.7	4.8	0.0	103%	0.7	5.2	0.0	119%
Centre West (Bern-Basel)	2020	2.8	3.2	0.1	100%								
	2030	2.6	2.9	0.1	91%	2.6	2.6	0.5	88%	2.7	3.1	0.6	94%
	2050	3.2	4.0	0.4	112%	3.3	6.0	1.2	112%	3.7	6.6	1.6	130%
Centre North	2020	2.7	3.4	0.1	100%								
	2030	2.4	2.4	0.1	86%	2.4	2.5	0.8	83%	2.4	3.0	0.9	89%
	2050	3.0	3.8	1.2	111%	3.2	5.7	1.5	111%	3.4	6.3	1.9	126%
Tessin	2020	0.7	1.6	0.0	100%								
	2030	0.6	1.6	0.0	85%	0.6	1.7	0.0	82%	0.6	1.8	0.0	87%
	2050	0.7	2.0	0.0	102%	0.7	2.1	0.0	103%	0.8	2.1	0.0	117%
Grau-buenden	2020	0.4	2.4	0.0	100%								
	2030	0.4	2.6	0.0	86%	0.4	2.6	0.0	84%	0.4	2.7	0.0	88%
	2050	0.4	3.0	0.0	91%	0.4	2.8	0.0	92%	0.5	3.6	0.0	108%
Centre North East (Zürich)	2020	4.1	2.8	1.9	100%								
	2030	3.9	3.6	1.2	95%	4.0	4.1	1.4	92%	4.1	4.9	1.5	98%
	2050	4.9	3.6	1.2	119%	5.1	9.6	2.4	119%	5.6	10.5	3.0	135%
Switzerland	2020	13.8	19.4	4.0	100%								
	2030	12.9	20.0	4.8	93%	13.6	21.1	4.8	91%	13.9	23.3	5.1	97%
	2050	15.8	28.6	7.7	114%	17.1	36.8	7.7	112%	18.9	41.8	9.5	129%

Increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. Our analysis found that with the smart distribution and management of electric vehicle charging stations, additional transmission lines—beyond those identified in the *Strategic Grid 2025* [42] strategy—will not be required. The high share of solar PV will lead to high generation peaks during summer months and low generation capacities during winter. To manage the generation peaks of solar PV generators, utility-scale installations will require onside storage capacity, whereas roof-top PV will increase 'behind-the-meter' storage facilities (see section 5.5).

[42] SwissGrid 2015, Bericht zum Strategischen Netz 2025, https://www.swissgrid.ch/dam/swissgrid/projects/strategic-grid/sg2025-technical-report-de.pdf

5.4 Switzerland: Development of Inter-regional Exchange of Capacity

Both Energy [R]evolution scenarios will follow the load developments of the REREFERENCE scenario over the next decade. Therefore, the grid requirements for all three scenarios will be similar. Careful planning of the distribution of electricity generation capacities (mainly solar PV) to match the local demand will be very important. Furthermore, charging devices for electric vehicles should be operated within a load management scheme.

The inter-regional exchange of capacity is a function of the load development and generation capacity in all seven regions. The [R]E 24/7 model distributes generation capacity according to the regional load and the conditions for power generation. The locations of hydro power plants will be fixed and the installation of new capacities will depend upon geographic conditions and the nature conservation requirements. Solar and wind power generation, as well as decentralized bio-energy power and/or co-generation plants, are more modular and can be distributed according to the load in the first place. However, as the share of variable renewable electricity increases, and the space available for utility-scale solar and the—very limited due to the 400 turbine restriction—onshore wind generation facilities will decrease. Power might have to be generated further from its point of consumption.

Switzerland is located in the centre of Europe and its exchange of electricity with France, Germany, Italy, and Austria will put an additional burden on the power grid. Table 30 shows the minimum, maximum, and average loads of electricity exported to Switzerland's four neighbouring countries, Austria, Germany, France, and Italy. The original data were provided by SwissGrid[43], and the time series have been analysed by the authors of this report.

Table 30: Switzerland—Electricity export to neighbouring countries (2019), SwissGrid data

	Cross Border Exchange	Cross Border Exchange	Cross Border Exchange	Cross Border Exchange	Transit
	Export to Austria	Export to Germany	Export to France	Export to Italy	
Minimum Load	0	0	0	44	194
Maximum Load	1,380	3,686	2,936	4,871	5,662
Average Load	189	701	547	2,529	2,677

Both Energy [R]evolution scenarios prioritize the security of supply with local generation while utilizing electricity import and export to surrounding countries for the management of generation. Although the REFERENCE scenario requires net electricity importation until 2050, both Energy [R]evolution scenarios will lead to a generation surplus for export.

Whereas both Energy [R]evolution scenarios include utility-scale solar PV installations, small and medium-sized decentralized power generation with local demand-side management and storage facilities (see section 5.5)—from dedicated *energy communities*—on low- and medium-voltage levels, will reduce grid upgrades of the distribution grid. It was beyond the scope of this project to quantify this effect, which requires additional research.

Figure 22, Figure 23, and Figure 24 show the calculated exchange capacities between the seven defined sub-regions in 2030, 2040, and 2050, respectively, for all three scenarios. The values on the left show the maximum imported loads into the sub-regions and those on the right show the maximum exported loads. Example: Under the REFERENCE scenario, the Centre North East/Zürich region (Figure 22) will require a maximum of around 1,500 MW imported energy to meet the load in 2030, 2040, and 2050, whereas the maximum export in those years will increase from around 750 MW to just over 2,000 MW. This is directly linked to the increase in solar PV installations. Exports will be higher if solar battery systems are unavailable for peak-shaving.

The current actual interconnection capacities between all regions seem sufficient for all three scenarios until 2030. Furthermore, the transfer capacities for the REFERENCE scenario (Figure 22) and both alternative scenarios (Figure 23 and Figure 24) are only estimates because these capacities can be reduced by demand-side management measures, increased storage capacities, and variations in the actual distribution of power generation. The net transfer capacity under the REFERENCE scenario will follow the same pattern in 2050 as that in the two alternative scenarios, whereas the 2040 values will differ. The modelling results indicate that the planned upgrades of the transmission grid within Switzerland published in *Strategic Grid 2025*[44] will be sufficient.

[43] Swiss Grid 2020, downloaded in June 2020, https://www.swissgrid.ch/de/home/operation/grid-data/generation.htm
[44] SwissGrid 2015, Bericht zum Strategischen Netz 2025, https://www.swissgrid.ch/dam/swissgrid/projects/strategic-grid/sg2025-technical-report-de.pdf

Figure 22: Switzerland—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to load increase, under the REFERENCE scenario

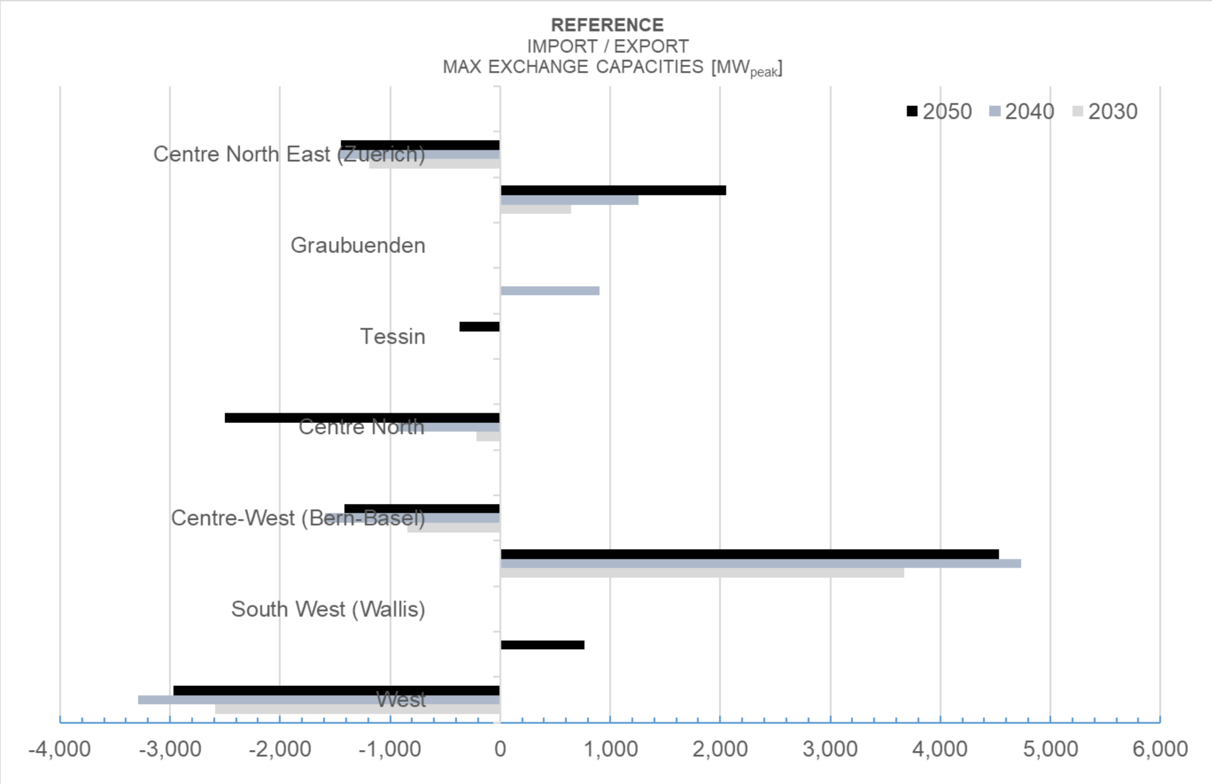


Figure 23: Switzerland—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to load increase, under the Energy [R]evolution scenario

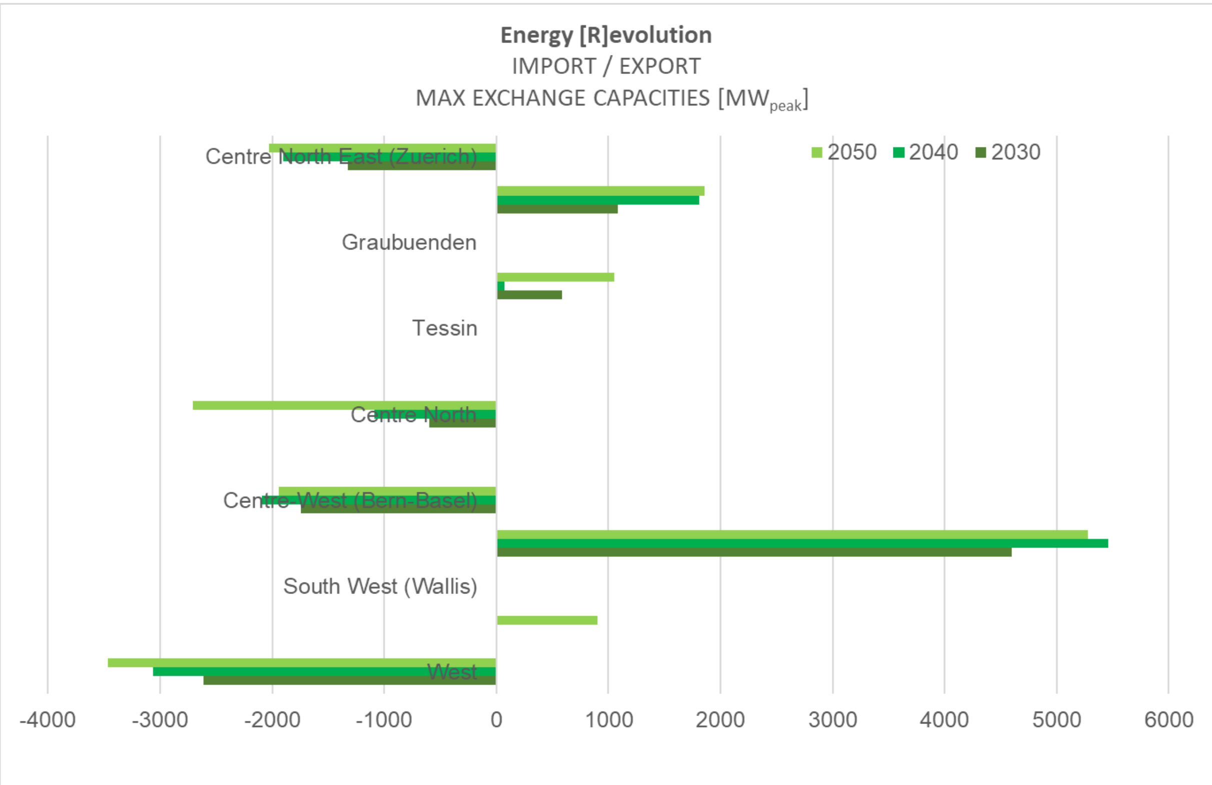
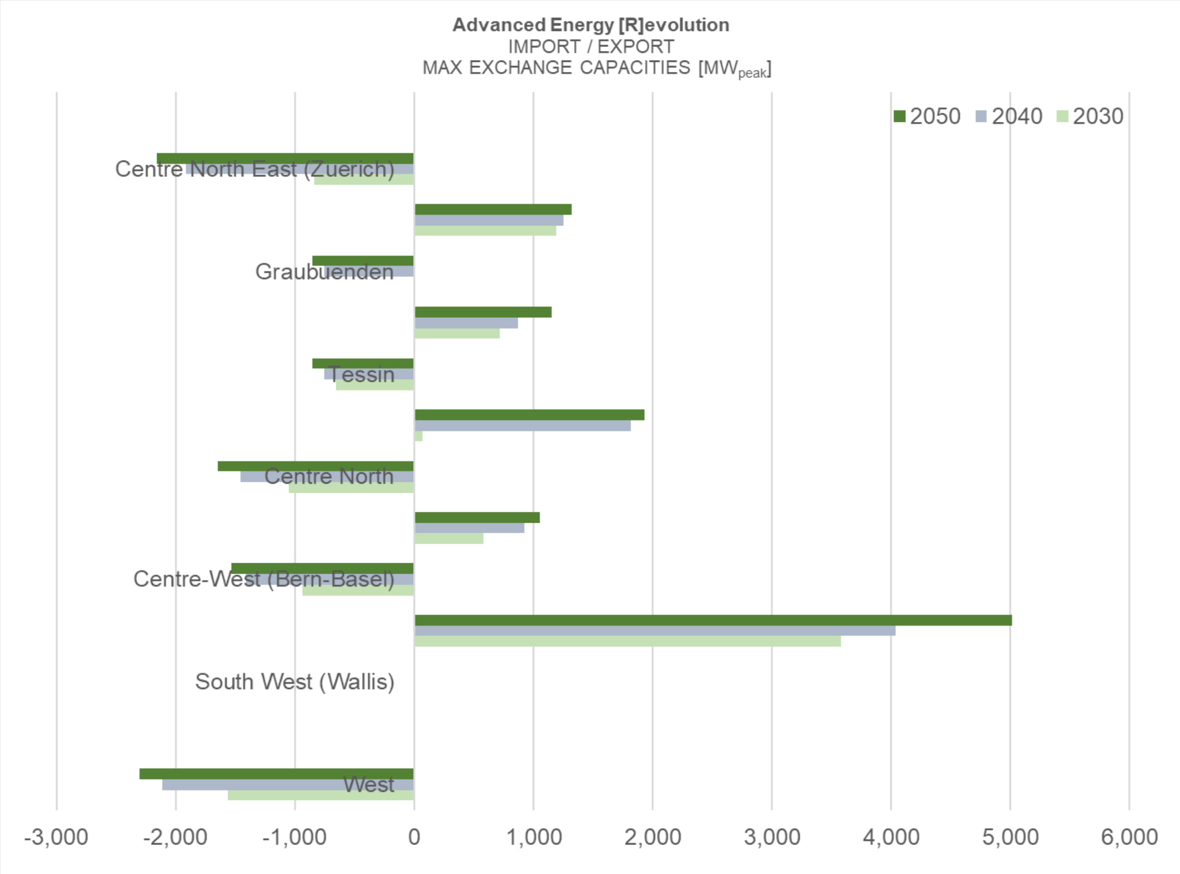


Figure 24: Switzerland—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to load increase, under the ADVANCED Energy [R]evolution scenario



Limitations

The calculated loads are not optimized with regard to local storage, self-consumption by decentralized producers of solar PV electricity, or demand-side management. Therefore, the calculated loads may differ from the actual values. Furthermore, the calculated export/import loads to neighbouring countries are simplified and combined into a single value. Peak load and peak generation events do not appear at the same time, so the values cannot be simply added. Moreover, peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole country. The maximum residual load[45] shows the maximum undersupply in a region and indicates the maximum load that will be imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. Optimizing the interconnection for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by one or more of the following options:

- imports from other regions through interconnections;
- battery storage facilities on-site at solar PV installations and for electric vehicles;
- available back-up capacities, such as gas peaking plants;
- load and demand-side management.

In practice, security of supply will be achieved with a combination of several measures and will require the in-depth analysis of regional technical possibilities.

[45] Residual load is the load remaining after local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and solar power plants.

5.5 Storage Requirements

5.5.1 Introduction

The quantity of storage required is largely dependent upon the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wendong 2016)[46]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than the storage costs. Cebulla et al. (2018)[47] reported that “in general terms, photovoltaic-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap”. In an analysis of 400 scenarios for Europe and the USA, they also found that once the share of variable renewables exceeds 40% of the total generation, the increase in electrical energy storage power capacity is about 1–2 GW for each percentage of variable renewable power generation in wind-dominated scenarios and 4–9 GW in solar-PV-dominated scenarios.

When variable power generation shares exceed 30%, storage requirements increase. The share of variable generation will exceed 30% between 2025 and 2030 under both Energy [R]evolution scenarios in all regions. Therefore, a smart grid integration strategy that includes demand-side management and the installation of additional decentralized and centralized storage capacities must go hand in hand.

Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. However, solar PV costs have also declined significantly. Storage is economic when the cost per kilowatt-hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are several reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[48]. The California Independent System Operator (CISO)[49] defines economic curtailment during times of oversupply as a market-based decision. “During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can ‘bid’ into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritized using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered ‘market-based’”.

5.5.2 Switzerland: Storage requirements

Switzerland operates a large fleet of run-of-river hydro power plants with and without water reservoir storage capacities and pumped hydro storage (PHS) facilities and is therefore in a comfortable position to integrate large amounts of variable solar PV power generation.
There are three types of hydro power plants in Switzerland:

I. Run-of-river power plants, which use the available volumes of passing river water and have limited possibilities to regulate the output; winter is usually the time with the lowest production volumes.
II. Storage power plants, which are ‘run-of-river’ power stations with a water storage reservoir on the intake side. Within the water reservoir capacity, power generation can be increased and reduced to complement the variable demand and/or solar generation.
III. Pumped hydro storage (PHS) power plants, which have a water storage reservoir on both sides (in-take and out-flow) and can pump water after electricity generation back in the in-take reservoir. PHS plants can operate as a short-, medium-, or long-term electricity storage technology. Historically, PHS systems have been used to balance inflexible nuclear power plants, which must operate in base-load mode, and to hedge against price fluctuations on power markets.

Table 31 shows the installed capacities and average generation of all three hydro power types in Switzerland. Under all three scenarios, we assume that those available dispatch and storage capacities

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46 Wendong (2016), Wei, Wendong et al. Regional study on investment for transmission infrastructure in China based on the State Grid data,10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016

47 Cebulla et al. (2018), How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

48 Wind and Solar Energy Curtailment: Experience and Practices in the United States; Lori Bird, Jaquelin Cochran, and Xi Wang, National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

49 Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

will be used primarily to meet the needs of the domestic power supply. The aim is to make optimal use of the local solar power generation and to provide the necessary network services.

Table 31: Installed hydro power—run-of-river, reservoir, and pumped in Switzerland in 2020

Hydro Power Plant Type	Amount	Installed Capacity (Generator)	Average Generation [GWh]		
		[MW]	Winter	Summer	Annual
Run-of-river (1)	548	4,133	6,264	11,423	17,687
Hydro power with reservoir lake (2)	80	8,223	8,148	9,059	17,207
Pumped hydro storage (PHS) (3)	15	2,562	964	590	1,554
Total	643	14,918	15,376	21,072	36,448

(1) Laufwasser
(2) Speicherkraft
(3) Pumpspeicher

In this analysis, we assume that 'peak-shaving' is used to avoid peak generation events. The term 'peak-shaving' refers to the reduction of the solar or wind generation capacity in times of high production. Peak-shaving involves proactively managing solar generation by reducing the output, e.g., from utility-scale PV to eliminate short-term spikes. These spikes only appear for a limited time—from minutes to hours—and increase the actual grid or storage capacity significantly because the capacity must cope with the highest peak. With peak-shaving, this peak can be reduced with only a minor effect on the overall annual generation because peak events are relative infrequent. The assumed "economic curtailment rate" for all three scenarios will increase to 5%—with regard to the annual generation (in GWh/a) for solar PV and onshore wind—for the years until 2030 and to 10% between 2031 and 2050. However, economic curtailment rates are dependent upon the available grid capacities and can vary significantly, even within Switzerland. Curtailment will be economic when the power generated by a wind turbine or PV power plant exceeds the demand for only a few hours a day and this event occurs rarely across the year. Therefore, the expansion of storage capacities will not be economically justifiable.

Table 32 shows the storage required to avoid curtailment, or in other words, the entire surplus generation at any given time, by region and under all three scenarios without peak-shaving. In the next step, we compare the theoretical storage capacity (shown in Table 32) with Switzerland's existing PHS system and assume that the entire capacity is available to manage variable solar electricity generation. When the PHS capacity of 2,562 MW is fully utilized—with an average annual throughput of 1,554 GWh—the remaining storage requirement after peak-shaving has been calculated.

To build up the additional required storage capacity, we assume that a percentage of the solar PV capacity will be installed with battery storage. The suggested solar battery system must be able to store the entire peak capacity for 4 full load hours.

Table 33 shows the calculated solar battery storage capacity and the share of solar systems with batteries for both Energy [R]evolution scenarios for 2020, 2030 and 2050. The Energy [R]evolution scenario requires 20% of all PV systems to be equipped with the battery technology described by 2030, whereas under the ADVANCED Energy [R]evolution scenario, it must be 40%. In 2050, 35% of all PV installations must have batteries under the Energy [R]evolution scenario and 50% under the ADVANCED scenario.

Table 32: Switzerland—Storage requirements to avoid curtailment

Storage Requirement to Avoid Curtailment		REFERENCE		Energy [R]evolution		ADVANCED Energy [R]evolution	
		Required storage to avoid curtailment (overproduction)	Required storage capacity to avoid curtailment	Required storage to avoid curtailment (overproduction)	Required storage capacity to avoid curtailment	Required storage to avoid curtailment (overproduction)	Required storage capacity to avoid curtailment
Switzerland		[GWh/a	[GW/a]	[GWh/a]	[GW/a]	[GWh/a]	[GW/a]
West	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.00	0	0.00	9	0.55
	2050	1,139	2.29	1,110	2.54	1,822	3.18
South West (Wallis)	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.01	119	0.39	193	0.57
	2050	403	0.77	1,013	1.16	1,532	1.44
Centre West (Bern-Basel)	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.00	277	0.84	603	1.25
	2050	806	1.63	2,852	3.45	3,914	4.33
Centre North	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.00	296	0.91	680	1.31
	2050	733	1.61	2,686	3.28	3,624	4.06
Tessin	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.00	113	0.26	231	0.37
	2050	334	0.51	937	0.97	1,217	1.16
Graubuenden	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.02	109	0.27	172	0.40
	2050	414	0.58	885	0.88	1,220	1.08
Centre North East (Zürich)	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.00	505	1.47	1,479	2.45
	2050	1,421	2.81	4,687	5.78	5,065	5.88
Switzerland	2020	0	0.00	0	0.00	0	0.00
	2030	0	0.04	1420	4.14	3367	6.91
	2050	5251	10.20	14171	18.06	18,394	21.12

Table 33: Switzerland—Estimated additional electricity storage requirements for both Energy [R]evolution scenarios

Additional PV Battery Storage Requirements		Energy [R]evolution		ADVANCED Energy [R]evolution	
		Energy capacity	Power capacity	Energy capacity	Power capacity
Switzerland		[GWh/yr]	[GW]	[GWh/yr]	[GW]
West	2020	0.27	0.1	0.27	0.1
	2030	2.28	0.6	3.37	0.8
	2050	9.31	2.3	14.49	3.6
South West (Wallis)	2020	0.07	0.0	0.07	0.0
	2030	0.61	0.2	0.90	0.2
	2050	2.51	0.6	4.54	1.1
Centre West (Bern-Basel)	2020	0.30	0.1	0.30	0.1
	2030	2.54	0.6	3.75	0.9
	2050	10.36	2.6	16.16	4.0
Centre North	2020	0.28	0.1	0.28	0.1
	2030	2.39	0.6	3.52	0.9
	2050	9.75	2.4	14.81	3.7
Tessin	2020	0.08	0.0	0.08	0.0
	2030	0.65	0.2	0.96	0.2
	2050	2.65	0.7	4.04	1.0
Graubuenden	2020	0.05	0.0	0.05	0.0
	2030	0.44	0.1	0.64	0.2
	2050	1.78	0.4	3.19	0.8
Centre North East (Zürich)	2020	0.46	0.1	0.46	0.1
	2030	3.93	1.0	5.79	1.4
	2050	16.03	4.0	20.89	5.2
Switzerland	2020	1.50	0.4	1.52	0.4
	2030	12.83	3.2	18.92	4.7
	2050	52.38	13.1	78.12	19.5
Share of solar PV systems with battery storage	2020	15%		15%	
	2030	20%		40%	
	2050	35%		50%	

The estimates provided for the storage requirements also presuppose that variable renewables will be first in the dispatch order, ahead all other types of power generation. Priority dispatch is the economic basis for investment in utility-scale solar PV and wind projects. The curtailment rates or storage rates will be significantly higher when priority dispatch is given to other types of power. This case has not been calculated because it would involve a lack of investment in solar and wind in the first place. With decreasing storage costs, as projected by Bloomberg (2019)[50], interconnections might become less economically favourable than batteries. The storage estimates provided are technology neutral and do not favour any specific battery technology.

[50] Bloomberg (2019), A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldi-Scot, BloombergNEF, March 5 2019, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

5.5.3 Investment in storage technologies

Battery technologies have developed significantly over the past decade and the global annual market increased from 700 MW in 2015 to 3,100 MW in 2019 (IEA-BAT 2020)[51]. The market is roughly split equally between grid-scale storage and 'behind-the-meter' solar PV projects. The rapidly growing demand for electric vehicles has significantly accelerated the development of battery technologies, and manufacturing capacities grew by double digits, with costs decreasing accordingly. The battery costs per kilowatt-hour storage capacity decreased from US$668 (CHF 595) in 2013 to US$137 (CHF 122) in 2020—a reduction of −79% over the past 7 years. Bloomberg New Energy Finance estimates that battery costs will decline further to around US$58 (CHF 58) by 2030.

The investment costs in storage technologies were estimated based on the assumptions presented in this section. Storage technologies are still at an early stage of development, so projected costs are highly uncertain. Battery costs might be significantly lower in 2050, because their cost curves have shown similar development to those of solar PV systems over the past decade. Table 34 shows the investment in battery storage technology required by 2050. The total required investment costs in storage technologies between 2035 and 2050 are calculated to be CHF 183 million for the REFERENCE scenario, CHF 2.7 billion for the Energy [R]evolution scenario, and CHF 4.0 billion for the ADVANCED Energy [R]evolution scenario.

Table 34: Switzerland: Investments in PV battery systems by 2050

Scenario	Peak Capacity [MW]	Battery Capacity [MWh/a]	Assumed Specific Investment Costs in 2050 [CHF/kWh]	Total Investment [million CHF]
REFERENCE	887	3,550	52	183
Energy [R]evolution	13,094	52,377		2,704
ADVANCED Energy [R]evolution	19,529	78,117		4,032

[51] IEA-BAT (2020) IEA Energy Storage – website, https://www.iea.org/reports/energy-storage

5.5.4 Interaction of load, generation, and storage

This section shows how the calculated load curves, the projected electricity generation, and storage interact to provide a secure power supply for Switzerland.

To show the changing generation structure, three different situations were selected: 1 week each with the lowest, highest, and average solar power generation. On the basis of the meteorological data used (see section 1.3.1), very little solar power generation can be expected in December, whereas the highest values can be expected in June. A week in April represents solar production that corresponds to the annual average. The same meteorological data are used for all years, so the periods of minimum and maximum generation are the same for all simulations.

Figure 25: Switzerland—North East/Zürich: ADVANCED Energy [R]evolution in 2030: Minimum variable renewable generation in December

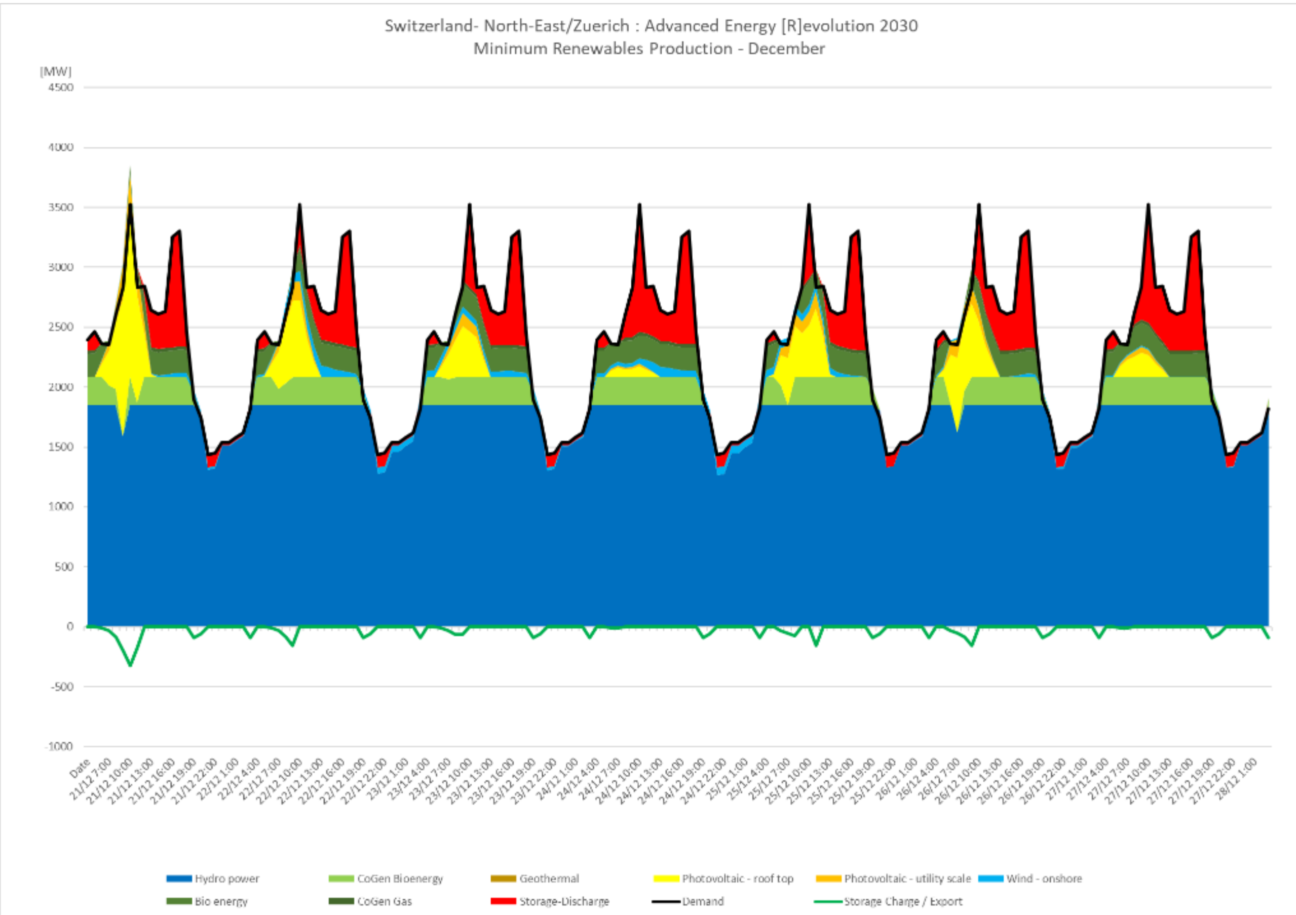


Figure 25 shows the simulated power supply for the North East/Zürich region for the last week of December 2030. Hydro power provides the base-load supply, whereas bio-energy co-generation balances variable solar power generation during daylight hours. Onshore wind adds to the generation. A small fraction of solar PV electricity will charge battery systems, whereas the areas marked in red show the need for additional supplies of stored electricity.

Figure 26 shows the supply situation for the same region shown in Figure 25, but with maximum variable renewable power generation (June) in 2030. The storage requirement will increase accordingly. Solar generation during the middle of the day will be about twice as high as the demand. Hydro power will fill the generation gaps between sunset and sunrise. In this case, hydro power could also be completely replaced with electricity from solar batteries. The network operators must decide individually whether to use electricity from batteries, run-of-river power, or PHS plants based on the respective fill levels of water reservoirs and batteries.

Figure 26: Switzerland—North East/Zürich ADVANCED Energy [R]evolution in 2030: Maximum variable renewable generation in June

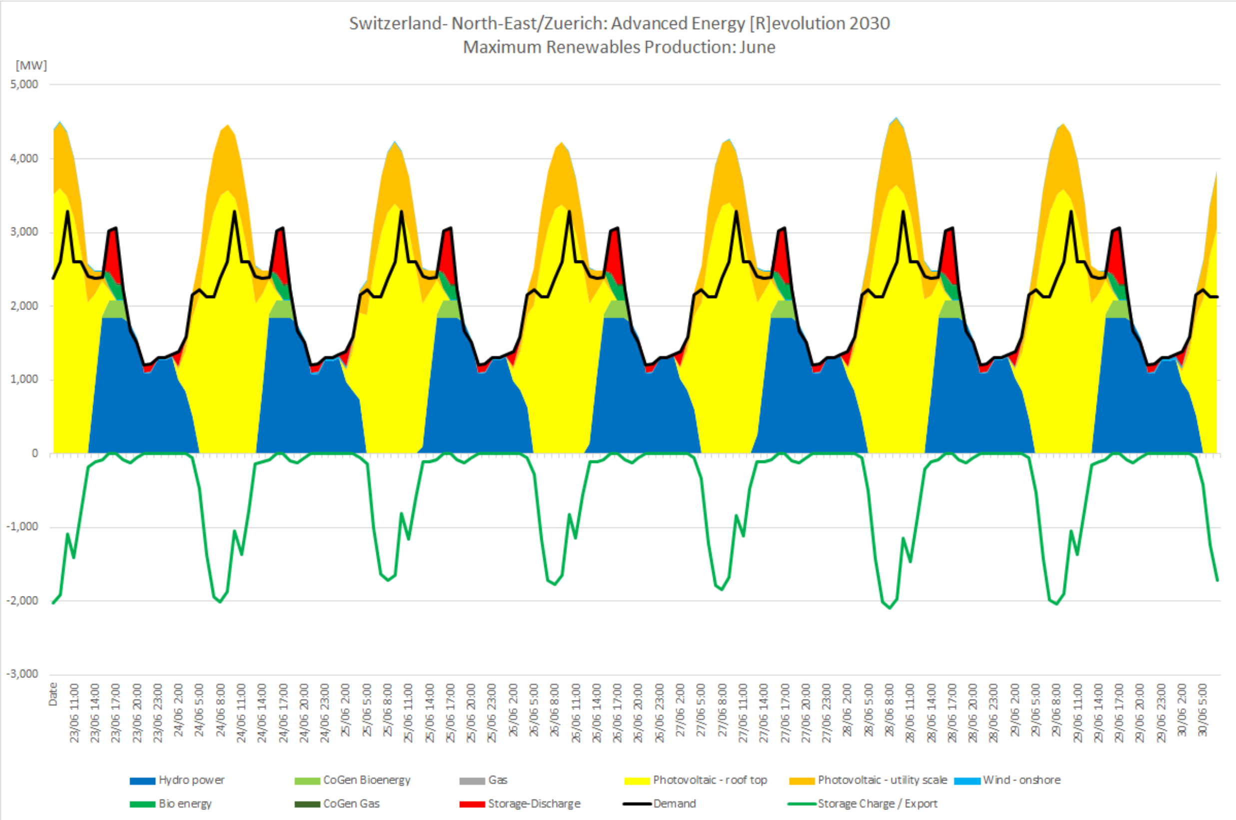
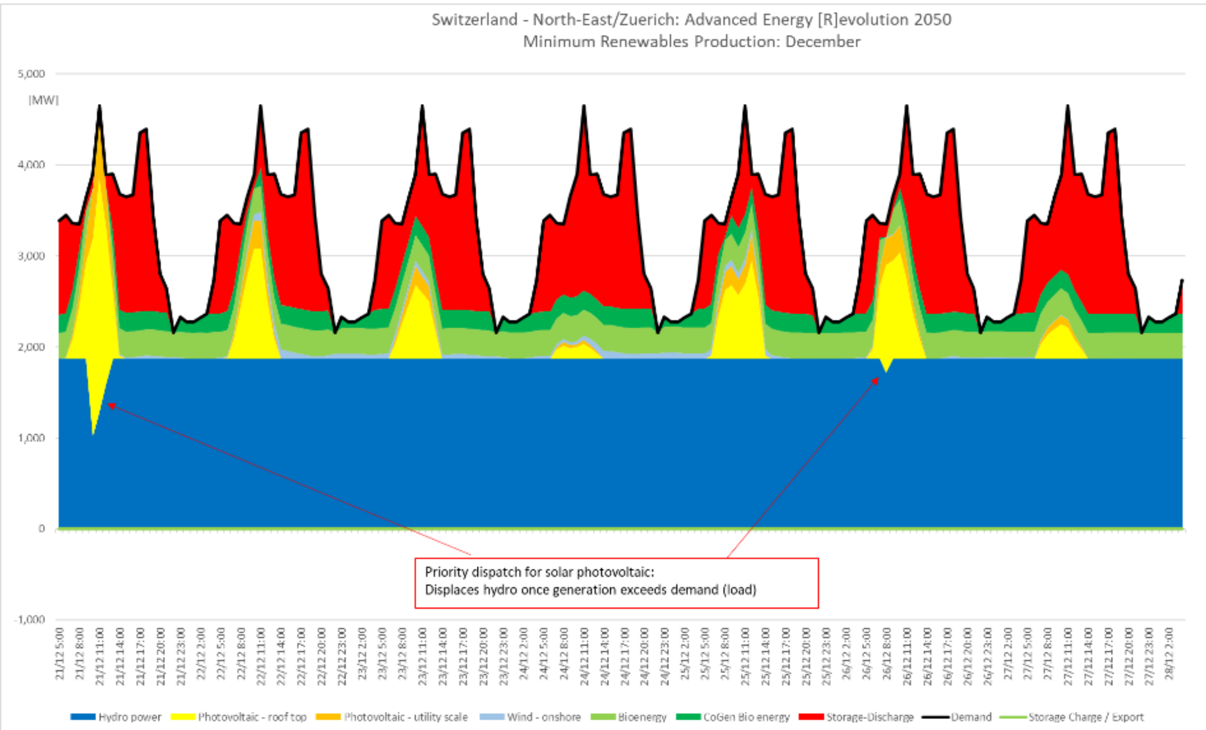
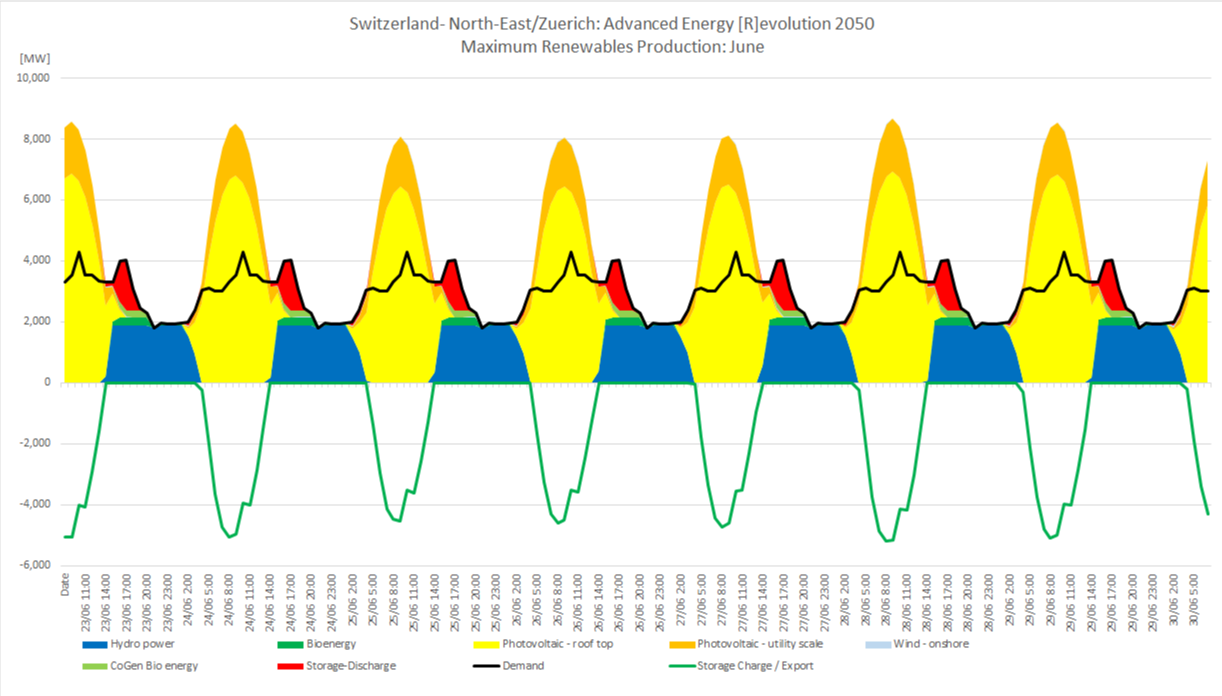


Figure 27 Switzerland—North East/Zürich: ADVANCED Energy [R]evolution in 2050: Minimum variable renewable generation in December



27 shows the same low solar electricity supply situation for the North East/Zürich region as in Figure 25, but with increased demand due to the greater use of electric vehicles and electric heating systems in 2050. The figure highlights the effect of increasing solar generation in the morning, which will cut into the supply band of hydro and bio-energy for some hours. During the exemplar week, the electricity from storage systems will complement most of the day-time demand.

Figure 28 Switzerland—North East/Zürich: ADVANCED Energy [R]evolution in 2050: Maximum variable renewable generation in June



The high solar supply for the North East/Zürich region in 2050 (Figure 28) will lead to a similar situation as that in 2030, but with significantly increased storage needs. Solar generation will peak at over 8,000 MW and the available PHS capacity across Switzerland will not be sufficient to store the electricity. Therefore, solar battery systems— operated as either 'behind-the-meter' or on-site storage for utility-scale power plants—can be used for peak-shaving. Demand-side management, e.g., with electric vehicle charging schemes, can also utilize solar peak generation. Storage will be used instead of hydro power for the generation shoulders, because the assumed dispatch order will place battery systems ahead of hydro power.

Figure 29 Switzerland: ADVANCED Energy [R]evolution 2050: Minimum variable renewable generation in December

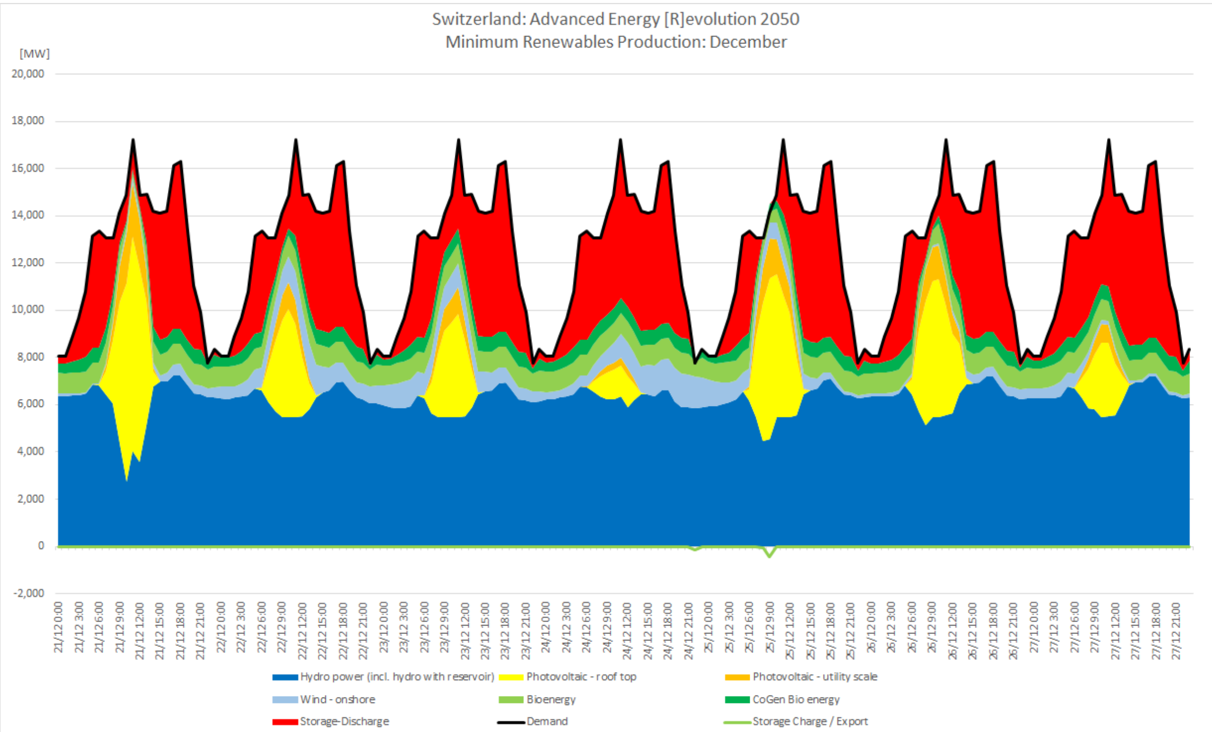
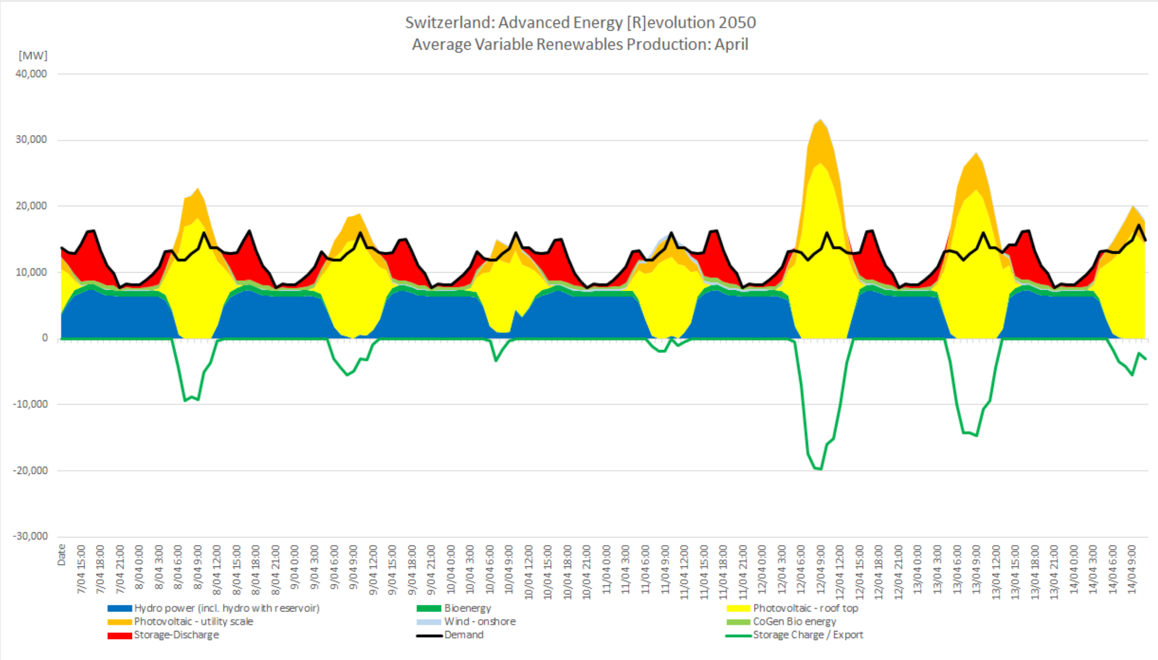


Figure 29 shows a situation of minimum solar supply for the whole of Switzerland. During periods of low solar production, stored electricity from PHS and batteries will be needed for the day-time supply, whereas evenings and nights will be supplied with hydro power.

Finally, Figure 30 shows a situation of average solar generation throughout the day. Battery storage systems will move electricity from production peaks to production lows. All available forms of hydro power stations (with and without storage) will be used to provide the base load and the dispatchable load required over longer time periods (weeks), as well as for seasonal storage.

Figure 30 Switzerland: ADVANCED Energy [R]evolution in 2050: Average variable renewable generation in April



5.6 Summary: Power Sector Analysis for Switzerland

Both Energy [R]evolution scenarios prioritize the use of regional hydro and solar power generation to rapidly decarbonize the electricity supply. Switzerland will increase its power demand under each scenario with the implementation of electric mobility and electric heating.

By 2030, variable power generation will reach > 45% in all regions, whereas the proportion of dispatchable renewables—bio-energy and hydro power—will remain over 40% in all regions except Wallis (29%) and the West sub-region (39%). The current actual interconnection capacities between all regions seem sufficient for all three scenarios until 2030. The modelling results indicate that the planned transmission grid upgrades within Switzerland, published in *Strategic Grid 2025*[52], will be sufficient.

Switzerland operates a large fleet of run-of-river hydro power plants with and without water reservoir storage capacities or PHS facilities, and is therefore in a comfortable position to integrate large amounts of variable solar PV power generation. After full utilization of the PHS capacity of 2,562MW—with an average annual throughput of 1,554 GWh—for the integration of variable solar power generation, peak-shaving will still be required.

With peak-shaving, solar production spikes can be reduced with only a minor effect on the overall annual generation because the peak events will be relatively infrequent. The assumed “economic curtailment rate” for all three scenarios will be up to 5%—with regard to the annual generation (in GWh/a) of solar PV and onshore wind—for the years until 2030 and 10% between 2031 and 2050. To build up the additional required storage capacity, we assume that a proportion of the solar PV capacity will be installed with battery storage. The suggested solar battery system should be able to store the entire peak capacity for 4 full load hours.

This will require 20% of all PV systems to be equipped with the described battery technology by 2030, whereas under the ADVANCED Energy [R]evolution scenario, it must be 40%. In 2050, 35% of all PV installations under the Energy [R]evolution scenario and 50% under the ADVANCED Energy [R]evolution scenario must have batteries. The total investment costs in storage technologies required between 2035 and 2050 are calculated to be CHF 183 million for the REFERENCE scenario, CHF 2.7 billion for the Energy [R]evolution scenario and CHF 4.0 billion for the ADVANCED Energy [R]evolution scenario.

To conclude, a large solar PV power generation share of around 50% by 2050 is feasible for Switzerland under the documented assumptions.

[52] SwissGrid 2015, Bericht zum Strategischen Netz 2025, https://www.swissgrid.ch/dam/swissgrid/projects/strategic-grid/sg2025-technical-report-de.pdf

6. SWITZERLAND: SENSITIVITY ANALYSIS

The Energy [R]evolution scenarios were developed with the *Long-Term [R]E 24/7* model (see section 1.2), whereas the power sector analysis documented in Chapter 4 was calculated with the [*R]E 24/7 Power Analysis* tool (section 1.3).

The long-term energy model computes holistic energy scenarios for countries and regions, and the [R]E 24/7 Power Analysis model was developed to simulate the power demand and supply with 1 hour resolution. Because the technical resolution is very high—in terms of both the supply technologies and the demand side, with various electrical applications, includi the temperature levels of industrial processes, transport modes—cost optimization across all sectors is not part of the model. Therefore, the open-source model OSeMOSYS was used, and its results are compared with those documented in Chapters 3 and 4.

In contrast to the [R]E 24/7 Power Analysis model, which simulates the power demand and supply for a full year with hourly resolution (= 8760 hours per year), the OSeMOSYS model is based on a defined number of time slices in a year (i.e., in the range of 10 or 20 time slices), and not on hourly resolution. Therefore, its solutions are built with a deterministic linear cost-optimization model. Constraints such as meeting a renewable energy target in each year under study can be defined (i.e., minimum percentage of energy generation supplied from renewables), as well as other possible constraints, such as the maximum installed capacity for a certain technology, and many others.

6.1 OSeMOSYS Scenarios

Only the power generation mix was optimized with OSeMOSYS. Neither thermal nor transport energy is included in the analysis below. The following three [R]E 24/7 scenarios were recalculated in OSeMOSYS:

1. REFERENCE: (REF LT)
2. Energy [R]evolution: (E[R]) – S1
3. ADVANCED Energy [R]evolution: (ADV E[R]) – S2

For the OSeMOSYS sensitivity analysis, the following five scenarios were calculated:

1. Reference OSeMOSYS: (Ref—Unconstrained—OS)
   The electricity demand and the renewable energy targets are the same as in the REFERENCE Long-Term scenario (REF LT), but the power generation mix is cost optimized, and there is no constraint on the capacity of either.

2. Energy [R]evolution—OSeMOSYS: (S1—Unconstrained—OS)
   The electricity demand and the renewable energy targets are the same as in the ENERGY [R]EVOLUTION Long Term, but the power generation mix is cost optimized, and there is no constraint on the capacity of either.

3. ADVANCED Energy [R]evolution—Unconstrained—OSeMOSYS (S2—Unconstrained—OS)
   The electricity demand and the renewable energy targets are the same as in the ADVANCED ENERGY [R]EVOLUTION, but the power generation mix is cost optimized, and there is no constraint on the capacity of either.

4. ADVANCED Energy [R]evolution—Constrained Hydro—OSeMOSYS (S2—Constrained Hydro—OS)
   The electricity demand and the renewable energy targets are the same as in the ADVANCED ENERGY [R]EVOLUTION Long Term (RE2 LT), but the power generation mix is cost optimized, and there is a constraint on the maximum capacity for hydro generation. This is consistent with the national preference for not increasing the hydro capacity beyond the available capacities, based on environmental considerations.

5. ADVANCED Energy [R]evolution—Constrained Hydro, Geo—OSeMOSYS (S2—Constrained Hydro, Geo—OS)
   The electricity demand and the renewable energy targets are the same as in the ADVANCED Energy [R]evolution, but the power generation mix is cost optimized, and there are constraints on the maximum capacity for hydro generation and geothermal energy. This is consistent with the national preference for not increasing the hydro capacity and for avoiding geothermal activities, based on environmental considerations.

Switzerland's average annual net power trading volume (imports minus exports) with Italy, Austria, Germany, and France over the past years was around 5.5. TWh, about 10% of the total annual demand.

Table 35: Overview: Region numbers and canton names

Scenario Region	Abbreviation	Canton
1	FR	Freiburg
	VD	Waadt
	NE	Neuenburg
	GE	Genf
2	VS	Wallis
3	BE	Bern
	SO	Solothurn
	BS	Basel-Stadt
	BL	Basel-Landschaft
	JU	Jura
4	LU	Luzern
	UR	Uri
	SZ	Schwyz
	OW	Obwalden
	NW	Nidwalden
	ZG	Zug
	AG	Aargau
5	TI	Tessin
6	GR	Graubünden
7	ZH	Zürich
	GL	Glarus
	SH	Schaffhausen
	AR	Appenzell Ausserrhoden
	AI	Appenzell Innerrhoden
	SG	St. Gallen
	TG	Thurgau

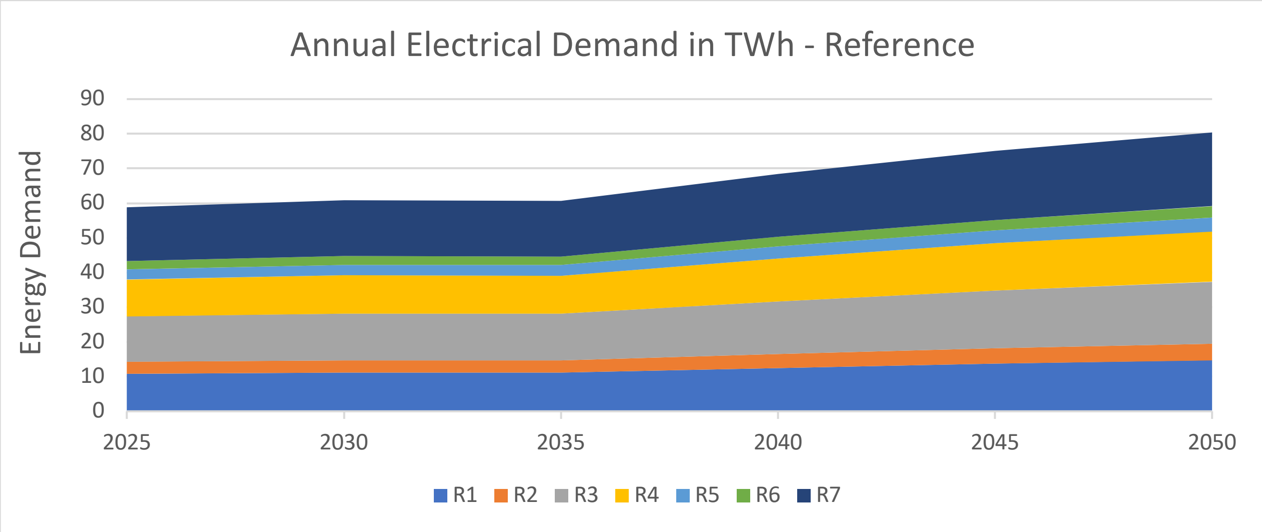
It is assumed in all the scenarios calculated with OSeMOSYS that the annual 5.5 TWh of net electricity importation will remain stable over the entire modelling period until 2050. The annual electricity demand for Switzerland, broken down into seven regions (R1–R7) for the REFERENCE and both Energy [R]evolution scenarios are shown in Figure 31. The assumed renewable electricity targets are shown in **Table 36**.

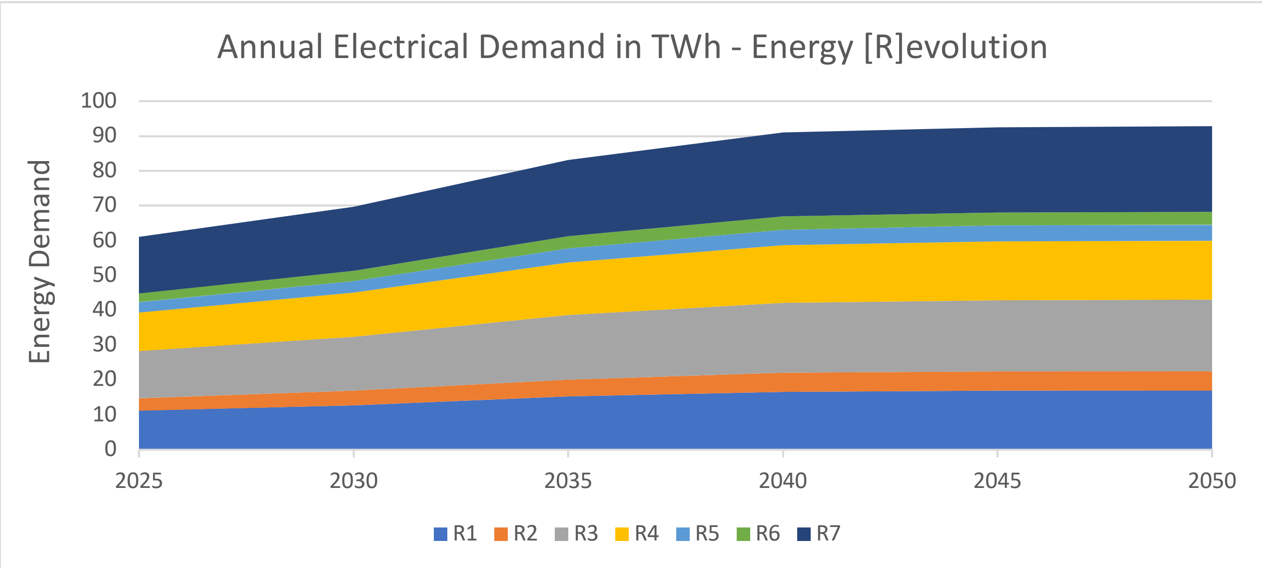
Table 36 Annual renewable energy targets for each of the three main scenarios

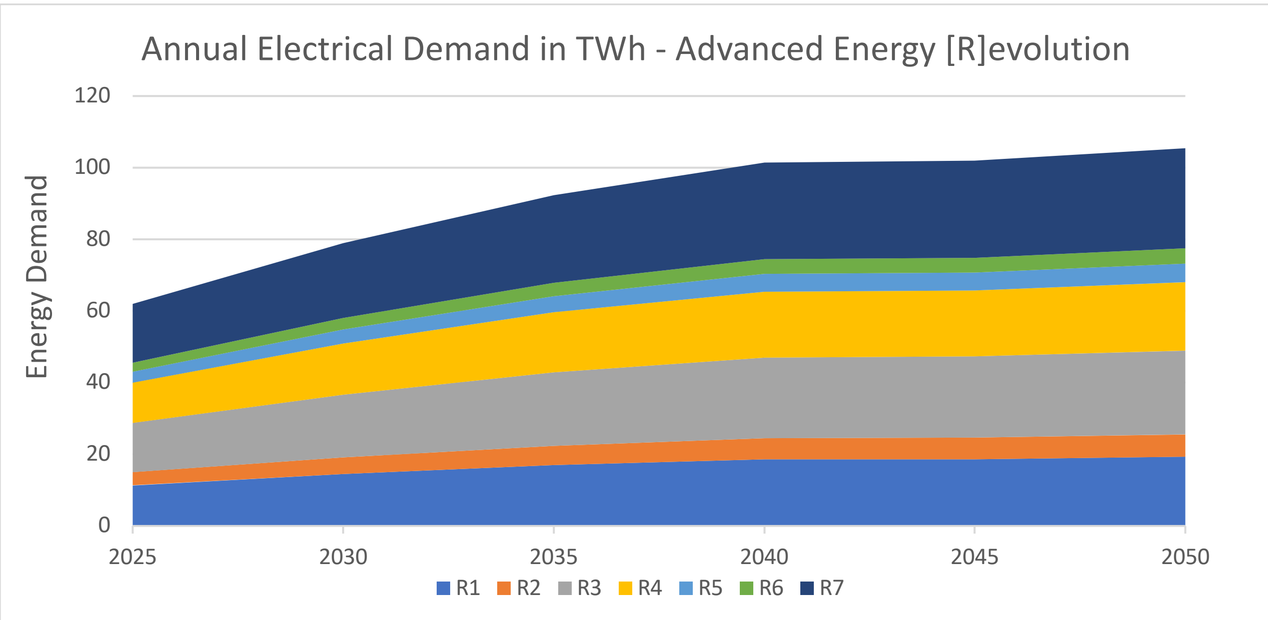
	2025	2030	2035	2040	2045	2050
REFERENCE	72%	77%	85%	85%	86%	87%
Energy [R]evolution (S1)	91%	99%	100%	100%	100%	100%
ADVANCED Energy [R]evolution (S2)	93%	98%	99%	100%	100%	100%

The net electricity demand is calculated as the total generation plus the net electricity imported minus both distribution losses and internal power plant consumption.

Figure 31: Annual electricity demand for the three main scenarios: Ref, S1, and S2







6.2 OSeMOSYS Time Slices

Twenty-four time slices per year are considered in OSeMOSYS to represent the electricity demand, in order to simulate the power supply, which depends upon the availability of solar and wind power generation and controllable power generation (hydropower, biomass, gas, and coal). One "time slice" includes:

- Three daily time brackets: 6 am–4 pm (day-time: "D"); 4–10 pm (evening "E"); 10 pm– 6 am (night-time "N").
- Two day types (weekday and weekend)
- Four seasons: winter, spring, summer, and autumn

There are six different "time slices" for each season:

SPD1: Spring, daytime, weekday
SPE1: Spring, evening, weekday
SPN1: Spring, night, weekday
SPD2: Spring, daytime, weekend
SPE2: Spring, evening, weekend
SPN2: Spring, night, weekend

SD1: Summer, daytime, weekday
SE1: Summer, evening, weekday
SN1: Summer, night, weekday
SD2: Summer, daytime, weekend
SE2: Summer, evening, weekend
SN2: Summer, night, weekend

AD1: Autumn, daytime, weekday
AE1: Autumn, evening, weekday
AN1: Autumn, night, weekday
AD2: Autumn, daytime, weekend
AE2: Autumn, evening, weekend
AN2: Autumn, night, weekend

WD1: Winter, daytime, weekday
WE1: Winter, evening, weekday
WN1: Winter, night, weekday
WD2: Winter, daytime, weekend
WE2: Winter, evening, weekend
WN2: Winter, night, weekend

6.3 OSeMOSYs Results and Analysis

The OSeMOSYS results for generation capacity, electricity generation, CO_2 emissions, and the cost of the power generation mix for all scenarios are documented in this section and compared with the three scenarios documented in Chapter 3.

6.3.1 Capacity and generation

The calculated installed capacities for the years 2025, 2030, and 2050 for the five OSeMOSYS cost optimization scenarios are compared with the three [R]E24/7 scenarios in Figure 32, Figure 33, and Figure 34, respectively. The capacities of the OSeMOSYS and [R}E 24/7-LT scenarios are very similar across all scenarios. The virtual capacity from net imports (equivalent to around 3 GW) is not shown in the graph and requires additional generation capacity from outside Switzerland.

Hydro power has been the single most important power generation technology over the past decades and will remain the backbone of the Swiss electricity supply. The aging nuclear power plants will be phased-out under all scenarios—although the time lines will vary. Whereas the REFERENCE scenario projects that the existing 3.3 GW will be shut down by 2035, the Energy [R]evolution scenarios suggests earlier retirement by 2025. Switzerland has a very minor fossil fuel power generation capacity of around 500 MW—all operated as co-generation power plants. The bulk of the new capacity to replace the outgoing fossil and nuclear power plants and to generate the additional electricity required for electric mobility and electrical heating system to decarbonize the transport and heating sectors must come from solar PV.

The reason is that Switzerland has limited potential for other renewables. Its wind resource is not sufficient to provide more than 6 GW, whereas the potential for additional hydro power is at—or very close to—the maximum acceptable ecological limit. Geothermal and bio-energy power generation have additional, albeit limited, capacities. However, we have assumed various different constraints for each technology to achieve a large spread of results.

Under the ADV-E[R]–*Unconstrained* scenario, the capacity of hydro will increase to > 20 GW in 2050, whereas it will be replaced by geothermal under A*DV-E[R]—Constrained Hydro*. In this latter scenario, the capacity of hydro will be around 12 GW (the current level; referred to as the 'residual capacity'), whereas the capacity of geothermal will increase to around 5 GW in 2050. The capacity factor for geothermal is higher as for solar PV, which will lead to lower additional capacity requirements for the same generation output. When both capacities—hydro and geothermal—are constrained in A*DV-E[R]—Constrained Hydro, Geo*, the bio- and wind energy capacities will increase in the OSeMOSYS scenario, and in the [R]E 24/7-LT model, solar PV will increase to around 50 GW in 2050.

Figure 32. Total capacity for each technology in all scenarios in 2025 (OSeMOSYS & LT)

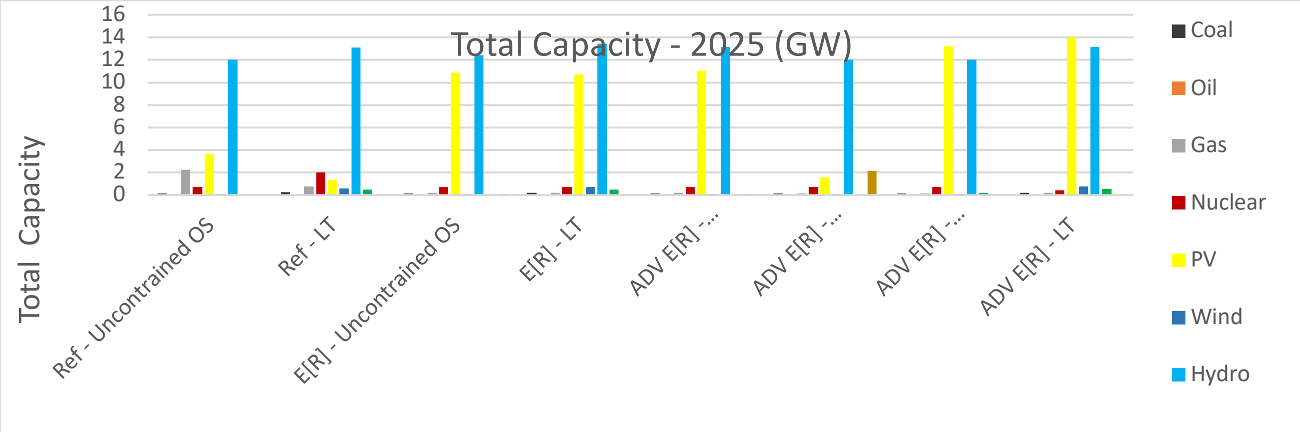


Figure 33. Total capacity for each technology in all scenarios in 2030 (OSeMOSYS & LT)

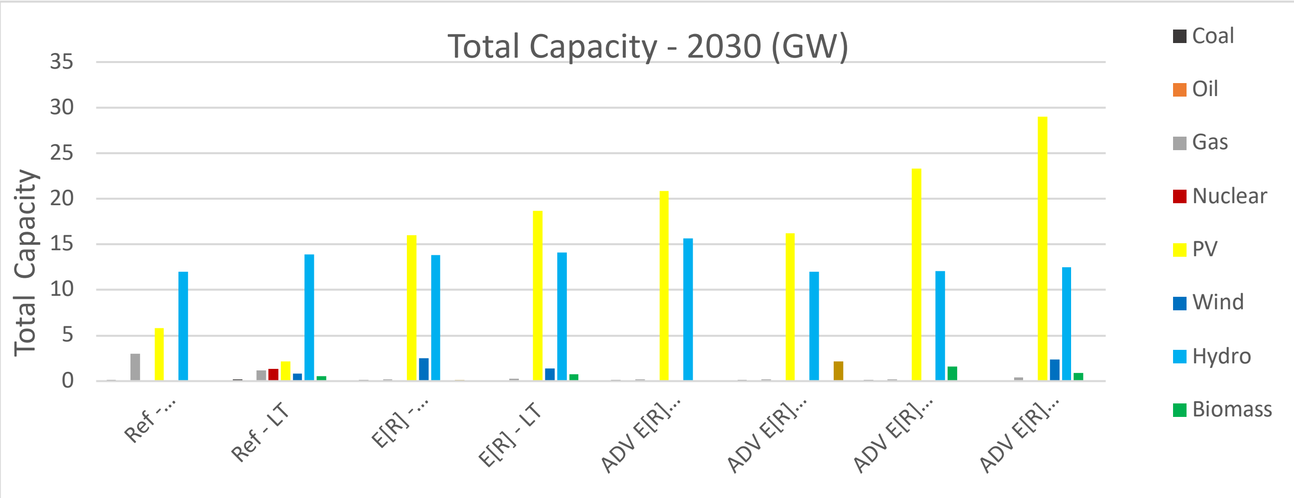
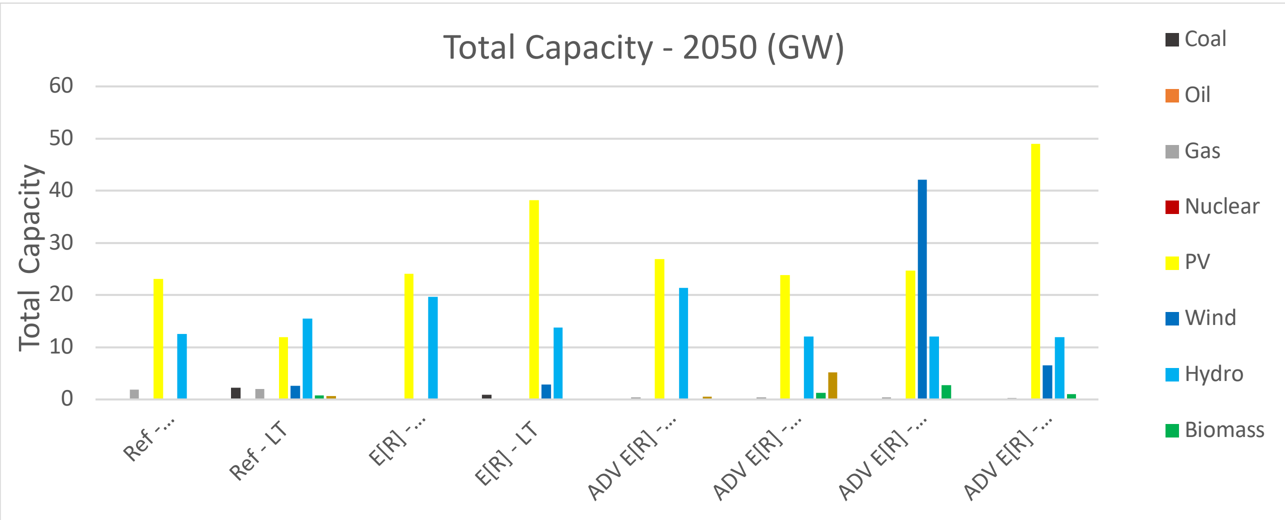


Figure 34. Total capacity for each technology in all scenarios in 2050 (OSeMOSYS & LT)



The corresponding annual electricity generation mixes under the eight described scenarios are shown in the following three figures for 2025, 2030, and 2050.

Figure 35. Comparison of electrical energy generation by technology in 2025 (OSeMOSYS & LT)

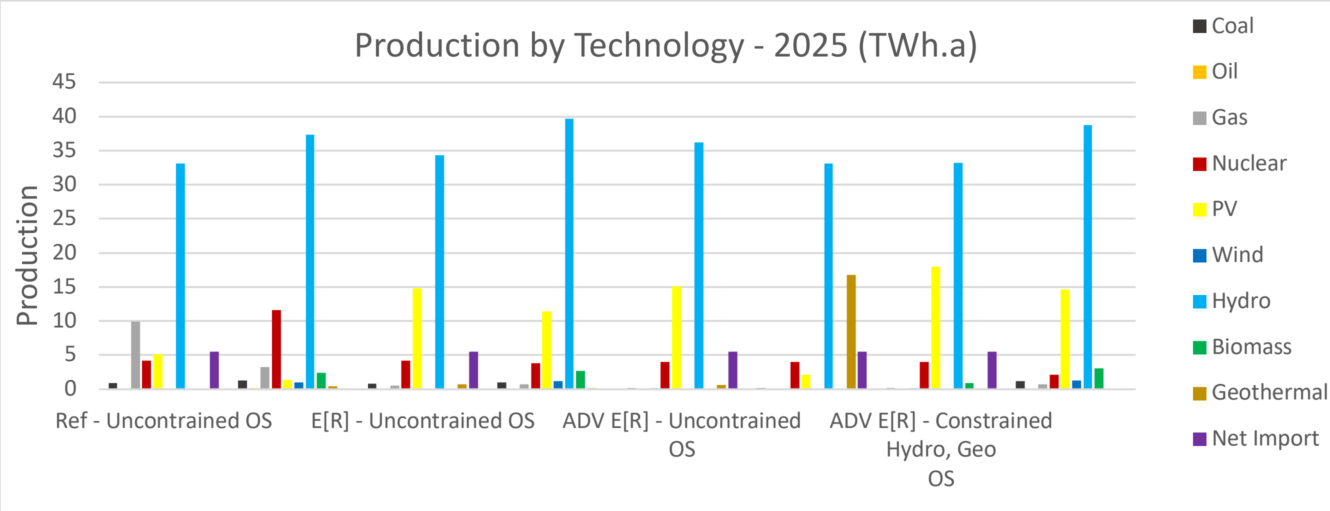


Figure 36. Comparison of electrical energy generation by technology in 2030 (OSeMOSYS & LT)

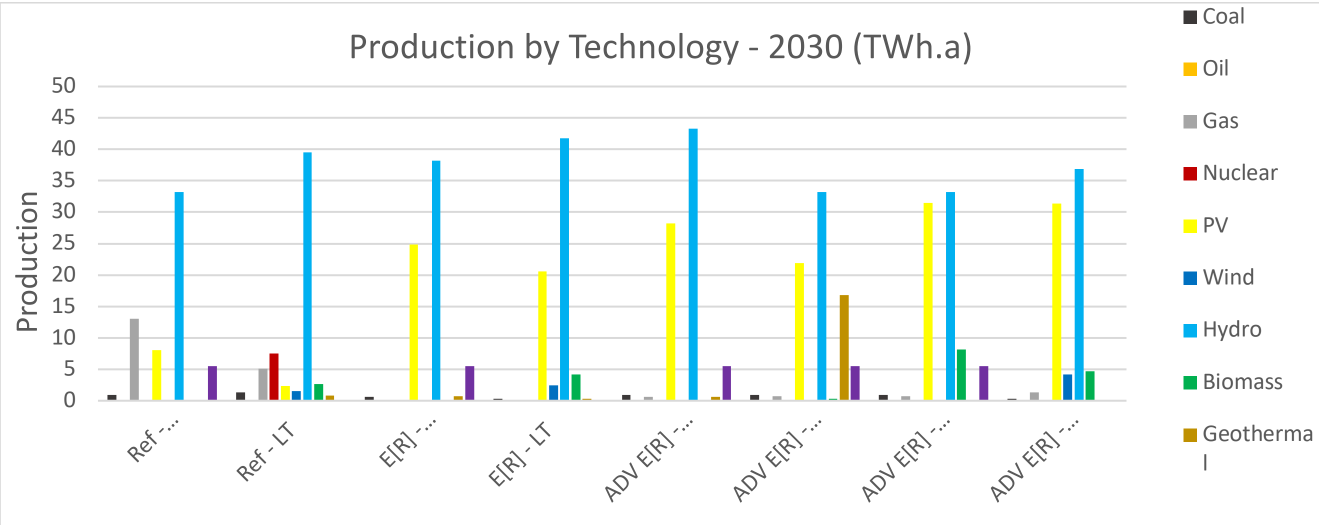
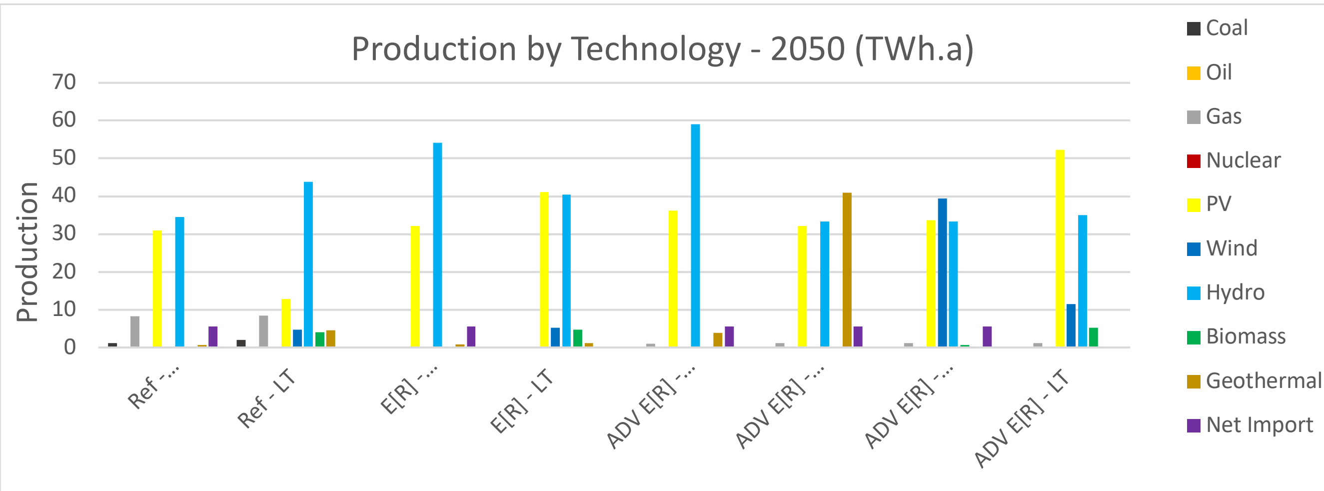
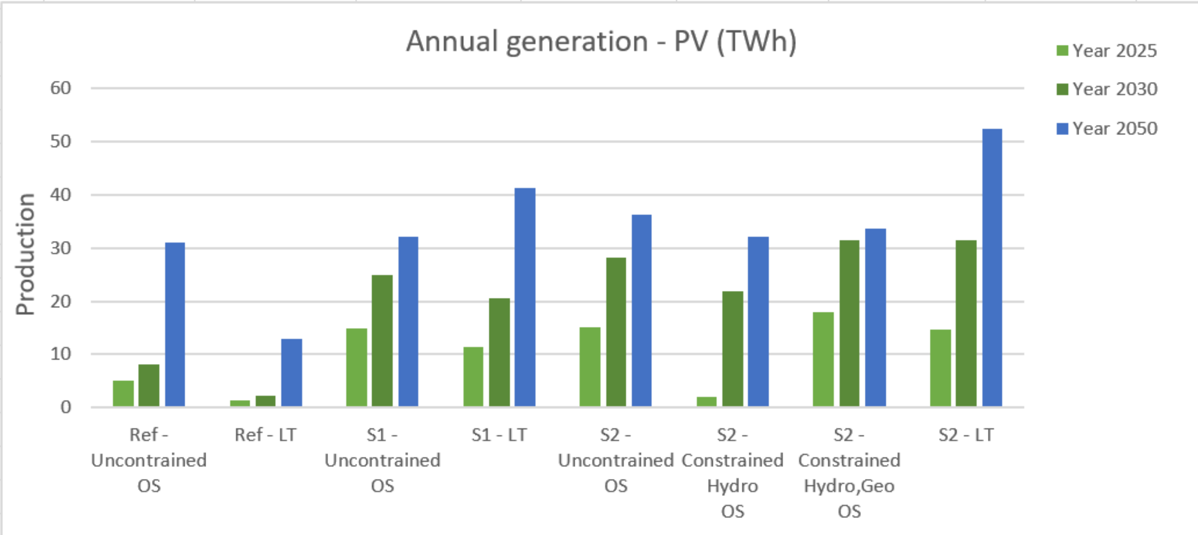


Figure 37. Comparison of electrical energy generation by technology in 2050 (OSeMOSYS & LT)



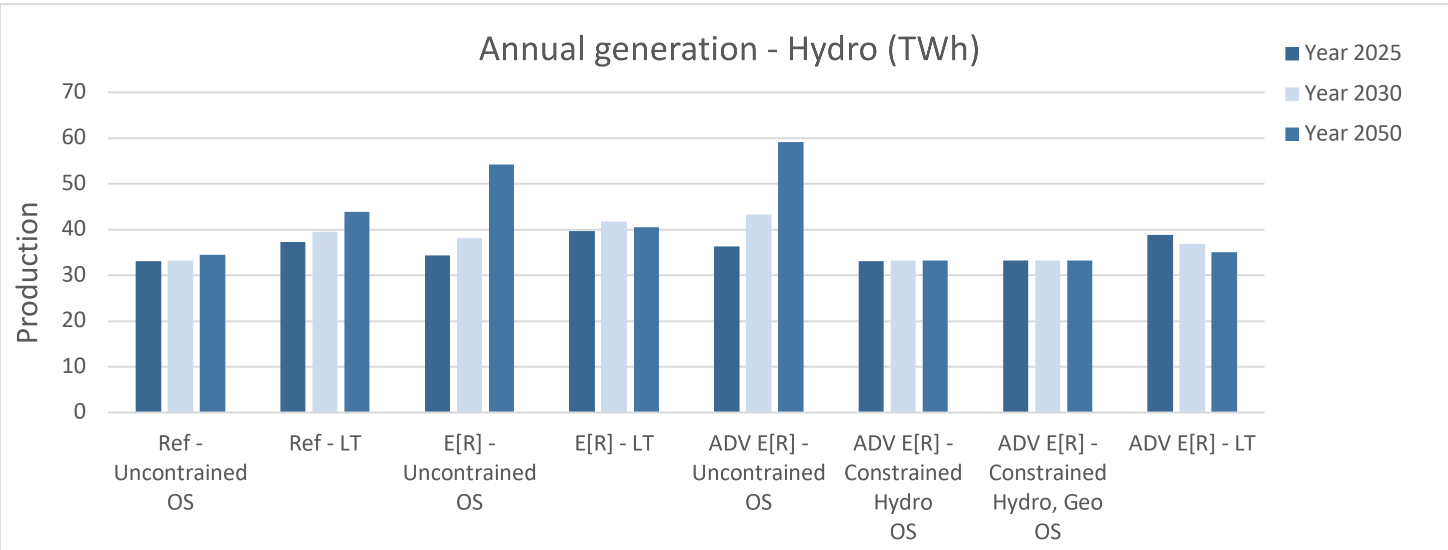
The annual generation from solar PV will increase significantly in all scenarios. **Fehler! Verweisquelle konnte nicht gefunden werden.** provides an overview of the eight different results. The key result is that solar PV will develop into the second main power source, with generation levels similar to those of hydropower by 2050 or earlier. Only the REFERENCE scenario predicts that solar PV will remain a minor component. Both models—OSeMOSYS and [R]E24/7—produce similar results and identify solar PV as the main future technology for renewable generation in Switzerland.

Figure 38. Comparison of annual solar photovoltaic generation under eight scenarios for 2025, 2030, and 2050



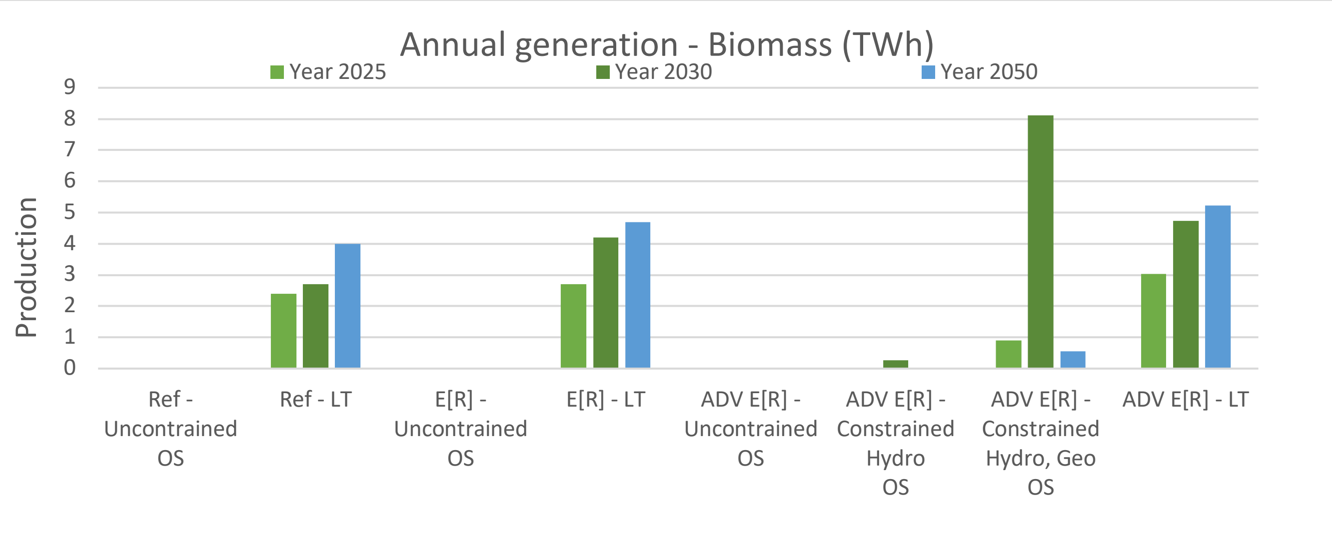
Under all *Unconstrained OSeMOSYS* scenarios, hydro power generation will increases further and supply up to 50% of Switzerland's future electricity demand, with annual production of up to 50–60 TWh (Figure 39). If ecological constraints are taken into account, the production level will not be able to double from current levels. Under the *Constrained OSeMOSYS* hydro scenarios, generation will be limited to around 35 TWh, as given by the residual capacity. In LT, this generation is suggested to increase to 40 TWh under both Energy [R]evolution scenarios.

Figure 39. Comparison of annual hydro power generation under eight scenarios for 2025, 2030, and 2050



Electricity generated with bio-energy—either solid biomass or biogas—will be important for system stability due to their dispatchability. Furthermore, bio-energy-fuelled co-generation plants will contribute to the heat and process heat demand. Biomass generation will increase slightly each year in [R]E 24/7 to a maximum of 5 TWh by 2050 under the ADVANCED Energy [R]evolution scenario, which will cover around 5% of the total electricity demand (Figure 40). Under *OSeMOSYS—Constrained Hydro, Geo*, bio-electricity will increase by up to 8 TWh as early as 2030. The operation of bio-energy-fuelled power plants will require a secure long-term supply of sustainable biomass.

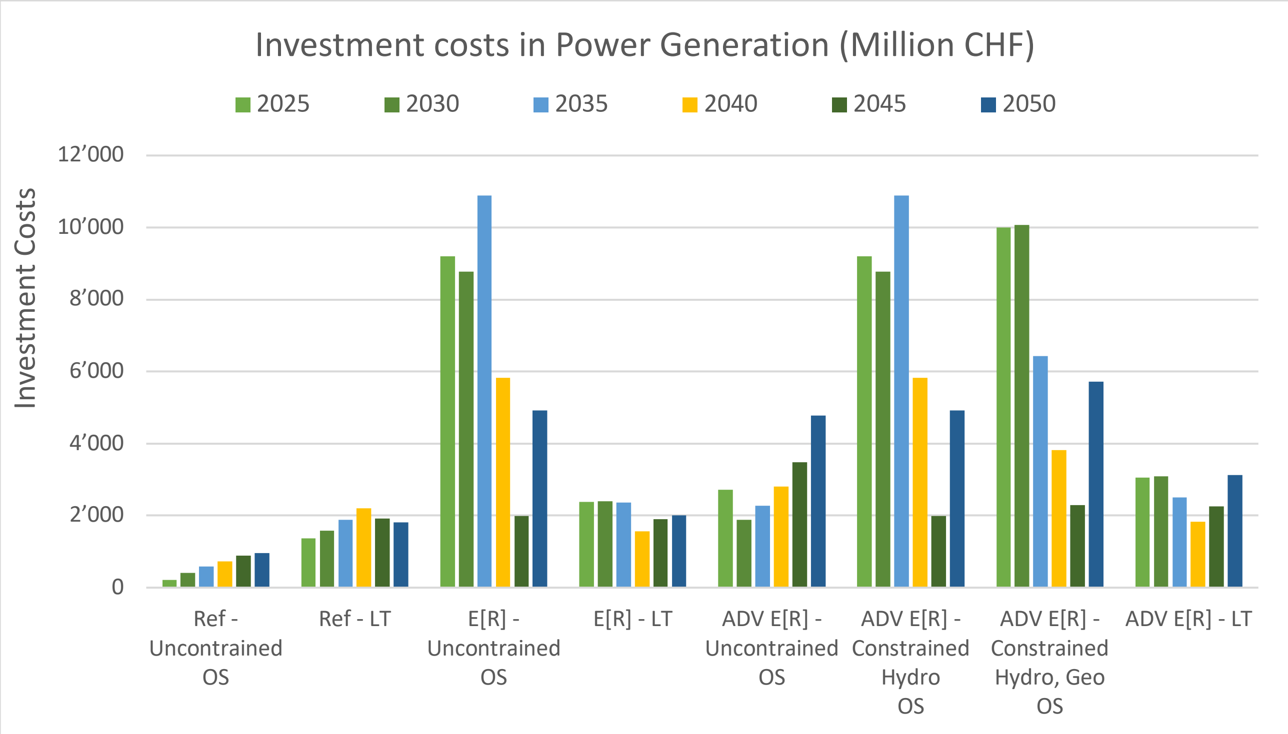
Figure 40. Comparison of annual energy generation from biomass under all scenarios in 2025, 2030, and 2050 (OSeMOSYS & LT)



6.3.2 Investment costs

Investment costs will be higher under constrained scenarios, which is as expected. On average, under other scenarios, investment costs will range between 5 and 10 billion CHF for each year in the study period (Figure 41).

Figure 41. Comparison of investment costs under all scenarios



6.3.3 Annual simulation—load profiles

This section shows a selection of load and generation profiles for Region 1 (R1), which includes the cantons of Freiburg, Waadt, Neuenburg, and Genf in the northwest of Switzerland.

The figures show the results of the Unconstrained OSeMOSYS—Energy [R]evolution scenario for 2025 (Figure 42) and 2050 (Figure 43). The significant contributions from solar PV in spring and summer and their reduced contributions to supply in autumn and winter are clearly apparent. Hydro will take over significant supply and will be important for generation management. However, the generation of solar PV will coincide with the demand curves during the day and significantly increase its share during weekends. Import and export will also be used as a—limited—source of generation management.

Figure 42. Generation simulation, region R1 OSeMOSYS scenario (E[R]—*Unconstrained,* OSeMOSYS), 2025

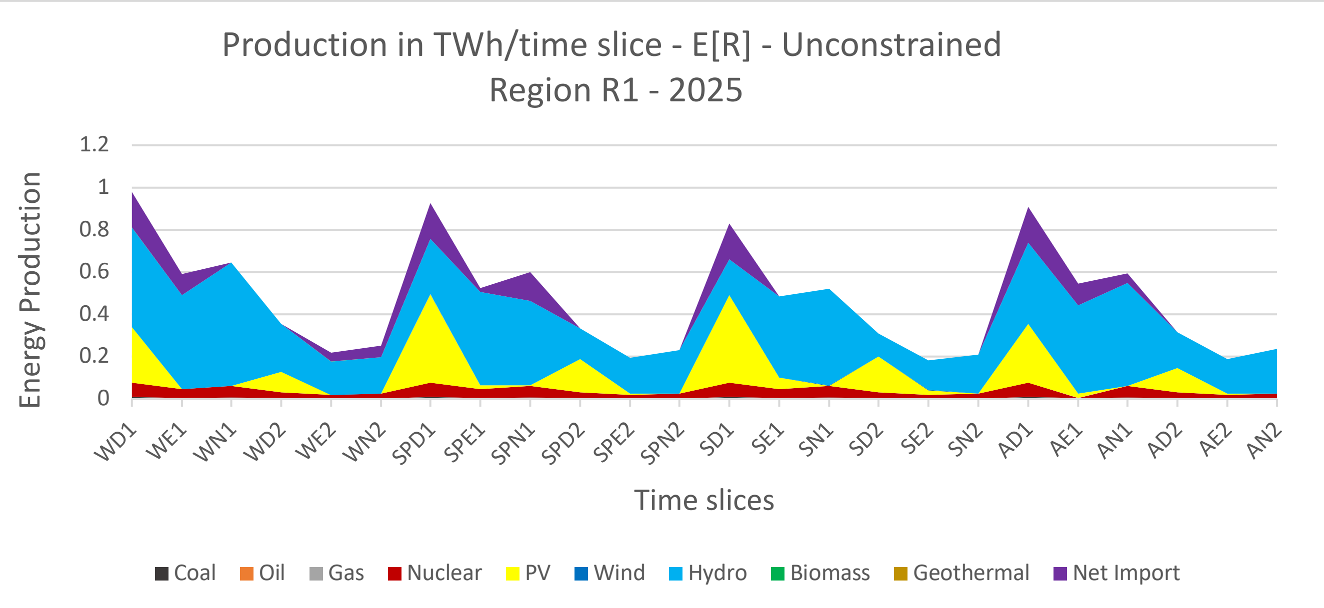


Figure 43. Generation simulation, region R1 OSeMOSYS scenario (E[R]—*Unconstrained,* OSeMOSYS), 2050

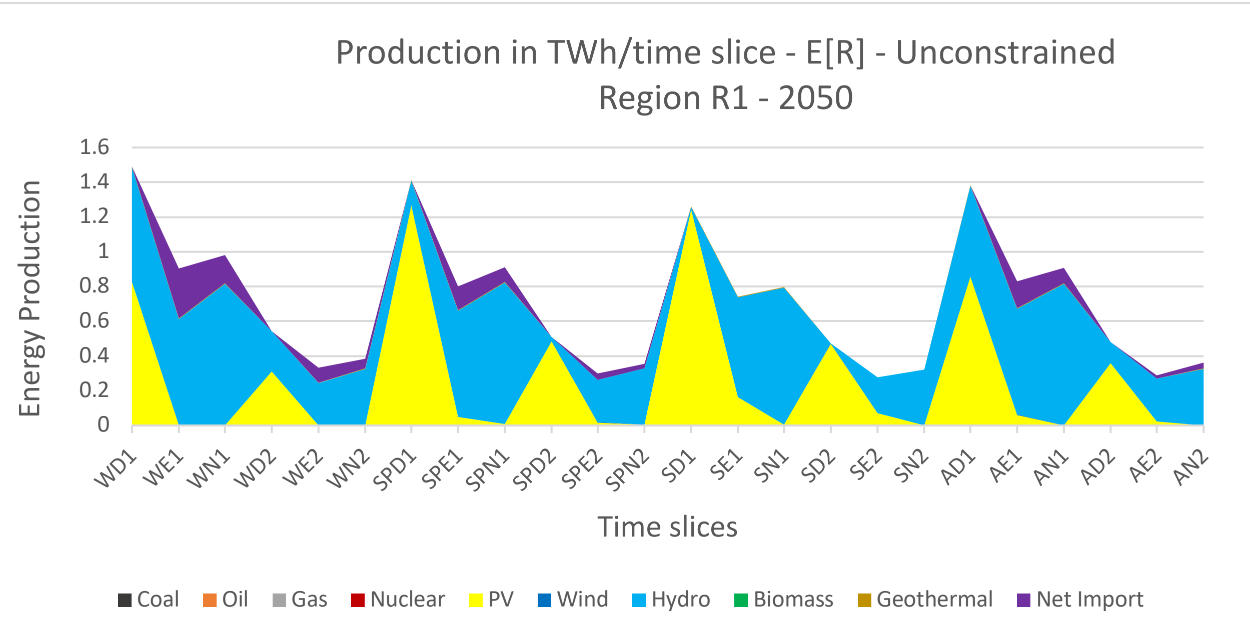
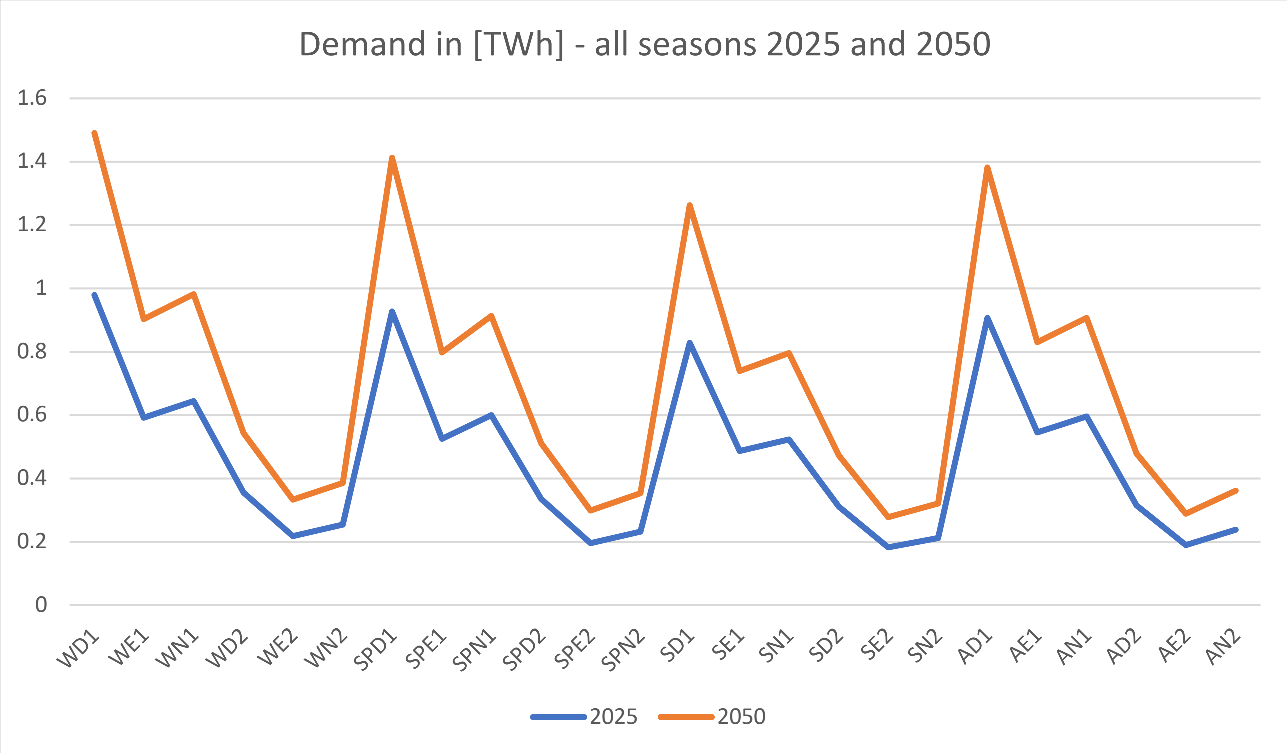


Figure 44. Simplified OSeMOSYS load curves—spring, summer, autumn, and winter for workdays and weekends in 2025 and 2050



7. SWITZERLAND: NET ZERO

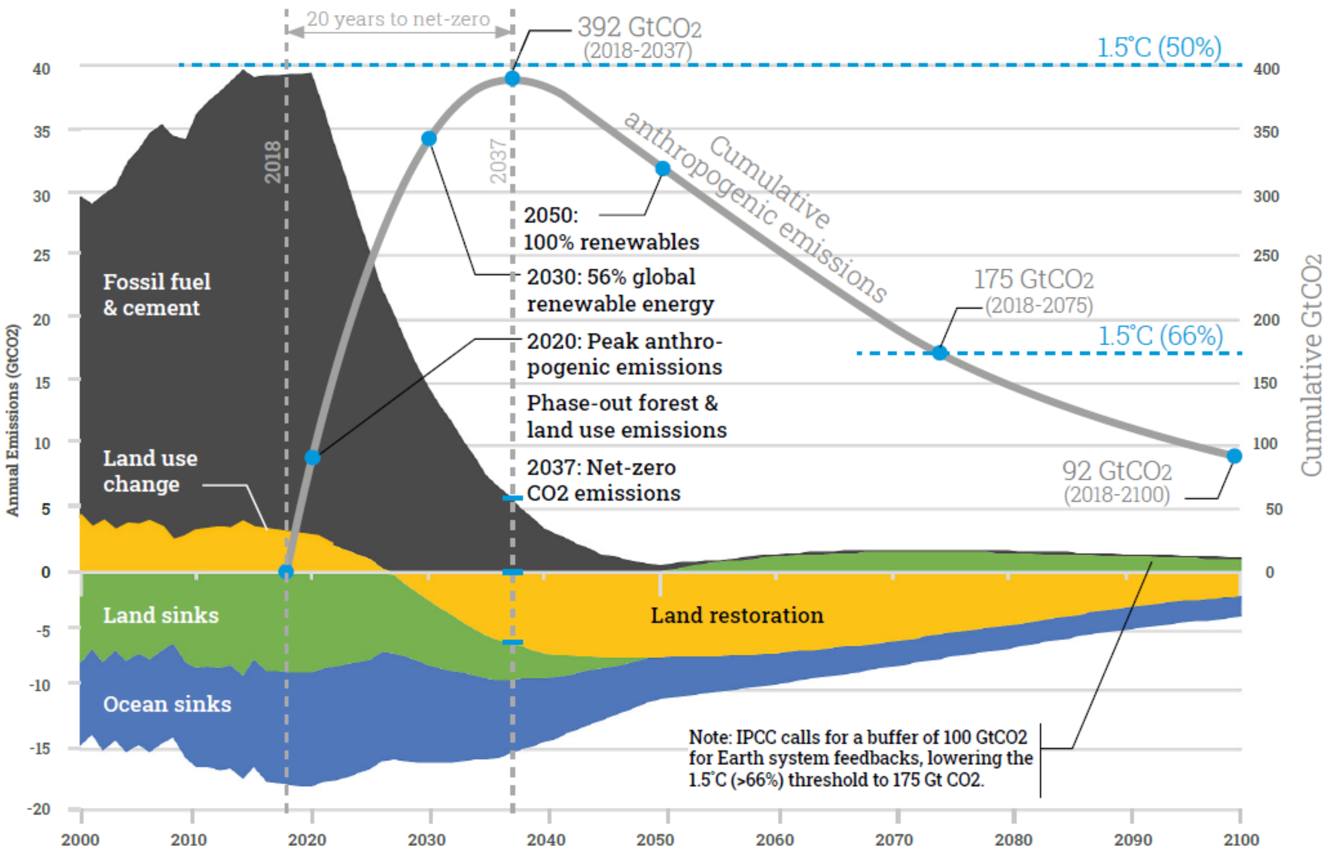
7.1 Global Carbon Budget for the 1.5 °C Pathway

The overall carbon budget for the 1.5 °C pathway (66% probability) is 450 $GtCO_2$, accumulated between 2015 and 2050. The majority (71%) of those energy-related carbon emissions must to be phase-out by 2030. In the 1.5 °C pathway, the cumulative CO_2 emissions between 2017 and 2030 will be 320 Gt, and the remaining approximately 80 Gt will be emitted between 2031 and 2050.

This trajectory is mandatory to comply with the central aim of the Paris Agreement "*to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius*"[53].

Therefore, the emissions reduction pathways for all countries are steep and will require very ambitious action in the next 5 years towards 2025. This is a requirement for reaching the 1.5 °C target, not a forecast.

Figure 45: Overview: One Earth Climate Model—Energy-related emissions and carbon sinks



The One Earth Climate Model achieves net zero annual CO_2 emissions in approximately 20 years, from 2018 to 2037. The black area represents the emissions from fossil fuels, which must decline by more than half by 2030. The gold area represents emissions from land use, including deforestation, the emissions from which will decline, and it will become a source of negative emissions in the late 2020s through forest restoration. The blue area represents natural ocean carbon sinks, which will continue absorbing CO_2 throughout the century. The green areas represent natural land carbon sinks, which will become a contributor of CO_2 emissions in the second half of the century through biosphere feedback. The blue dotted lines show the carbon budgets (commencing on January 1, 2018) that are required to ensure that the global temperature remains below 1.5 °C with 50% probability (top line) or with > 66% probability (lower line).

[53] UNFCCC, website viewed October 2020; https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Carbon Sinks—nature-based solutions

The following section is based on modelling work conducted by Dr. Malte Meinshausen and Dr. Kate Dooley of the University of Melbourne, as part of research work for the One Earth Climate Model, published in Teske et al. (2019), Chapters 4 and 12.

The One Earth Climate Model (OECM) combines energy decarbonization with large-scale natural restoration, calculating the carbon removal required to achieve a maximum global temperature increase of 1.5 °C. Restoration of natural carbon sinks through forestry and land-use pathways can remove up to 513 $GtCO_2$ by the end of the century.

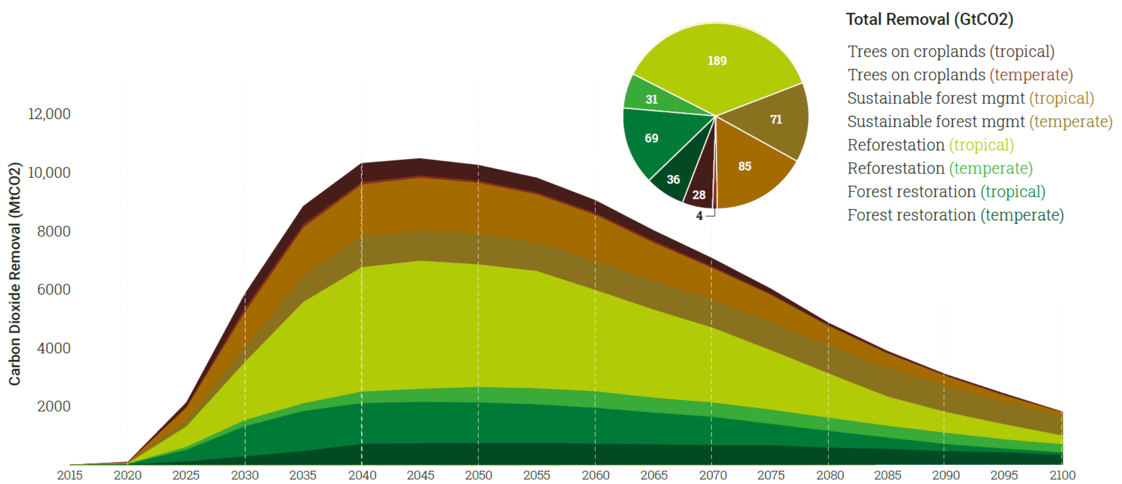
However, a significant proportion of this will be required to offset on-going agriculture, forestry, and other land use (AFLOU) emissions, estimated to be 124 $GtCO_2$ through to 2100 (UNFCCC—Shared Socio-Economic Pathway No 2 [SSP][54]), which assumes a gradual phase-out of AFOLU emissions to 2080. Given political realities, realizing 100% of the identified restoration potential is unlikely).

Therefore, deforestation and other forms of land conversion must decline much more quickly. Reductions in methane and nitrogen must also be achieved in the agriculture sector. Without nature-based solutions, the 1.5 °C limit is not possible, even with a rapid decline in fossil fuel emissions.

Four main natural sequestration pathways are utilized in the model, divided into temperate and tropical zones: reforestation, natural forest restoration, sustainable forest management, and cropland afforestation (trees in croplands):

1. Wildlands cover approximately 50% of the Earth's terrestrial area and are vital to the world's carbon cycle, sequestering as much as one quarter of anthropogenic carbon emissions and storing approximately 450 gigatons of solid carbon (Heinz 2017)[55]. Preserving these lands and forests intact is key to maintaining our global carbon sinks, making the 1.5 °C limit possible.
2. End deforestation: Today, land use changes account for more than 10% of global CO_2 emissions, (approximately 4 $GtCO_2$ per year), resulting largely from the clearing of forests for agriculture or other forms of development. Rapidly phasing-out the practice of deforestation will greatly increase the chance of achieving the 1.5 °C limit.
3. Large-scale reforestation: The most important sequestration measure identified is large-scale reforestation, particularly in the sub-tropics and tropics. Under the global 1.5 °C pathway, 300 megahectares (Mha) of land area will be reforested in the tropics and an additional 50 Mha will be reforested in temperate regions.
4. Natural restoration: The second most important pathway for carbon removal relies upon natural forest restoration or 'rewilding', increasing the carbon density within approximately 600 Mha of existing forests. Reduced logging and better forestry practices in managed forests will also contribute significantly to reducing the total carbon removal.

Figure 46: Carbon removal potential of land restoration pathways in 2020–2100



OECM presents a statistical analysis (Monte Carlo) of the time horizons and potential cumulative carbon uptakes for four major forest-restoration pathways, divided into temperate and tropical zones. The chart shows the total potential carbon removal of 513 $GtCO_2$ through these pathways, with rapid deployment beginning in the 2020s.

[54] UNFCCC, The Shared Socio-Economic Pathways (SSPs), https://unfccc.int/sites/default/files/part1_iiasa_rogelj_ssp_poster.pdf
[55] Heinz 2017, Erb, Karl-Heinz et al. (2017). Unexpectedly large impact of forest management and grazing on global vegetation biomass, https://www.nature.com/articles/nature25138

Planting trees on croplands

Tree cropping—a strategy in which trees are planted within croplands—can significantly increase carbon storage on agricultural lands. The model estimates that planting trees on 400 Mha of cropland will achieve approximately 30 $GtCO_2$ of carbon removal by 2100. The four sequestration pathways occur in all countries and regions, although we have excluded reforestation in the boreal forest zone because of the albedo effect.

All four sequestration pathways start in 2020, but have different phase-in and phase-out rates, which also differ between the boreal/temperate and tropical/sub-tropical biomes.

- Forest restoration: boreal/temperate—full potential by 2035, saturation by 2065 (decline to zero around 2100); tropical/sub-tropical—full potential by 2030, saturation by 2045 (decline to zero around 2100).
- Reforestation: boreal/temperate—full potential by 2045, saturation by 2075 (decline to zero around 2150); tropical/sub-tropical—full potential by 2040, saturation by 2065 (decline to zero around 2120).
- Sustainable use of forests: boreal/temperate—full potential by 2040, saturation by 2070 (decline to zero around 2150); tropical/sub-tropical—full potential by 2035, saturation by 2055 (decline to zero around 2100).
- Agroforestry: boreal/temperate—full potential by 2040, saturation by 2060 (decline to zero around 2080); tropical/sub-tropical—full potential by 2030, saturation by 2050 (decline to zero around 2080).

7.2 Net-Zero Requirements for Switzerland

All scenarios will lead to a phase-out of energy-related carbon emissions in Switzerland by 2050. However, the cumulative emissions between 2017 and 2050 differ significantly across scenarios. The REFERENCE scenario will lead to almost twice as high emissions (0.85 Gt CO_2) as the ADVANCED Energy [R]evolution scenario.

Table 37: Comparison of cumulative energy-related carbon dioxide emissions under three scenarios

Switzerland	2019	2030	2050	SUM 2017–2030 [Gt CO_2]	Difference to REF [Gt CO_2] (billion tones)	SUM 2017–2050 [Gt CO_2]	Difference to REF [Gt CO_2] (billion tones)
REFERENCE	40	29	0	0.499		0.804	
Energy [R]evolution	38	21	0	0.447	0.052	0.534	0.270
ADVANCED Energy [R]evolution	39	17	0	0.420	0.080	0.489	0.315

Table 38: Annual and cumulative carbon dioxide emissions by sector—REFERENCE

Annual energy-related CO_2 emissions				Cumulative energy-related CO_2 emissions		
Sectorial Emissions	2019	2030	2050	SUM 2017–2030 [Gt CO_2]	SUM 2017–2050 [Gt CO_2]	SUM 2030–2050 [Gt CO_2]
Reference	36	29	0	**0.499**	**0.804**	0.305
Industry	6	5	0	0.078	0.136	0.058
Buildings/Other Sectors	14	10	0	0.167	0.248	0.081
Transport	16	11	0	0.204	0.330	0.126
Power	0	1	0	0.008	0.021	0.013
Other conversions	3	3	0	0.042	0.069	0.027

Table 39: Annual and cumulative carbon dioxide emission by sector—Energy [R]evolution

Annual Energy-related CO_2 Emissions				Cumulative Energy-related CO_2 Emissions		
Sectorial Emissions	2019	2030	2050	SUM 2017–2030 [Gt CO_2]	SUM 2017–2050 [Gt CO_2]	SUM 2030–2050 [Gt CO_2]

Energy [R]evolution	36	21	0	0.447	0.534	0.087
Industry	6	2	0	0.063	0.072	0.009
Buildings/Other Sectors	13	6	0	0.145	0.175	0.030
Transport	16	11	0	0.197	0.230	0.034
Power	0	0	0	0.004	0.012	0.008
Other conversions	3	2	0	0.038	0.045	0.007

Table 40: Annual and cumulative carbon dioxide emissions by sector—ADVANCED Energy [R]evolution

Annual Energy-related CO_2 Emissions				Cumulative Energy-related CO_2 Emissions		Net-Zero Requirement
Sectorial Emissions	2019	2030	2050	SUM 2017–2030 [Gt CO_2]	SUM 2017–2050 [Gt CO_2]	SUM 2030–2050 [Gt CO_2]
ADVANCED Energy [R]evolution	36	17	0	0.420	0.489	0.069
Industry	6	2	0	0.066	0.077	0.011
Buildings/Other Sectors	13	6	0	0.132	0.155	0.023
Transport	16	8	0	0.183	0.206	0.023
Power	0	0	0	0.006	0.013	0.007
Other conversions	3	1	0	0.033	0.038	0.005

Nature-based carbon sinks will be required even when global energy-related carbon emissions have been reduced in line with the One Earth Climate Model (OECM), as shown in Figure 45. However, implementing the required carbon removal pathways seems more challenging than the energy transition itself. To start a reversal of deforestation and the trends in land-use emissions and to support sustainable agriculture and forest management, new programs must be commenced, especially in developing countries. Deforestation, especially of tropical rainforests, has even accelerated in recent years. New business models for forest management and reforestation programs are urgently required.

The implementation of the equity carbon budget for Switzerland is possible using a compensation scheme that focuses on forest management and reforestation. With a reliable and long-term carbon price, the protection of primeval forests and reforestation will bring more economic benefits than their destruction. For developing countries, it is fundamentally important that regional resources be used economically. Natural forests play a vital role in global climate protection and thus the preservation of the basis of life on the entire Earth. The economic system must be adapted accordingly, so that the preservation of these ecosystems is economically more interesting than their short-term exploitation—which will inevitably lead to destruction. Switzerland can play an important pioneering role here and establish bilateral agreements with developing countries.

8. APPENDIX

REFERENCE-SCENARIO (REF)

Tabelle 2: Electricity generation [TWh/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Power plants	**65.5**	**59.2**	**62.1**	**58.3**	**58.2**	**55.8**	**65.4**	**72.3**	**78.2**
- Hard coal (& non-renewable waste)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.0	0.0	0.0	1.0	1.7	1.8	1.6	1.4	1.3
of which from H2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.0
- Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Diesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24.2	18.7	18.7	11.7	7.5	0.0	0.0	0.0	0.0
- Biomass (& renewable waste)	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
- Hydro	39.0	37.7	40.2	40.7	41.7	42.0	43.8	44.2	42.7
- Wind	0.1	0.1	0.2	1.0	1.5	2.0	2.6	3.5	4.7
of which wind offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- PV	2.2	2.7	2.7	3.3	4.8	8.9	15.9	21.3	27.1
- Geothermal	0.0	0.0	0.2	0.4	0.8	1.0	1.3	1.7	2.1
- Solar thermal power plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Combined heat and power plants	**3.7**	**3.5**	**4.1**	**4.4**	**4.8**	**5.2**	**5.6**	**6.1**	**6.7**
- Hard coal (& non-renewable waste)	1.1	1.1	1.2	1.1	0.6	0.1	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.6	0.6	0.7	1.0	1.6	2.3	2.5	2.7	2.9
of which from H2	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.2	2.9
- Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
- Biomass (& renewable waste)	1.8	1.7	2.0	2.2	2.4	2.7	3.0	3.4	3.8
- Geothermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHP by producer									
- Main activity producers	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
- Autoproducers	3.1	3.0	3.5	3.8	4.2	4.6	5.0	5.5	6.1
Total generation	**69.2**	**62.8**	**66.2**	**62.7**	**63.0**	**61.0**	**71.0**	**78.5**	**84.8**
- Fossil	1.9	1.8	2.1	3.2	4.0	4.2	3.8	2.6	0.3
- Hard coal (& non-renewable waste)	1.1	1.1	1.2	1.1	0.7	0.1	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.6	0.6	0.7	2.0	3.3	4.0	3.7	2.6	0.3
- Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
- Diesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24.2	18.7	18.7	11.7	7.5	0.0	0.0	0.0	0.0
- Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.6	3.9
of which renewable H2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.5	3.7
- Renewables (w/o renewable hydrogen)	43.2	42.2	45.4	47.8	51.5	56.7	66.8	74.2	80.6
- Hydro	39.0	37.7	40.2	40.7	41.7	42.0	43.8	44.2	42.7
- Wind	0.1	0.1	0.2	1.0	1.5	2.0	2.6	3.5	4.7
- PV	2.2	2.7	2.7	3.3	4.8	8.9	15.9	21.3	27.1
- Biomass (& renewable waste)	1.8	1.7	2.2	2.4	2.6	2.9	3.2	3.6	4.0
- Geothermal	0.0	0.0	0.2	0.4	0.8	1.0	1.3	1.7	2.1
- Solar thermal power plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution losses (incl.hydro pumpstorage)	4.2	3.9	4.7	4.6	4.7	4.9	5.1	5.4	5.6
Own consumption electricity	6.8	7.0	7.0	7.5	8.0	8.4	8.8	8.8	8.8
Domestic Electricity for hydrogen production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	2.8
Electricity for synfuel production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Final energy consumption (electricity)	**56.6**	**53.2**	**60.5**	**59.8**	**59.9**	**62.4**	**65.4**	**69.7**	**73.1**
Variable RES (PV, Wind, Ocean)	2.4	2.8	2.8	4.3	6.3	10.8	18.5	24.7	31.8
Share of variable RES	3%	4%	4%	7%	10%	18%	26%	32%	37%
RES share (domestic generation)	62%	67%	69%	76%	82%	93%	95%	97%	99%

Tabelle 3: Installed Capacity [GW]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total generation	**20**	**20**	**20**	**21**	**22**	**25**	**33**	**38**	**44**
- Fossil	0	0	0	1	1	1	1	1	1
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	1	1	1	1	1
- Oil	0	0	0	0	0	0	0	0	0
- Diesel	0	0	0	0	0	0	0	0	0
- Nuclear	3	3	3	2	1	0	0	0	0
- Hydrogen (fuel cells, gas power plants, gas CHP)	0	0	0	0	0	0	0	0	0
- Renewables	16	16	16	18	20	24	32	38	43
- Hydro	13	13	13	14	14	14	15	15	14
- Wind	0	0	0	1	1	1	1	2	3
of which wind offshore	0	0	0	0	0	0	0	0	0
- PV	2	2	2	3	5	8	15	20	25
- Biomass (& renewable waste)	0.4	0.3	0.444	0.478	0.533	0.589	0.653	0.7	0.8
- Geothermal	0	0	0	0	0	0	0	0	0
- Solar thermal power plants	0	0	0	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	2	3	3	4	5	9	16	22	28
Share of variable RES	11%	13%	13%	18%	24%	37%	50%	57%	63%
RES share (domestic generation)	81%	82%	82%	87%	90%	96%	97%	97%	98%

Tabelle 4: Heat supply and air conditioning [PJ/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
District heating plants	**19**	**17**	**21**	**23**	**26**	**25**	**24**	**23**	**22**
- Fossil fuels	19	17	21	20	20	12	6	3	0
- Biomass	0	0	0	3	5	12	18	20	22
- Solar collectors	0	0	0	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0	0	0	0
Heat from CHP 1)	**17**	**16**	**19**	**20**	**20**	**20**	**22**	**26**	**34**
- Fossil fuels	7	7	5	7	6	4	1	1	0
- Biomass	10	9	14	13	14	16	21	25	31
- Geothermal	0	0	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0	0	3
Direct heating	**298**	**280**	**304**	**268**	**238**	**215**	**200**	**154**	**138**
- Fossil fuels	215	200	218	185	160	140	128	88	0
- Biomass	33	30	35	34	34	33	33	32	31
- Solar collectors	3	2	5	6	7	8	8	9	9
- Geothermal	0	0	0	0	0	0	0	0	1
- Heat pumps 2)	0	0	0	0	0	0	1	1	1
- Electric direct heating	48	48	47	42	36	33	29	25	22
- Hydrogen	0	0	0	0	0	0	0	0	74
Total heat supply3)	**333**	**313**	**344**	**311**	**283**	**259**	**246**	**204**	**194**
- Fossil fuels	241	225	244	212	186	156	136	92	0
- Biomass	42	39	49	51	53	62	72	77	84
- Solar collectors	3	2	5	6	7	8	8	9	9
- Geothermal	0	0	0	0	0	0	0	0	1
- Heat pumps 2)	0	0	0	0	0	0	1	1	1
- Electric direct heating	48	48	47	42	36	33	29	25	22
- Hydrogen	0	0	0	0	0	0	0	0	77
RES share (including RES electricity)	**22%**	**23%**	**25%**	**28%**	**32%**	**39%**	**44%**	**54%**	**99%**
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2

REFERENCE-SCENARIO (REF)

Tabelle 5: Transport - Final Energy [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
road	**222**	**206**	**222**	**200**	**180**	**158**	**129**	**110**	**85**
- fossil fuels	215	199	215	189	160	126	85	54	0
- biofuels	7	6	6	7	12	13	15	16	31
- synfuels	0	0	0	0	0	0	0	0	0
- natural gas	1	1	1	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0	0	0	0
- electricity	0	0	1	4	9	18	29	40	54
rail	**12**	**11**	**12**	**13**	**14**	**14**	**15**	**15**	**16**
- fossil fuels	0	0	0	0	0	0	0	0	1
- biofuels	0	0	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0	0	0
- electricity	11	10	11	13	13	14	14	15	15
navigation	**2**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
- fossil fuels	2	1	2	2	2	2	2	2	2
- biofuels	0	0	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0	0	0
aviation	**3**	**3**	**2**	**3**	**3**	**3**	**3**	**3**	**3**
- fossil fuels	3	3	2	3	3	3	3	3	3
- biofuels	0	0	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0	0	0
total (incl. pipelines)	**238**	**221**	**238**	**217**	**198**	**176**	**149**	**141**	**275**
- fossil fuels	219	204	219	194	164	131	90	59	5
- biofuels (incl. biogas)	7	6	6	7	12	13	15	16	31
- synfuels	0	0	0	0	0	0	0	0	59
- natural gas	1	1	1	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0	1	12	110
- electricity	11	10	12	17	22	32	43	54	69
total RES	**14**	**13**	**15**	**19**	**30**	**43**	**57**	**80**	**268**
RES share	14%	35%	6%	9%	14%	23%	35%	45%	99%

Tabelle 6: Energy-Releated CO_2 Emissions [Million tons/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Condensation power plants	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	1	1	0	0	0
- Oil & Diesel	0	0	0	0	0	0	0	0	0
Combined heat and power plants	**2**	**2**	**2**	**2**	**2**	**1**	**1**	**1**	**2**
- Hard coal (& non-renewable waste)	1	1	1	1	1	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	1	1	1	1	1	1
- Oil	0	0	0	0	0	0	0	0	0
CO_2 emissions power and CHP plants	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
- Hard coal (& non-renewable waste)	1	1	2	1	1	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	1	1	2	2	2	1
- Oil & diesel	0	0	0	0	0	0	0	0	0
CO_2 intensity (g/kWh)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
without credit for CHP heat	0	0	0	0	0	0	0	0	0
- CO_2 intensity fossil electr. generation	988	987	974	736	569	470	490	671	4727
- CO_2 intensity total electr. generation	27	28	31	38	36	33	26	22	18
CO_2 emissions by sector	**39**	**36**	**40**	**35**	**29**	**24**	**19**	**13**	**0**
- % of 1990 emissions (Mill t)	92%	86%	95%	84%	70%	58%	46%	32%	1%
- Industry 1)	6	6	6	5	5	4	3	3	0
- Other sectors 1)	13	12	14	12	10	8	8	4	0
- Transport	17	15	16	14	11	9	6	5	0
- Power generation 2)	0	0	0	1	1	1	1	1	0
- Other conversion 3)	2	2	3	3	2	1	0	0	0
Population (Mill.)	5	4	5	4	3	2	2	1	0
CO_2 emissions per capita (t/capita)	9	9	9	9	9	10	10	10	10

Tabelle 7: Primary Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total	**1012**	**909**	**1027**	**913**	**824**	**716**	**699**	**647**	**641**
- Fossil	532	495	577	518	443	377	313	219	22
- Hard coal	28	27	28	24	16	7	2	0	0
- Lignite	3	2	0	0	0	0	0	0	0
- Natural gas	146	136	153	156	161	152	148	117	0
- Crude oil	355	330	396	338	266	219	164	103	21
- Nuclear	256	198	197	122	77	0	0	0	0
- Renewables	224	215	253	274	304	338	386	428	619
- Hydro	140	136	145	147	150	151	158	159	154
- Wind	0	0	1	3	5	7	9	13	17
- Solar	11	12	14	18	25	40	66	86	107
- Biomass	72	67	86	92	97	109	120	124	131
- Geothermal	0	0	7	15	27	31	32	34	41
- Ocean energy	0	0	0	0	0	0	0	0	0
of which non-energy use	19	18	20	21	21	21	21	21	21
Total RES	220	219	268	300	332	388	414	450	638
RES share	22%	24%	25%	31%	38%	50%	57%	67%	97%

Tabelle 8: Final Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total (incl. non-Energy use)	**759**	**705**	**778**	**717**	**648**	**606**	**566**	**512**	**492**
Total Energy use 1)	740	688	758	696	627	585	545	491	471
Transport	**238**	**221**	**238**	**215**	**177**	**160**	**134**	**130**	**128**
- Oil products	219	204	218	193	149	122	85	69	0
- Natural gas	1	1	1	0	0	0	0	0	0
- Biofuels	7	6	6	6	6	6	6	7	7
- Synfuels	0	0	0	0	0	0	0	0	59
- Electricity	11	10	14	17	22	32	43	54	62
RES electricity	7	7	9	13	18	30	41	53	62
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Transport	6%	6%	6%	9%	14%	23%	35%	45%	99%
Industry	**145**	**134**	**146**	**137**	**129**	**124**	**116**	**110**	**101**
- Electricity	62	58	66	62	59	58	56	55	54
RES electricity	39	39	45	48	48	54	53	53	53
- Public district heat	7	7	7	7	7	7	7	7	7
RES district heat	1	1	1	1	1	1	2	2	2
- Hard coal & lignite	14	13	11	9	7	5	2	0	0
- Oil products	12	11	14	11	8	6	4	2	1
- Gas	39	37	36	36	35	34	33	32	25
- Solar	0	0	1	1	1	1	1	1	1
- Biomass	10	9	11	11	11	11	12	12	11
- Geothermal	0	0	0	0	0	0	0	1	2
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Industry	34%	36%	39%	44%	48%	55%	59%	62%	69%
Other Sectors	**357**	**332**	**374**	**343**	**321**	**301**	**295**	**251**	**242**
- Electricity	134	125	139	136	135	135	136	139	142
RES electricity	84	84	95	104	110	126	129	134	141
- Public district heat	13	12	15	16	19	18	17	17	16
RES district heat	2	2	2	3	4	4	4	5	5
- Hard coal & lignite	2	2	0	0	0	0	0	0	0
- Oil products	104	97	114	89	71	58	47	6	0
- Gas	72	67	72	67	62	56	61	56	51
- Solar	2	2	4	5	6	7	7	8	8
- Biomass	29	27	31	30	29	28	27	26	25
- Geothermal	0	0	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Other Sectors	33%	35%	35%	41%	46%	55%	57%	69%	74%
Total RES	**181**	**177**	**205**	**221**	**235**	**268**	**282**	**300**	**377**
RES share	24%	26%	27%	32%	37%	46%	52%	61%	80%
Non energy use	**19**	**18**	**20**	**21**	**21**	**21**	**21**	**21**	**21**
- Oil	19	18	20	21	21	21	21	21	21
- Gas	0	0	0	0	0	0	0	0	0
- Coal	0	0	0	0	0	0	0	0	0

ENERGY-[R]EVOLUTION-SCENARIO (E[R])

Tabelle 9: Electricity generation [TWh/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Power plants	**65.5**	**59.2**	**62.1**	**58.3**	**58.2**	**55.8**	**65.4**	**72.3**	**78.2**
- Hard coal (& non-renewable waste)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.0	0.0	0.0	1.0	1.7	1.8	1.6	1.4	1.3
of which from H2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.0
- Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Diesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24.2	18.7	18.7	11.7	7.5	0.0	0.0	0.0	0.0
- Biomass (& renewable waste)	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2
- Hydro	39.0	37.7	40.2	40.7	41.7	42.0	43.8	44.2	42.7
- Wind	0.1	0.1	0.2	1.0	1.5	2.0	2.6	3.5	4.7
of which wind offshore	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- PV	2.2	2.7	2.7	3.3	4.8	8.9	15.9	21.3	27.1
- Geothermal	0.0	0.0	0.2	0.4	0.8	1.0	1.3	1.7	2.1
- Solar thermal power plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Combined heat and power plants	**3.7**	**3.5**	**4.1**	**4.4**	**4.8**	**5.2**	**5.6**	**6.1**	**6.7**
- Hard coal (& non-renewable waste)	1.1	1.1	1.2	1.1	0.6	0.1	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.6	0.6	0.7	1.0	1.6	2.3	2.5	2.7	2.9
of which from H2	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.2	2.9
- Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
- Biomass (& renewable waste)	1.8	1.7	2.0	2.2	2.4	2.7	3.0	3.4	3.8
- Geothermal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHP by producer									
- Main activity producers	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
- Autoproducers	3.1	3.0	3.5	3.8	4.2	4.6	5.0	5.5	6.1
Total generation	**69.2**	**62.8**	**66.2**	**62.7**	**63.0**	**61.0**	**71.0**	**78.5**	**84.8**
- Fossil	1.9	1.8	2.1	3.2	4.0	4.2	3.8	2.6	0.3
- Hard coal (& non-renewable waste)	1.1	1.1	1.2	1.1	0.7	0.1	0.0	0.0	0.0
- Lignite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0.6	0.6	0.7	2.0	3.3	4.0	3.7	2.6	0.3
- Oil	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
- Diesel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24.2	18.7	18.7	11.7	7.5	0.0	0.0	0.0	0.0
- Hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.6	3.9
of which renewable H2	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.5	3.7
- Renewables (w/o renewable hydrogen)	43.2	42.2	45.4	47.8	51.5	56.7	66.8	74.2	80.6
- Hydro	39.0	37.7	40.2	40.7	41.7	42.0	43.8	44.2	42.7
- Wind	0.1	0.1	0.2	1.0	1.5	2.0	2.6	3.5	4.7
- PV	2.2	2.7	2.7	3.3	4.8	8.9	15.9	21.3	27.1
- Biomass (& renewable waste)	1.8	1.7	2.2	2.4	2.6	2.9	3.2	3.6	4.0
- Geothermal	0.0	0.0	0.2	0.4	0.8	1.0	1.3	1.7	2.1
- Solar thermal power plants	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution losses (incl.hydro pumpstorage)	4.2	3.9	4.7	4.6	4.7	4.9	5.1	5.4	5.6
Own consumption electricity	6.8	7.0	7.0	7.5	8.0	8.4	8.8	8.8	8.8
Domestic Electricity for hydrogen production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	2.8
Electricity for synfuel production	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Final energy consumption (electricity)	**56.6**	**53.2**	**60.5**	**59.8**	**59.9**	**62.4**	**65.4**	**69.7**	**73.1**
Variable RES (PV, Wind, Ocean)	2.4	2.8	2.8	4.3	6.3	10.8	18.5	24.7	31.8
Share of variable RES	3%	4%	4%	7%	10%	18%	26%	32%	37%
RES share (domestic generation)	62%	67%	69%	76%	82%	93%	95%	97%	99%

ITabelle 10: nstalled Capacity [GW]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total generation	**20**	**20**	**20**	**21**	**22**	**25**	**33**	**38**	**44**
- Fossil	0	0	0	1	1	1	1	1	1
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	1	1	1	1	1
- Oil	0	0	0	0	0	0	0	0	0
- Diesel	0	0	0	0	0	0	0	0	0
- Nuclear	3	3	3	2	1	0	0	0	0
- Hydrogen (fuel cells, gas power plants, gas CHP)	0	0	0	0	0	0	0	0	0
- Renewables	16	16	16	18	20	24	32	38	43
- Hydro	13	13	13	14	14	14	15	15	14
- Wind	0	0	0	1	1	1	1	2	3
of which wind offshore	0	0	0	0	0	0	0	0	0
- PV	2	2	2	3	5	8	15	20	25
- Biomass (& renewable waste)	0.4	0.3	0.444	0.478	0.533	0.589	0.653	0.7	0.8
- Geothermal	0	0	0	0	0	0	0	0	0
- Solar thermal power plants	0	0	0	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	2	3	3	4	5	9	16	22	28
Share of variable RES	11%	13%	13%	18%	24%	37%	50%	57%	63%
RES share (domestic generation)	81%	82%	82%	87%	90%	96%	97%	97%	98%

Tabelle 11: Heat supply and air conditioning [PJ/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
District heating plants	**19**	**17**	**17**	**19**	**18**	**17**	**16**	**15**	**13**
- Fossil fuels	19	17	17	17	6	0	0	0	0
- Biomass	0	0	0	1	11	15	14	12	10
- Solar collectors	0	0	0	0	1	2	2	3	3
- Geothermal	0	0	0	0	0	0	0	0	0
Heat from CHP 1)	**17**	**16**	**24**	**25**	**25**	**27**	**27**	**26**	**26**
- Fossil fuels	7	7	3	10	4	0	1	0	0
- Biomass	10	9	22	15	22	27	25	0	0
- Geothermal	0	0	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0	0	0
Direct heating	**298**	**280**	**291**	**242**	**210**	**185**	**169**	**150**	**141**
- Fossil fuels	215	200	209	143	92	41	20	0	0
- Biomass	33	30	32	24	24	26	26	23	15
- Solar collectors	3	2	3	13	26	25	31	30	35
- Geothermal	0	0	0	0	0	0	0	0	0
- Heat pumps 2)	0	0	1	18	47	80	82	88	82
- Electric direct heating	48	48	48	43	20	13	9	8	8
- Hydrogen	0	0	0	0	0	0	0	0	0
Total heat supply3)	**333**	**313**	**333**	**285**	**254**	**229**	**211**	**191**	**180**
- Fossil fuels	241	225	228	170	102	41	21	1	0
- Biomass	42	39	54	40	57	68	65	61	50
- Solar collectors	3	2	3	14	27	27	34	32	38
- Geothermal	0	0	0	0	0	0	0	0	0
- Heat pumps 2)	0	0	1	18	47	80	82	88	82
- Electric direct heating 2)	48	48	48	43	20	13	9	8	8
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share (including RES electricity)	**22%**	**23%**	**27%**	**39%**	**60%**	**82%**	**90%**	**100%**	**100%**
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.2	1.0	4.3	5.8	6.1	5.8	5.3

ENERGY-[R]EVOLUTION-SCENARIO (E[R])

Tabelle 12: Transport - Final Energy [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
road	**222**	**206**	**214**	**192**	**164**	**103**	**83**	**84**	**89**
- fossil fuels	215	199	211	184	143	40	6	0	0
- biofuels	7	6	2	2	4	5	8	11	13
- synfuels	0	0	0	0	0	0	0	0	0
- natural gas	1	1	0	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0	0	0	0
- electricity	0	0	2	5	17	58	68	73	76
rail	**12**	**11**	**12**	**13**	**13**	**14**	**14**	**14**	**15**
- fossil fuels	0	0	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0	0	0
- electricity	11	10	12	13	13	14	14	14	15
navigation	**2**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
- fossil fuels	2	1	2	1	1	0	0	0	0
- biofuels	0	0	0	0	0	1	2	2	2
- synfuels	0	0	0	0	0	0	0	0	0
aviation	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**3**
- fossil fuels	3	3	2	2	2	2	0	0	0
- biofuels	0	0	0	0	0	1	2	2	3
- synfuels	0	0	0	0	0	0	0	0	0
total (incl. pipelines)	**238**	**221**	**231**	**211**	**185**	**127**	**109**	**112**	**119**
- fossil fuels	219	204	215	188	147	42	6	0	0
- biofuels (incl. biogas)	7	6	2	2	4	7	12	15	17
- synfuels	0	0	0	0	0	0	0	0	0
- natural gas	1	1	0	0	0	0	0	0	0
- hydrogen	0	0	0	0	1	2	3	4	5
- electricity	11	10	13	18	31	72	82	87	90
total RES	**14**	**13**	**11**	**19**	**35**	**81**	**97**	**106**	**112**
RES share	6%	35%	5%	10%	20%	66%	93%	99%	100%

Tabelle 13: Energy-Releated CO_2 Emissions [Million tons/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Condensation power plants	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil & Diesel	0	0	0	0	0	0	0	0	0
Combined heat and power plants	**2**	**2**	**2**	**2**	**1**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	1	1	1	1	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0	0	0
CO_2 emissions power and CHP plants	**2**	**2**	**2**	**2**	**1**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	1	1	1	1	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil & diesel	0	0	0	0	0	0	0	0	0
CO_2 intensity (g/kWh)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
without credit for CHP heat	0	0	0	0	0	0	0	0	0
- CO_2 intensity fossil electr. generation	988	987	967	1'002	855	1'108	1'031	533	402
- CO_2 intensity total electr. generation	27	28	29	28	11	4	3	1	1
CO_2 emissions by sector	**39**	**36**	**38**	**31**	**21**	**7**	**2**	**0**	**0**
- % of 1990 emissions (Mill t)	92%	86%	90%	74%	51%	16%	5%	0%	0%
- Industry 1)	6	6	5	5	2	1	0	0	0
- Other sectors 1)	13	12	13	9	6	2	1	0	0
- Transport	17	15	16	14	11	3	1	0	0
- Power generation 2)	0	0	0	0	0	0	0	0	0
- Other conversion 3)	2	2	3	3	2	1	0	0	0
Population (Mill.)	9	9	9	9	9	10	10	10	10
CO_2 emissions per capita (t/capita)	5	4	4	3	2	1	0	0	0

Tabelle 14: Primary Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total	**1012**	**909**	**976**	**782**	**699**	**602**	**562**	**554**	**559**
- Fossil	532	495	541	443	311	115	46	15	13
- Hard coal (& non-renewable waste)	28	27	22	26	6	2	2	0	0
- Lignite	3	2	0	0	0	0	0	0	0
- Natural gas	146	136	150	110	77	45	23	1	0
- Crude oil	355	330	369	307	228	68	21	14	13
- Nuclear	256	198	204	42	0	0	0	0	0
- Renewables	224	215	231	298	387	487	516	539	545
- Hydro	140	136	145	146	147	148	148	148	148
- Wind	0	0	1	4	9	11	14	17	18
- Solar	11	12	12	60	88	138	150	161	180
- Biomass (& renewable waste)	72	67	70	70	103	123	128	126	116
- Geothermal	0	0	3	17	41	68	76	86	83
- Ocean energy	0	0	0	0	0	0	0	0	0
- of which non-energy use	19	18	16	14	14	14	13	13	13
- Total RES	220	219	231	298	387	487	516	539	545
- RES share	22%	24%	23%	37%	54%	80%	91%	97%	98%

Tabelle 15: Final Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total (incl. non-energy use)	**759**	**705**	**748**	**662**	**598**	**491**	**446**	**428**	**428**
Total energy use 1)	740	688	732	648	584	477	432	415	415
Transport	**238**	**221**	**233**	**212**	**185**	**125**	**105**	**108**	**114**
- Oil products	219	204	217	190	148	42	6	0	0
- Natural gas	1	1	0	0	0	0	0	0	0
- Biofuels	7	6	2	2	4	7	12	15	17
- Synfuels	0	0	0	0	0	0	0	0	0
- Electricity	11	10	13	18	31	72	82	87	90
RES electricity	7	7	9	16	30	72	82	87	90
- Hydrogen	0	0	1	2	2	3	4	5	7
RES share Transport	6%	6%	5%	10%	20%	66%	93%	99%	100%
Industry	**145**	**134**	**140**	**125**	**120**	**112**	**108**	**102**	**97**
- Electricity	62	58	65	61	63	60	60	57	54
RES electricity	39	39	45	56	62	60	60	57	54
- Public district heat	7	7	6	6	5	5	5	4	4
RES district heat	1	1	1	1	1	3	4	4	4
- Hard coal & lignite	14	13	5	12	1	0	0	0	0
- Oil products	12	11	17	12	9	5	0	0	0
- Gas	39	37	37	20	11	6	3	0	0
- Solar	0	0	0	3	9	3	5	6	6
- Biomass	10	9	9	9	11	18	20	19	17
- Geothermal	0	0	0	2	11	15	16	16	15
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Industry	34%	36%	40%	57%	80%	88%	96%	99%	100%
Other Sectors	**357**	**332**	**359**	**310**	**279**	**241**	**219**	**206**	**204**
- Electricity	134	125	138	134	118	112	107	111	116
RES electricity	84	84	95	122	117	112	106	111	116
- Public district heat	13	12	13	14	15	14	13	12	11
RES district heat	2	2	4	6	7	10	10	11	11
- Hard coal & lignite	2	2	2	0	1	0	1	0	0
- Oil products	104	97	103	72	46	5	0	0	0
- Gas	72	67	72	50	42	30	17	0	0
- Solar	2	2	2	10	17	22	27	24	30
- Biomass	29	27	29	20	17	14	11	9	1
- Geothermal	0	0	0	11	23	42	44	49	46
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Other Sectors	33%	35%	36%	54%	65%	83%	91%	99%	100%
Total RES	**181**	**177**	**197**	**260**	**313**	**381**	**400**	**412**	**414**
RES share	24%	26%	27%	40%	54%	80%	93%	99%	100%
Non energy use	**19**	**18**	**16**	**14**	**14**	**14**	**13**	**13**	**13**
- Oil	19	18	16	14	14	14	13	13	13
- Gas	0	0	0	0	0	0	0	0	0
- Coal	0	0	0	0	0	0	0	0	0

ADVANCED ENERGY-[R]EVOLUTION-SCENARIO (ADV-E[R])

Tabelle 16: Electricity generation [TWh/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Power plants	**66**	**59.2**	**61.8**	**58.6**	**64.8**	**77.5**	**86.5**	**90.4**	**96.0**
- Hard coal (& non-renewable waste)	0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0
- Lignite	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
of which from H2	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Oil	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Diesel	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24	18.7	18.7	3.3	0.0	0.0	0.0	0.0	0.0
- Biomass (& renewable waste)	0	0.0	0.0	0.5	0.8	0.7	1.0	1.5	1.5
- Hydro	39	37.7	40.2	40.6	40.8	41.0	41.0	41.2	41.2
- Wind	0	0.1	0.2	1.3	4.0	5.1	5.6	5.7	5.8
of which wind offshore	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- PV	2	2.7	2.7	12.7	19.0	30.6	38.8	41.8	47.3
- Geothermal	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
- Solar thermal power plants	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Combined heat and power plants	**4**	**3.5**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**	**3.8**
- Hard coal (& non-renewable waste)	1	1.1	1.1	1.1	0.3	0.0	0.0	0.0	0.0
- Lignite	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	1	0.6	0.6	0.6	0.3	0.1	0.0	0.0	0.0
of which from H2	0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
- Oil	0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
- Biomass (& renewable waste)	2	1.7	1.9	2.0	3.1	3.6	3.8	3.8	3.8
- Geothermal	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Hydrogen	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CHP by producer									
- Main activity producers	1	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
- Autoproducers	3	3.0	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Total generation	**69**	**62.8**	**65.6**	**62.4**	**68.6**	**81.3**	**90.3**	**94.1**	**99.8**
- Fossil	2	1.8	1.9	2.1	0.7	0.2	0.0	0.0	0.0
- Hard coal (& non-renewable waste)	1	1.1	1.1	1.4	0.4	0.0	0.0	0.0	0.0
- Lignite	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Gas	1	0.6	0.7	0.6	0.3	0.1	0.0	0.0	0.0
- Oil	0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0
- Diesel	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Nuclear	24	18.7	18.7	3.3	0.0	0.0	0.0	0.0	0.0
- Hydrogen	0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
of which renewable H2	0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0
- Renewables (w/o renewable hydrogen)	43	42.2	45.0	57.0	67.8	81.1	90.2	94.1	99.7
- Hydro	39	37.7	40.2	40.6	40.8	41.0	41.0	41.2	41.2
- Wind	0	0.1	0.2	1.3	4.0	5.1	5.6	5.7	5.8
- PV	2	2.7	2.7	12.7	19.0	30.6	38.8	41.8	47.3
- Biomass (& renewable waste)	2	1.7	1.9	2.5	3.9	4.3	4.8	5.2	5.2
- Geothermal	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
- Solar thermal power plants	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
- Ocean energy	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution losses (incl.hydro pumpstorage)	4	3.9	4.6	4.6	4.2	5.0	5.0	4.7	4.9
Own consumption electricity	7	7.0	6.8	7.8	8.4	9.0	9.6	10.3	11.1
Domestic Electricity for hydrogen production	0	0.0	0.0	0.0	1.4	3.0	4.0	4.9	5.2
Electricity for synfuel production	0	0.0	0.0	0.0	1.7	3.7	7.7	8.8	10.9
Final energy consumption (electricity)	**57**	**53.2**	**59.6**	**59.0**	**54.5**	**63.9**	**63.8**	**60.7**	**63.2**
Variable RES (PV, Wind, Ocean)	2	2.8	2.8	13.9	23.0	35.7	44.4	47.5	53.1
Share of variable RES	3%	4%	4%	22%	34%	44%	49%	50%	53%
RES share (domestic generation)	62%	67%	69%	91%	99%	100%	100%	100%	100%

Tabelle 17: Installed Capacity [GW]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total generation	**20**	**20**	**20**	**28**	**34**	**45**	**53**	**56**	**61**
- Fossil	0	0	0	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0	0	0
- Diesel	0	0	0	0	0	0	0	0	0
- Nuclear	3	3	3	1	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants, gas CHP)	0	0	0	0	0	0	0	0	0
- Renewables	16	16	16	26	34	45	53	56	61
- Hydro	13	13	13	14	14	14	14	14	14
- Wind	0	0	0	0.6	1.9	2.1	2.3	2.4	2.4
of which wind offshore	0	0	0	0	0	0	0	0	0
- PV	2	2	2	12	18	29	36	39	44
- Biomass (& renewable waste)	0.4	0.3	0.366	0.472	0.735	0.819	0.905	1.015	1.015
- Geothermal	0.0	0	0	0.0	0.0	0.0	0.0	0.0	0.0
- Solar thermal power plants	0	0	0	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	2	3	3	12	20	31	39	41	47
Share of variable RES	11%	13%	13%	45%	58%	68%	73%	74%	76%
RES share (domestic generation)	81%	82%	81%	96%	99%	100%	100%	100%	100%

Tabelle 18: Heat supply and air conditioning [PJ/a]

[1]Estimation GDP decrease [2]No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
District heating plants	**19**	**17**	**18**	**17**	**17**	**15**	**11**	**10**	**10**
- Fossil fuels	19	17	17	16	6	0	0	0	0
- Biomass	0	0	0	1	10	13	9	8	8
- Solar collectors	0	0	0	0	1	2	2	2	2
- Geothermal	0	0	0	0	0	0	0	0	0
Heat from CHP 1)	**17**	**16**	**24**	**25**	**26**	**26**	**27**	**26**	**26**
- Fossil fuels	7	7	2	11	3	0	0	0	0
- Biomass	10	9	22	13	23	26	26	26	26
- Geothermal	0	0	0	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0	0	0	0
Direct heating	**298**	**280**	**291**	**230**	**188**	**178**	**164**	**144**	**133**
- Fossil fuels	215	200	211	114	84	34	15	1	0
- Biomass	33	30	31	32	31	22	24	23	14
- Solar collectors	3	2	3	26	31	34	34	33	33
- Geothermal	0	0	0	0	0	0	0	0	0
- Heat pumps 2)	0	0	1	18	23	78	81	83	78
- Electric direct heating	48	48	45	41	18	10	9	4	8
- Hydrogen	0	0	0	0	3	7	8	9	9
Total heat supply3)	**333**	**313**	**333**	**272**	**233**	**226**	**209**	**189**	**178**
- Fossil fuels	241	225	230	141	92	34	15	1	0
- Biomass	42	39	54	47	64	62	59	57	48
- Solar collectors	3	2	3	26	33	36	35	34	35
- Geothermal	0	0	0	0	0	0	0	0	0
- Heat pumps 2)	0	0	1	18	23	78	81	83	78
- Electric direct heating 2)	48	48	45	41	18	10	9	4	8
- Hydrogen	0	0	0	0	3	7	8	9	9
RES share (including RES electricity)	**22%**	**23%**	**27%**	**47%**	**60%**	**85%**	**93%**	**99%**	**100%**
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.2	0.9	1.3	5.6	5.9	5.7	5.1

ADVANCED ENERGY-[R]EVOLUTION-SCENARIO (ADV-E[R])

Tabelle 19: Transport - Final Energy [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
road	**222**	**206**	**212**	**171**	**124**	**68**	**62**	**54**	**51**
- fossil fuels	215	199	209	161	100	11	7	0	0
- biofuels	7	6	2	2	2	2	3	2	1
- synfuels	0	0	0	0	0	0	0	0	0
- natural gas	1	1	0	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0	2	4	5
- electricity	0	0	2	7	22	55	50	48	45
rail	**12**	**11**	**13**	**14**	**14**	**15**	**15**	**16**	**16**
- fossil fuels	0	0	0	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0	0	0	0
- electricity	11	10	13	14	14	15	15	16	16
navigation	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**
- fossil fuels	2	1	1	1	1	1	0	0	0
- biofuels	0	0	0	0	0	1	1	2	2
- synfuels	0	0	0	0	0	0	0	0	0
aviation	**3**	**3**	**2**	**2**	**2**	**1**	**1**	**1**	**1**
- fossil fuels	3	3	2	2	1	1	0	0	0
- biofuels	0	0	0	0	0	1	1	1	1
- synfuels	0	0	0	0	0	0	0	0	0
total (incl. pipelines)	**238**	**221**	**230**	**189**	**142**	**86**	**81**	**73**	**71**
- fossil fuels	219	204	213	165	102	12	7	0	0
- biofuels (incl. biogas)	7	6	2	2	3	4	5	5	4
- synfuels	0	0	0	0	0	0	0	0	0
- natural gas	1	1	0	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0	2	4	5
- electricity	11	10	15	21	36	69	65	64	61
total RES	**14**	**13**	**12**	**21**	**39**	**73**	**73**	**72**	**70**
RES share	6%	35%	5%	11%	27%	84%	91%	100%	100%

Tabelle 20: Energy-Releated CO_2 Emissions [Million tons/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Condensation power plants	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	0	0	0	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil & Diesel	0	0	0	0	0	0	0	0	0
Combined heat and power plants	**2**	**2**	**2**	**2**	**1**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	1	1	1	1	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil	0	0	0	0	0	0	0	0	0
CO_2 emissions power and CHP plants	**2**	**2**	**2**	**2**	**1**	**0**	**0**	**0**	**0**
- Hard coal (& non-renewable waste)	1	1	1	2	0	0	0	0	0
- Lignite	0	0	0	0	0	0	0	0	0
- Gas	0	0	0	0	0	0	0	0	0
- Oil & diesel	0	0	0	0	0	0	0	0	0
CO_2 intensity (g/kWh)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
without credit for CHP heat	0	0	0	0	0	0	0	0	0
- CO_2 intensity fossil electr. generation	988	987	981	989	771	464	357	352	168
- CO_2 intensity total electr. generation	27	28	29	33	9	1	0	0	0
CO_2 emissions by sector	**39**	**36**	**39**	**26**	**17**	**4**	**2**	**0**	**0**
- % of 1990 emissions (Mill t)	92%	86%	93%	63%	41%	10%	4%	0%	0%
- Industry 1)	6	6	6	4	2	1	0	0	0
- Other sectors 1)	13	12	13	7	6	2	1	0	0
- Transport	17	15	16	12	8	1	1	0	0
- Power generation 2)	0	0	0	1	0	0	0	0	0
- Other conversion 3)	2	2	3	2	1	0	0	0	0
Population (Mill.)	9	9	9	9	9	10	10	10	10
CO_2 emissions per capita (t/capita)	5	4	4	3	2	0	0	0	0

Tabelle 21: Primary Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total	**1012**	**909**	**983**	**728**	**631**	**548**	**552**	**541**	**545**
- Fossil	532	495	553	380	247	76	39	13	11
- Hard coal (& non-renewable waste)	28	27	33	48	39	1	0	0	0
- Lignite	3	2	0	0	0	0	0	0	0
- Natural gas	146	136	137	118	66	39	19	1	0
- Crude oil	355	330	383	214	141	36	20	12	11
- Nuclear	256	198	204	36	0	0	0	0	0
- Renewables	224	215	227	312	384	473	513	528	534
- Hydro	140	136	145	146	147	148	148	148	148
- Wind	0	0	1	5	14	18	20	21	21
- Solar	11	12	12	71	100	144	174	183	204
- Biomass (& renewable waste)	72	67	68	77	106	106	111	113	101
- Geothermal	0	0	1	13	17	56	60	63	60
- Ocean energy	0	0	0	0	0	0	0	0	0
- of which non-energy use	19	18	16	14	14	13	12	12	11
- Total RES	220	219	227	312	384	473	513	528	531
- RES share	22%	24%	23%	41%	60%	84%	93%	101%	100%

Tabelle 22: Final Energy Demand [PJ/a]

[1] Estimation GDP decrease [2] No GDP decrease

	2018	2020[1]	2020[2]	2025	2030	2035	2040	2045	2050
Total (incl. non-energy use)	759	705	747	599	494	442	417	383	378
Total energy use 1)	740	688	731	585	480	429	404	371	366
Transport	**238**	**221**	**231**	**190**	**143**	**86**	**80**	**73**	**70**
- Oil products	219	204	214	166	103	13	7	0	0
- Natural gas	1	1	0	0	0	0	0	0	0
- Biofuels	7	6	2	2	3	4	5	5	4
- Synfuels	0	0	0	0	0	0	0	0	0
- Electricity	11	10	15	21	36	69	65	64	61
RES electricity	7	7	10	19	36	69	65	64	61
- Hydrogen	0	0	0	0	0	0	2	4	5
RES share Transport	6%	6%	5%	11%	27%	84%	91%	100%	100%
Industry	**145**	**134**	**139**	**120**	**115**	**114**	**110**	**104**	**103**
- Electricity	62	58	64	61	57	65	65	61	64
RES electricity	39	39	44	56	56	65	65	61	64
- Public district heat	7	7	6	5	5	3	0	0	0
RES district heat	1	1	1	1	1	1	0	0	0
- Hard coal & lignite	14	13	18	9	6	0	0	0	0
- Oil products	12	11	17	11	9	5	0	0	0
- Gas	39	37	25	21	18	14	13	10	9
- Solar	0	0	0	3	9	3	4	6	6
- Biomass	10	9	9	7	7	10	12	11	10
- Geothermal	0	0	0	2	3	15	16	15	14
- Hydrogen	0	0	0	0	0	3	7	8	9
RES share Industry	34%	36%	39%	57%	67%	84%	94%	98%	100%
Other Sectors	**357**	**332**	**361**	**275**	**223**	**228**	**214**	**195**	**193**
- Electricity	134	125	136	131	103	96	100	94	103
RES electricity	84	84	93	119	102	96	100	94	103
- Public district heat	13	12	12	13	13	14	13	12	12
RES district heat	2	2	4	7	7	11	11	11	12
- Hard coal & lignite	2	2	2	0	1	0	1	0	0
- Oil products	104	97	108	11	11	5	0	0	0
- Gas	72	67	72	56	29	23	10	0	0
- Solar	2	2	2	23	23	31	29	27	28
- Biomass	29	27	29	31	30	17	16	16	6
- Geothermal	0	0	0	10	13	41	44	46	44
- Hydrogen	0	0	0	0	0	0	0	0	0
RES share Other Sectors	33%	35%	36%	69%	78%	86%	94%	99%	100%
Total RES	**181**	**177**	**194**	**281**	**290**	**364**	**377**	**368**	**366**
RES share	24%	26%	27%	48%	60%	85%	93%	99%	100%
Non energy use	**19**	**18**	**16**	**14**	**14**	**13**	**12**	**12**	**11**
- Oil	19	18	16	14	14	13	12	12	11
- Gas	0	0	0	0	0	0	0	0	0
- Coal	0	0	0	0	0	0	0	0	0

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