Bachelor thesis at the Lucerne School of Engineering and Architecture

Title	**Impact of renewable energies on the winter energy supply and possibilities for energy storage technologies**
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Bachelor's degree program	**Bachelor in Energy and Environmental Systems Engineering**
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Abstract German

Diese Bachelorarbeit wird im Rahmen des Studienprammes Energy and Environmental Systems Engineering an der Hochschule Luzern Im Auftrag des Instituts für Innovation und Technologiemanagement verfasst.Mit der Arbeit soll der Einfluss des Ausbaus erneuerbarer Energien auf die Winterstromlücke in der Schweiz untersucht und das Potential für Energiespeichertechnologien untersucht werden.

Mittels quantitativer Methoden wird ein Modell des heutigen Energiesystems der Schweiz erstellt und untersucht. Mit dem Modell werden verschiedene Ausbauszenarien nachgebildet und ausgewertet.

Die Resultate zeigen, dass die Winterstromlücke zwischen 20217 und 2021 rund 5 TWh beträgt. Mit der fortschreitenden Energiewende und damit verbundenen Elektrifizierung wird sich die Winterstomlücke auf rund 11 TWh vergrössern. Mit gross angelegten Energiespeichersystemen kann die Winterstromlücke verkleinert und die Abhängigkeit von Stromimporten verkleinert werden.

Abstract English

This bachelor thesis is written in the framework of the study program Energy and Environmental Systems Engineering at the Lucerne University of Applied Sciences and Arts on behalf of the Institute for Innovation and Technology Management. The thesis aims to investigate the influence of the expansion of renewable energies on the winter electricity gap in Switzerland and to investigate the potential for energy storage technologies.

Using quantitative methods, a model of the current energy system in Switzerland is created and examined. The model is used to replicate and evaluate different expansion scenarios.

The results show that the winter electricity gap between 20217 and 2021 is about 5 TWh. With the advancing energy transition and associated electrification, the winter electricity gap will increase to around 11 TWh. With large-scale energy storage systems, the winter electricity gap can be narrowed and dependence on electricity imports reduced.

Lucerne, 09/06/2023

Executive summary

This thesis presents a comprehensive analysis of Switzerland's electricity production and consumption, with a focus on transitioning to renewable energy sources, their impact on the winter electricity gap and the potential for energy storage technologies. Using a model based on averaged electricity data from 2017-2021, an actual state analysis is conducted, revealing a positive annual electricity balance with a surplus of 1.1 TWh. However, a winter electricity gap of 4.6 TWh has to be covered with imports.

To explore the impact of renewable expansion on the winter electricity gap, four scenarios are developed by scaling the existing production profiles. It is shown that the massive expansion of conventional photovoltaic plants does not contribute to closing the winter electricity gap. The production portfolio must be supplemented with photovoltaics at alpine locations and wind power plants, which, according to the profiles determined, generate more electricity in winter than in summer. Sustainable thermal energy sources would have the potential to replace the base load of nuclear power plants. However, the studies examined see only little expansion potential for this. While run-of-river power plants have a similar peak as photovoltaics in summer, pumped storage power plants have the potential to generate more electricity in winter. However, the studies examined estimate the expansion potential of hydropower at only a few terawatt hours per year.

In addition to the expansion scenarios, the study investigates the potential of energy storage for bridging the winter electricity gap. Calculations with a storage system with a round-trip efficiency of 58% show, that only one of the four scenarios has a big enough summer surplus to cover the winter electricity gap and the storage round-trip losses. Various long-term storage technologies, including pumped storage hydro, power-to-X, battery storage, compressed air storage, and gravity-based alternatives, are considered for future investigation.

In addition, the economic aspects of expansion and storage technologies are assessed. Expansion costs for renewable energy production are estimated based on levelized cost of electricity and range from 3.9 to 9.7 billion Swiss francs across scenarios. Storage costs, calculated assuming a mixed Power-to-Hydrogen and Pumped Hydro Storage system, vary from 1.2 to 13.9 billion Swiss francs to cover the winter electricity gap. The study suggests that expanding production capacities is more cost-efficient than relying heavily on storage technologies, but further research is required to refine cost estimates and consider the broader advantages of storage systems.

The thesis acknowledges certain limitations, such as data availability and quality, reliability of the calculated production profiles as a future scenario, and simplifications made in storage potential and economic assessments. To address these limitations, future research directions are proposed, including optimizing the production and storage portfolios for economical and economical parameters, integrating storage capacities into the model of production and consumption, and assess the influence of sector coupling to the energy system.

In conclusion, Switzerland possesses the potential for a sustainable and self-sufficient electricity system. Political decisions play a crucial role in shaping the energy transition, as the country aims to phase out nuclear power and shift towards renewable sources. The findings emphasize the importance of diversifying the production portfolio and incorporating storage systems to achieve a more balanced and reliable energy distribution.

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Abbreviations and acronyms

avg17-21 .... *averaged 2017-2021 electricity model*
BFE .... *Swiss Federal office of Energy*
CCS .... *Carbon Capture and Storage*
CHP .... *Combined Heat and Power*
DSO .... *distribution grid operator*
ENTSO-E .... *European association for the cooperation of transmission system operators*
EP2050+ .... *Energy perspectives 2050+*
HSLU .... *Lucerne University of Applied Sciences and Arts*
MAS .... *Maximal Autarky Scenario*
NBS .... *Neutral Balance Scenario*
PHS .... *Pumped Hydro Storage*
PSI .... *Paul Scherrer Institute*
PtH .... *Power-to-Hydrogen*
PtX .... *Power to Gas, usually hydrogen or methane, with possibility for sector coupling*
PV .... *Photovoltaics*
VSE .... *Association of Swiss Energy Producers*

1 Introduction

This bachelor thesis is developed at the Lucerne University of Applied Sciences and Arts (HSLU) as the final thesis in the study program Energy and Environmental Systems Engineering.

The Swiss energy market is facing an enormous challenge: According to the current energy strategy and climate targets, 70% of today's primary energy sources will no longer be viable by 2050.

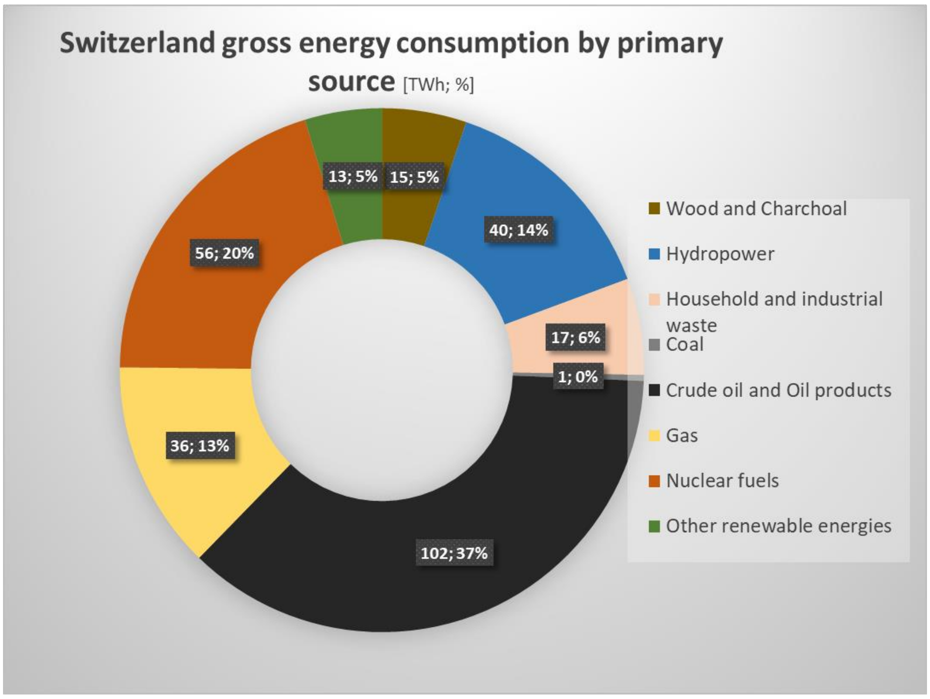

Figure 1 Gross energy consumption by primary sources in 2021
Data: (Bundesamt für Energie C, 2022, S. 17)

The technical, social, and economic feasibility to replace the share of fossil fuels (Crude oil and oil products, Gas, Coal) and nuclear energy in the primary energy mix has not been proven so far. This study compares the electricity production and consumption data of Switzerland to identify a possible winter energy gap. It investigates whether energy storage technologies have the potential to significantly smooth the consumption curve to optimize the annual balance. The purpose is to find out how the Swiss energy system is affected by the expansion of different technologies and which synergies exist between them.

The project targets consist of four main points:

1. Creating a situation analysis of Switzerland's energy supply and demand.
2. Defining possible scenarios in the development of energy supply and demand until 2050.
3. Determining the potential for energy storage within the evaluated system of supply & demand.
4. Evaluating the system for synergies between different technologies.

The study will focus on the electricity system of Switzerland. Changes in the consumption of other energy carriers will only be considered if they affect the electricity system.

2 Basics and definitions

This chapter provides an overview of the relevant definitions, as well the most important findings from the literature research on which the results of this thesis are based on. The political trends in the field of energy, leading to diverse developments in society, technology and economy are presented. Furthermore, the energy supply and demand situation, as well as the state-of-the-art technologies for energy storage are introduced.

Energy storage system
"An energy storage is an energy technology facility for storing energy in the form of internal, potential, or kinetic energy. An energy storage system performs three processes: charging (loading), storing (holding), and discharging (unloading). These processes are physically implemented by energy converters (charging and discharging), storage units (holding), and peripherals. A complete facility, including all these components, is called an energy storage system." (Sterner Michael, 2019)

Primary and secondary energy storage systems
"Primary energy storage usually refers to fuels such as wood or oil. They can be charged and discharged only once. Secondary energy storages can be charged and discharged multiple times." (Sterner Michael, 2019)

Energy sectors
Energy sectors can be subdivided according to different criteria. In the field of energy storage, it makes sense to subdivide the energy sectors according to their intended use: Heating/air conditioning, electricity and mobility. From this, it can already be deduced which energy quality is required, which limits the choice of storage technologies. Other sector distinctions can be made in terms of production type or consumer group, among others.

Cross-sectoral energy storage systems
"Energy storage systems that may be used in more than one energy sectors, and in one or both directions, thereby linking two or more sectors. Charging and discharging do not necessarily occur in the same sector." (Sterner Michael, 2019)
Cross sectoral energy storages allow higher usage of produced energy, as energy surpluses and shortages can be balanced more flexibly. This can also be described as "Sectoral coupling" and is essential for the expansion of renewable energies.

Gross-consumed energy
In the field of general energy, gross-consumed energy refers to the total invested primary energy into a system before any conversion steps. Within this thesis, the focus is on the electricity system and gross-consumed electricity refers to the total produced electricity, including the consumption of hydro storage pumps, self-consumption of power plants and losses in the distribution grid.

2.1 Political Situation

Switzerland ratified the Paris Agreement in 2017 and therefore committed to take measures to limit global warming to 1.5°C. In the same year, Switzerland's population voted in support of an updated Energy law. The main changes with the updated Energy law are the following:

- Incentives for energy efficiency measures
- Renewable energies are being promoted
- Prohibition to build new nuclear energy plants
- Accelerated expansion of the electricity grid
  (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation, 2023)

The energy law is closely linked to the climate strategy of Switzerland. The "CO2 law" was planned to be updated in 2021 but was declined by the Swiss electorate. The existing law for CO2 reductions from 2011 remains in place. This weakens the long-term energy strategy of Switzerland from 2021 and makes it difficult to implement significant measures for climate protection. Also measures to upgrade the energy sector are hindered with the current situation. Another vote on an updated climate change bill will be held on June 18, 2023. The outcome of this vote will have a decisive influence on the political and legal framework for tackling the climate crisis and the energy transition in Switzerland.

The start of the Russian-Ukrainian war in 2022 represented a challenge for the European energy markets, as the supply of natural gas and oil by one of the key contributors, Russia, had to be replaced on short notice (axpo, 2022).This shock launched discussions about the security of energy supply and gave the expansion of renewable energy new inertia (Bjarne Steffen, 2022).

2.2 Energy supply and demand situation in Switzerland

Primary energy use of all sectors adds up to 282 TWh in 2021. The composition by energy carrier is presented in Figure 1. End energy use in Switzerland increased since 1910 and shows a slight decreasing trend since 2010. Figure 2 shows the composition of energy carriers over the time from 1920 until 2020. Total end-consumed energy in 2021 is 221 TWh. 2021, the foreign dependence on primary energy imports was 70.3% in 2021 (Bundesamt für Energie C, 2022).

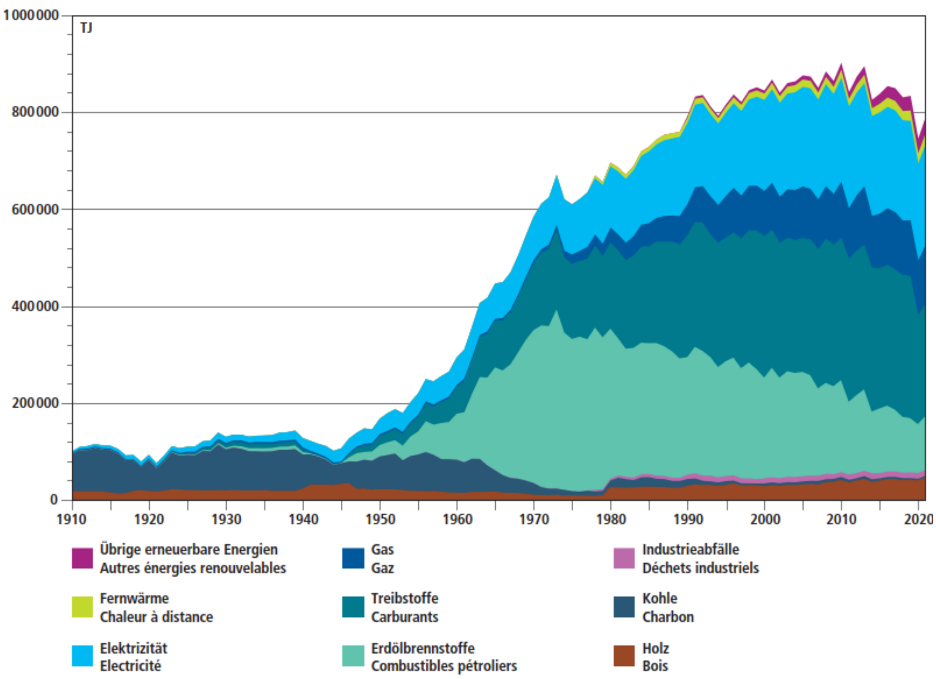

Figure 2 End-consumed energy by energy carrier, 1910 – 2020
(Bundesamt für Energie C, 2022, S. 3)

Figure 3 shows the shares of end-consumed energy in 2021, on the left side dived into sectors by energy carriers:

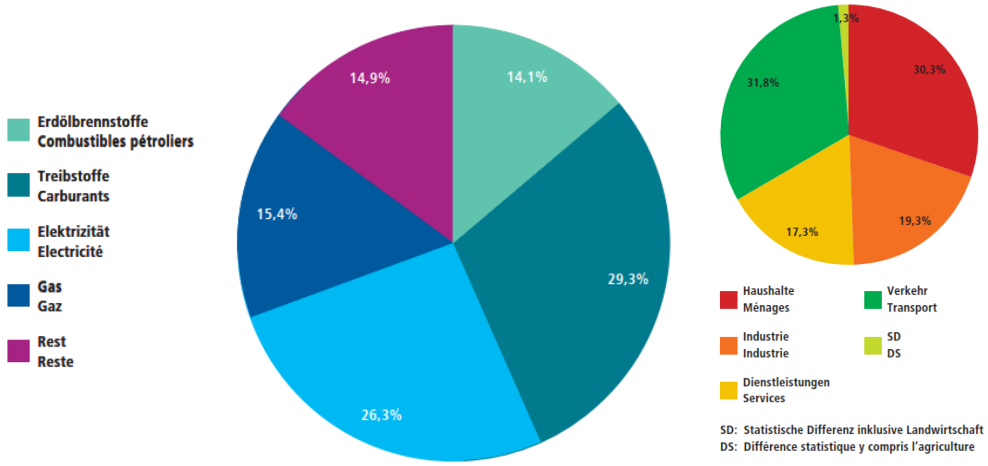

Figure 3 End-consumed energy 2021 by energy carrier and consumption group (Bundesamt für Energie C, 2022)

Crude oil fuels (Erdölbrennstoffe), Fuels (Brennstoffe), Electricity (Elektrizität) and Others (Rest). On the right side, the end-consumed energy is divided into 4 main user consumption groups: Households (Haushalte), Mobilit (Verkehr), Industry (Industrie) and Services (Dienstleistungen). SD accounts for statistical inaccuracies.

Electricity production and consumption

To deliver the end-consumed 58 TWh of electricity in 2021, 64 TWh electricity were produced. The difference accounts for the self-consumption of the electricity providers, grid losses and the import-/ export of the specific year.

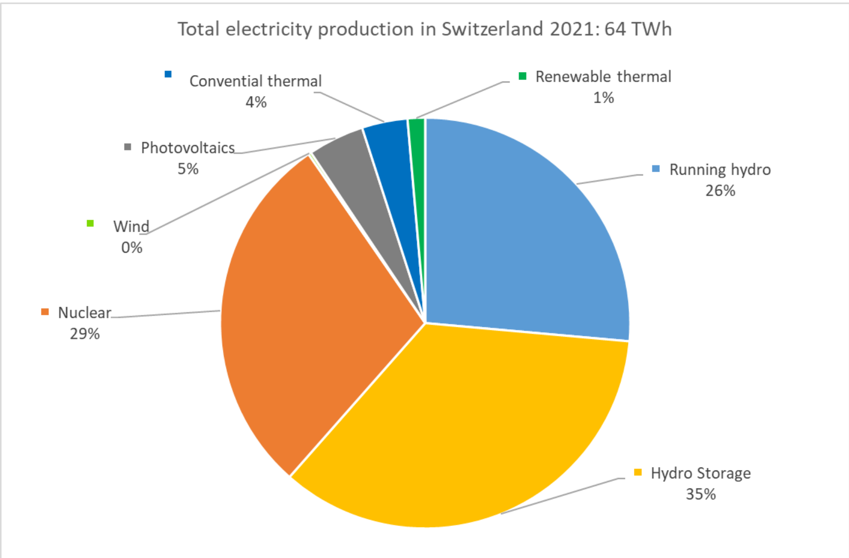

Figure 4 2021 Electricity production per type
Data: (Bundesamt für Energie C, 2022)

Development Scenarios

The Federal Office of Energy publishes a holistic overview about the energy system of Switzerland "Energy perspectives" wich is updated every few years. It models different future scenarios according to the national Energy Strategy. The lastest issue from November 2020 takes into account, that Switzerland plans to be climate neutral by 2050. The study involves developement assumptions in all relevant fields:

- Population development
- Econimoc development
- Development of energy consuming area
- Transport mileage
- Energy and CO2 prices
- Climate and weather changes

With its profound research background data the document is used as basis for other scenario development studies, such as "Energiezukunft 2050" by the Association of Swiss Energy Producers (VSE) (Marti, 2022, S. 32). The future scenarios are divided into four scenarios, of which "ZERO Basis" is viewed as the most realisitic according to todays developments. All information for the energy scenarios in this chapter refer to the ZERO Basis scenario, if not stated elsewise. The following assumptions are made for the scenario:

- Energy efficiency measures become implemented as early as possible and on a high level
- End energy use shifts towards electricity, especially in the mobility and heating sectors
- Heat networks become important for urban areas
- Waste incineration and cement plants implement Carbon Capture and Storage (CCS) methods
- Hydropower is expanded to 39 TWh by 2050
- Other renewable enegies are expanded to 24 TWh by 2050
- Nuclear power plants are shut down after 50 years of lifetime
  (Bundesamt für Energie A, 2020)

Figure 5 illustrates, how the energy system of Switzerland could look by 2050. It is divided in 13 bulletpoints, that are translated subsequently.

Figure 5 Mission statement of the energy perspectives 2050+ (Bundesamt für Energie B, 2020)

1. Hydrogen production at running water plants
2. Waste incineration with CCS
3. Biomass is used for process heat
4. Expansion of heating networks in urban areas
5. Cement and chemical industries are equipped with CCS
6. High isolation of buildings
7. Expansion of photovoltaics (PV)-production to 34 TWh
8. High efficiency for industrial processes
9. Expansion of hydropower to 45 TWh
10. Impmentation of negative domestic negative emission technologies for 3 Mt CO_{2eq}
11. 3.6 million EVs
12. Heavy transport by train or biofuels / hydrogen
13. Use of 1.5 million heat pumps

The bulletpoints can be interpreted as visonary targets. They go beyondt the targets defined in the scenarios, but give a good general impression of the trends in the energy system of Switzerland.

Development of energy consumption

All the assumed measures in the EP2050+ study influence the amount and composition of total end energy use. Figure 6 indicates a decrease of used end energy of 31% from 210 TWh in 2019 to 145 TWh in 2050.

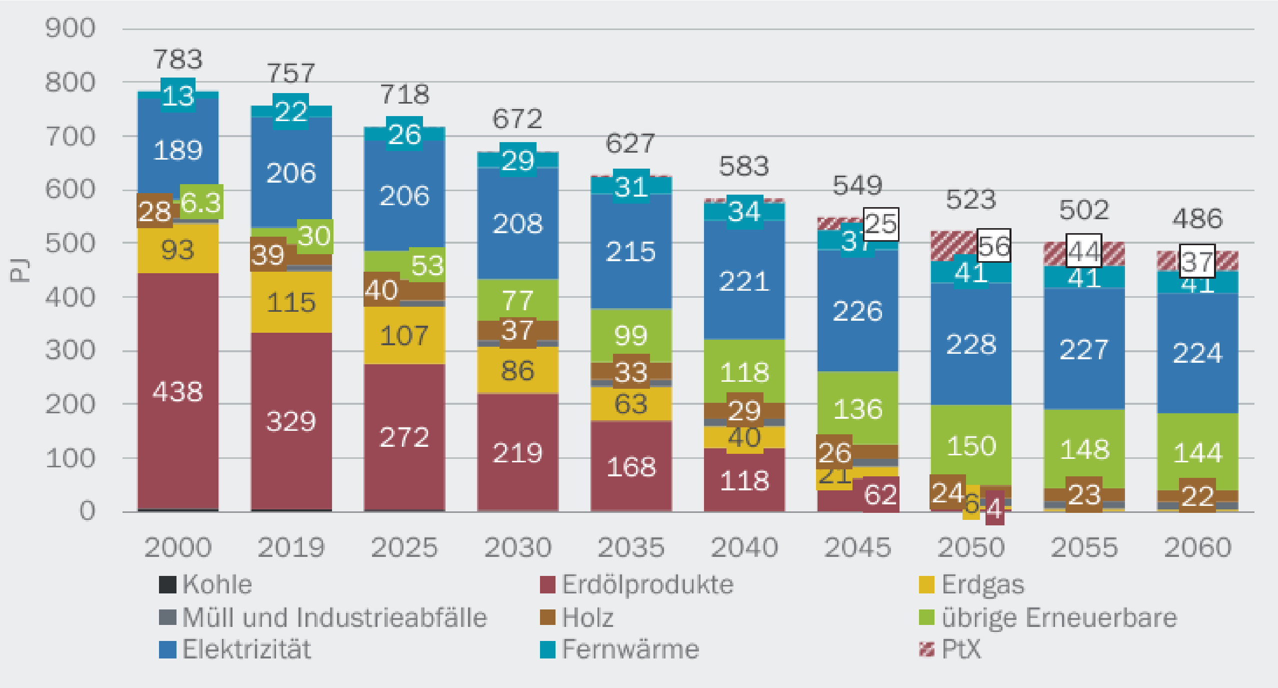

Figure 6 Development of end energy use by energy carrier
(Prognos AG/TEP Energy GmbH/INFRAS AG, 2021, S. 215)

Kohle: Coal, Müll und Industrieabfälle: Household and industrial waste, Elektrizität: Electricity, Erdölprodukte: Crude oil products, Holz: Wood, Fernwärme: Distant heat, Erdgas: Natural gas, Other renewables: Biogas, Biomethane, Biofuels, Solar heat, Ambient heat and waste heat, PtX: Electricity based energy carriers

The biggest share of the energy portfolio in 2050 will be electricity with 43%, followed by other renewables with 29%. The group of other renewables is assumed to consist mainly of ambient heat from heat pumps and biogas/methane. In absolute numbers, the gross electricity consumption is expected to rise from 65.6 TWh in 2019 to 84.4 TWh in 2050 (Prognos AG/TEP Energy GmbH/INFRAS AG, 2021, S. 316).

Development of electricity production

Energy Perspective 2050+

The Energy perspectives 2050+ (EP2050+) study developed a model for the electricity production portfolio until 2060. The development of electricity consumption and the achievement of climate targets by 2030 and 2050 are considered in the model (Prognos AG/TEP Energy GmbH/INFRAS AG, 2021). Table 1 presents the modelling results for the production portfolio.

Table 1 Modelled electricity production portfolio by EP2050+ (Prognos AG/TEP Energy GmbH/INFRAS AG, 2021)

Szenario		2000	2019	2025	2030	2035	2040	2045	2050	2055	2060
ZERO Basis KKW 50	Wasserkraftwerke	37.9	40.6	40.4	41.7	41.9	43.8	44.2	44.7	44.1	43.8
	Kernkraftwerke	24.9	25.3	16.6	8.8	0.0	0.0	0.0	0.0	0.0	0.0
	Fossile KW*	1.7	1.9	1.5	1.6	1.6	1.4	1.2	1.0	1.0	1.0
	Erneuerbare*/**	0.8	4.2	6.1	10.9	17.3	25.8	32.9	39.1	42.0	43.9
	Landeserzeugung (brutto)	65.3	71.9	64.6	63.0	60.9	71.0	78.4	84.8	87.2	88.7
	Verbrauch Speicher-pumpen	-2.0	-4.1	-5.3	-6.3	-6.1	-8.0	-8.3	-8.5	-7.9	-7.6
	Landeserzeugung (netto)	63.4	67.8	59.4	56.7	54.8	63.0	70.0	76.4	79.3	81.1
	Importsaldo	-7.1	-6.3	3.2	7.5	12.7	8.5	4.5	-0.4	-3.0	-5.0
	Landesverbrauch	56.3	61.5	62.5	64.1	67.4	71.5	74.6	76.0	76.4	76.2
	Gesamter Verbrauch inkl. Speicherpumpen	58.3	65.6	67.8	70.4	73.5	79.5	82.9	84.4	84.3	83.7

Wasserkraftwerke: *Hydropower*
Kernkraftwerke: *Nuclear power plants*
Fossile KW:* *Fossil fuel plants, coupled and uncoupled*
Erneuerbare/**:* *Renewables, coupled and uncoupled, including restricted production capabilites*
Verbrauch Speicherpumpen: *Consumption of hydro storage pumps*
Importsaldo: *Import balance*
Gesamter Verbrauch inkl. Speicherpumpen: *Gross consumed electricity including hydro storage pumps*

Expansion capacities of renewable energies according to an alternative source

To set the EP2050+ study in perspective, The study “Potentials, costs and environmental impacts of electricity plants” from the Paul Scherrer Institute (PSI) is considered as well. The PSI study predicts a lower expansion potential for most production types. Table 2 presents the expected capacity per production type for 2035 and 2050.

Table 2 Modelled electricity production portfolio by PSI, TWh/a (Hirschberg, 2017)

Technologie	Produktion 2015/2016	2035	2050
Grosswasserkraft[2]	32.7	32.7-34.0	32.7-34.0
Kleinwasserkraft[3]	3.5	4.3-5.5	4.3-5.5
Windenergie	0.1	0.7-1.7	1.4-4.3
Fotovoltaik[4]	1.1	5.5-16	11-19
Holz-BHKW	0.1	0.1-0.6	0.1-1.1
Landwirtschaftliche Bio-gasanlagen	0.1	0.1-0.7	0.1-1.3
Tiefengeothermie	nicht vorhanden	voraussichtlich noch nicht in grossem Masstab verfügbar	4.5 (Ziel)

Grosswasserkraft: big-scale hydro power, Kleinwasserkraft: small-scale hydro power, Windenergie: wind power, Fotovoltaik: photovoltaics, Holz-BHKW: wood CHP, Landwirtschaftliche Biogasanlagen: agricultural biogas plants, Tiefengeothermie: deep geothermal

The study estimates the expansion of PV lower than the EP2050+ study by a factor of 2, as it does not include the potential of free-standing plants for reasons of public acceptance.
Another result of the PSI study is a calculation of the Levelized Cost Of Energy (LCOE) for new constructed electricity plants in Switzerland:

Table 3 Expansion costs for renewable energies in Switzerland, Rp/kWh (Hirschberg, 2017)

Technologie	Neuanlagen		
	heute	2035	2050
Grosswasserkraft[9]	7-30	7-30	7-30
Kleinwasserkraft	12-28	14-33	14-34
Windenergie Schweiz	13-21	10-17	9-15
Windenergie offshore	13-27	12-23	10-20
Fotovoltaik: 10 kW	18-31	9-22	8-19
1000 kW	8-13	4-10	3-9
Holz-BHKW[10]	18-36	18-41	18-45
Landwirtschaftliche Biogasanlagen[11]	20-49	18-50	16-51
Tiefengeothermie[12]	nicht vorhanden	16-58	13-47

2.3 Alpine photovoltaics

The avg17-21 model does not include alpine photovoltaics, such as the first pioneer plants like on the Muttsee dam started operating in 2022. The production profile of alpine PV differs from “conventional” PV and offers chances for higher winter capacities. As the topic of alpine PV is very present in 2023, its production profile is presented in Figure 7.

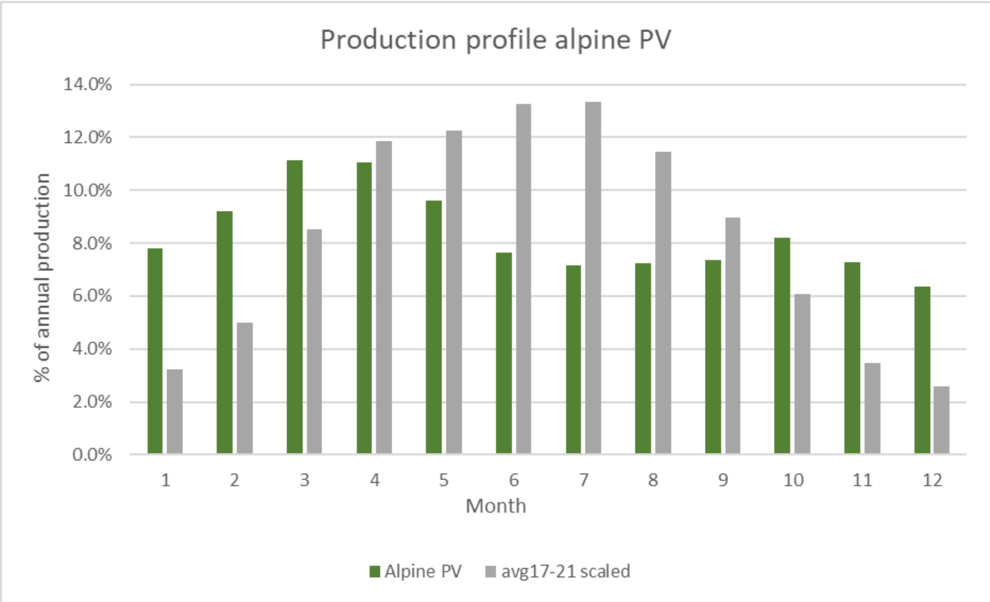

Figure 7 Alpine PV annual production profile compared to today's PV production (avg17-21)

The data for the production profile is derived from a study conducted by the Zurich University of applied sciences (Rohrer, 2023).

2.4 Overview of energy storage options

To understand the basics of energy storage technologies, the following terms should be defined:

Classification of energy storage systems

Energy storage systems can be classified according to physical, energetical, temporal, spatial and economic characteristics, as Figure 8 shows.

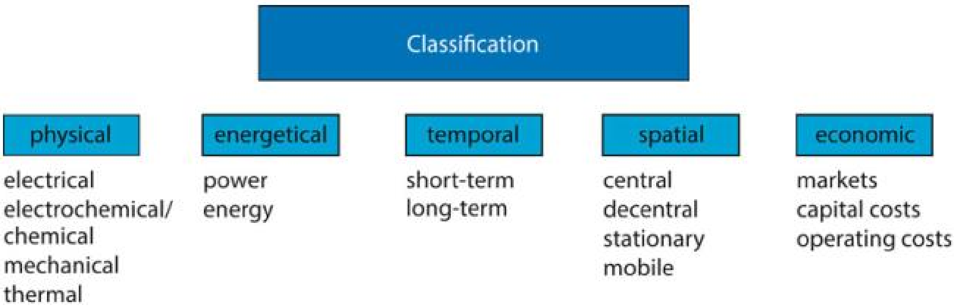

Figure 8 Classification of energy storage systems
(Sterner Michael, 2019, S. 35)

Use and benefits of energy storage

The electricity market is subject to a unique principle: electricity must be produced at the same time as it is consumed. If the balance between production and consumption is not achieved, grid stability is compromised and there is a risk of a blackout in the power grid. Flexibility means how fast and at what scale the grid operator can react to changes in the grid load to stabilize the grid frequency. Flexibility is subject to market laws but is mainly defined by the composition of the production portfolio, as some sources can be ramped up very quickly and others are very inflexible. With a transition to a purely renewable portfolio, the flexibility on the production side decreases. As a result, flexibility on the consumer side must increase, or the flexibility of the system can be generated by intermediate energy storage. (Oberholzer, 2021, S. 4)

Overview of storage technologies

Figure 9 is from the report "Energy storage short overview" from the Federal office of Energy (BFE). It gives a first overview of different energy storage technologies. On the Y-axis is the power, on the X-axis the capacity. The diagonal dotted lines indicate the storage duration between charging and discharging.

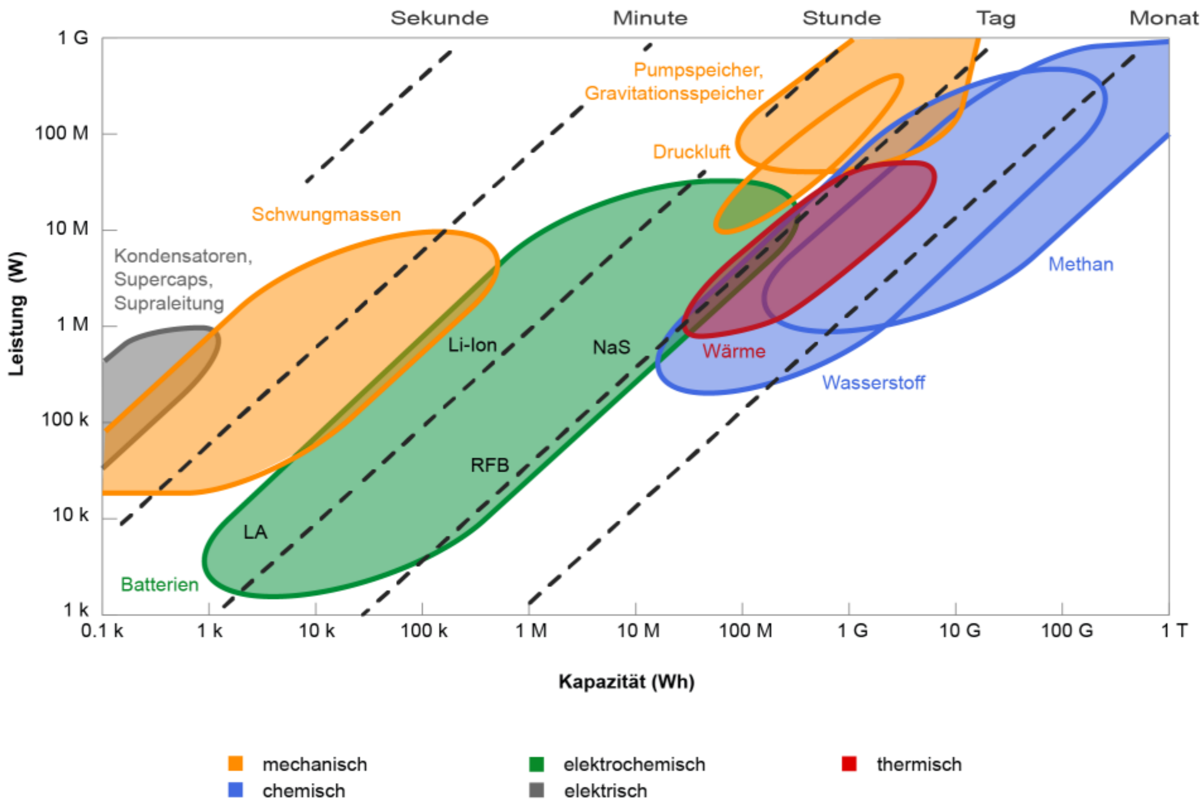

Figure 9 Capacity, power and storage duration of different energy storage technologies (Oberholzer, 2021)

Table 4 is derived from the same report and is complemented with efficiency and self-discharge data from other sources. The self-discharge rate serves as a first indicator, which technologies can be considered to store energy over longer time periods. Round-trip efficiency is the main efficiency factor of a storage system and describes its efficiency from charging until discharging. The columns for the energy sectors indicate which energy storage technologies have the potential for sector coupling and are directly adopted from the source (Oberholzer, 2021).

Table 4 Overview of energy storage technologies

Storage technology				**Energy sectors**			
Storage type	Form of energy storage	Self-discharge rate [%/d]	Roundtrip efficiency [%]	Electricity	Gas	Heat	Mobility
Mechanical							
Pumped hydro (PHS)	Potential energy	0-0.5[1]	70-82[1]	X			
Gravitational	Potential energy	0[2]		X			
Compressed air	kinetic energy of gas pressure	0-10[1]	40-95[1]	X			
Flywheel masses	kinetic energy of rotating masses	72-100[1]	83-93[1]	X			
Electrochemical							
Batteries	electrochemical energy in the electrodes	0.008-0.17[1]	71-97[1]	X			X
Redox flow batteries	electrochemical energy in the electrolyte	0.3[1]	70-79[1]	X			
Electrical							
Capacitors	energy in the electric field	0.004-0.013[1]	90-95[1]	X			
Superconducting coils	energy in magnetic field	10-12[1]	92[1]	X			
Chemical							
Power-to-Hydrogen (PtH)	chemical energy in hydrogen	n/a[1]	34-44[1]	X	X	X	X
Power-to-Gas	chemical energy in synthetic methane	n/a[1]	30-44[1]	X	X	X	X
Power-to-Liquid	chemical energy in hydrocarbons	n/a[1]	No data	X			X
Thermal							
Sensible heat	thermal energy in particle motion	No data	45-75[1]			X	
Latent (phase change)	transformation enthalpy	No data	75-90[1]			X	
Thermochemical	endothermic reaction energy	No data	80-100[1]			X	
Power to heat	Thermal energy storage	No data		X		X	
Cryogenic storage	Cryogenic liquid	No data		X			
Carnot batteries	High temperature heat	No data		X	(X)	(X)	

[1] (Sterner Michael, 2019, S. 641-645)
[2] Assumed, due to lack of data.

Levelized Cost of Storage for different energy storage technologies

From another study “Comparison of electricity storage options using levelized cost of storage (LCOS) method” by the Fraunhofer Institute, the estimated expansion cost for storage technologies is derived.

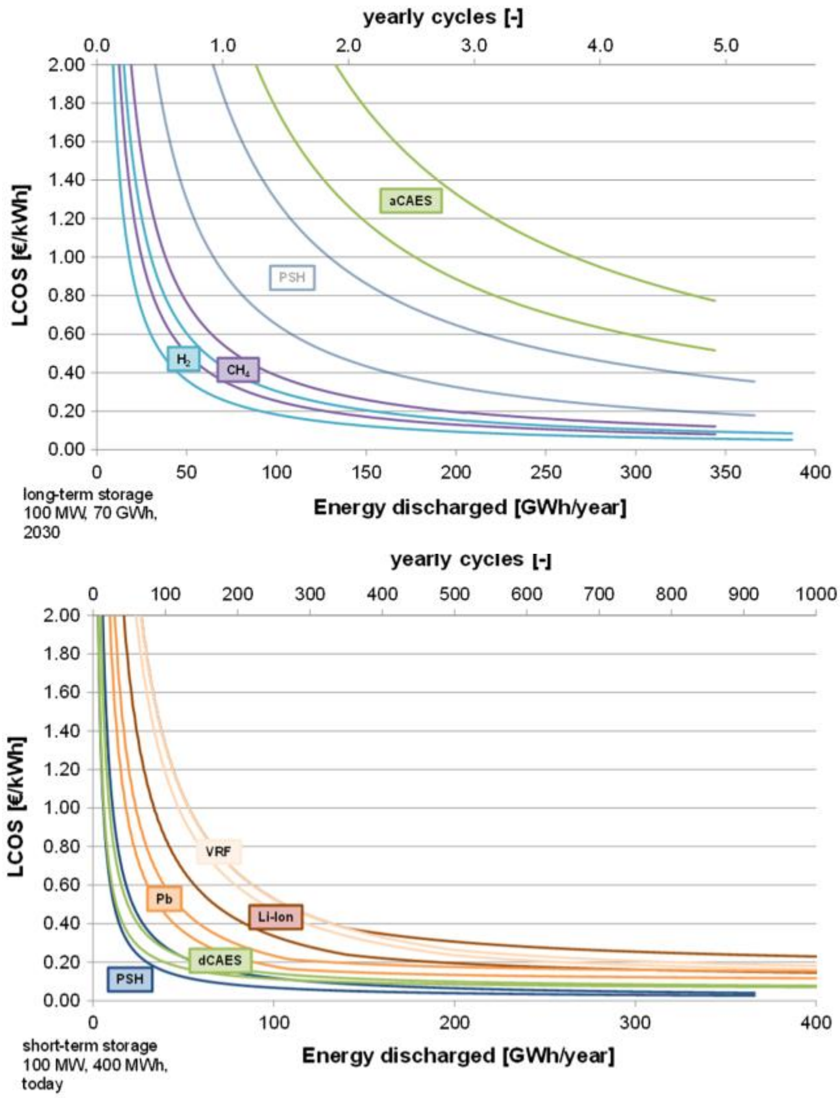

Figure 10 LCOS for different energy storage technologies for long-term and short-term storage (Jülch, 2016)

The costs for long-term storage are assumed for a 100 MW storage unit with 70 MWh capacity in 2030 and depend on the amount of yearly charging cycles. For the short-term storage, a 100 MW storage unit with 400 MWh capacity is assumed, the prices are assumed for 2016. Pumped hydro storage is the only technology that is installed and operated in large-scale today. From the figure can be seen, that the LCOS for long-term storage with PHS are around 5 times higher as for short-term storage.

2.5 Data acquisition

To create a reliable basis for the energy system model, different public sources of electricity data are being considered. The following tables provide an overview of the different data sets and allow an initial comparison of the data quality for further use.

Table 5 Source summary: European association for the cooperation of transmission system operators (ENTSO-E)

Source description	The ENTSO-E transparency platform collects and publishes electricity generation, transportation and consumption data for the European market.	
Production source document name	Actual Generation per Production Type_202101010000-202201010000	
Demand source document name	Load - Day Ahead _ Actual_202101010000-202201010000	
Production type information	Yes	
Available time series	2012-2022	
Time resolution	1 h	
Electricity production / demand for 01.2021	4409 GWh	6250 GWh
Source citation	(ENTSO-E Transparency platform A, 2023) (ENTSO-E Transparency platform B, 2023)	

Table 6 Source summary: Swiss Federal office of Energy

Source description	Swiss Federal office of Energy (BFE)	
Source document name (production and demand)	5634-Zeitreihe_Elektrizitätsbilanz_Schweiz_Monatswerte	
Production type information	No	
Available time series	1990-2022	
Time resolution	month	
Electricity production for 01.2021	5821 GWh	6152 GWh
Source citation	(Bundesamt für Energie E, 2022)	

Table 7 Source summary: Swiss energy dashboard

Source description	The energy dashboard from opendata.swiss publishes data on electricity production, import, export and demand in Switzerland, on behalf of the BFE. The platform is operated by the Swiss federal office of statistics.	
Restrictions	Data consists of measured and modelled data.	
Source Document name	ogd104_stromproduktion_swissgrid ogd103_stromverbrauch_swissgrid_lv_und_endv	
Production type information	Yes	
Available time series	2014-2022	
Time resolution	day	
Electricity production for 01.2021	5804 GWh	Only available from December 2021.
Source citation	(opendata.swiss, 2023)	

Table 8 Source summary: Swissgrid electricity overview

Source description	Swissgrid is the electricity distribution grid operator (DSO) and balance group coordinator of Switzerland.	
Restrictions	Data is reliable after 6 months after publication date.	
Source Document name	EnergieUebersichtCH-2021	
Production type information	No	
Available time series	2009-2022	
Time resolution	15 minutes	
Electricity production for 01.2021	5613 GWh	6248 GWh
Source citation	(Swissgrid AG, 2022)	

Table 9 Source summary: Pronovo

Source description	Pronovo is a subsidiary of Swissgrid and is responsible for subsidizing renewable energy sources according to the federal programs.	
Restrictions	Production data only for renewable energies	
Source Document name	Lastgangprofile 01 2021	
Production type information	yes	
Available time series	2020-2023	
Time resolution	15 minutes	
Electricity production for 01.2021	2965 GWh	Not available
Source citation	(Pronovo, 2023)	

3 Methodology

This chapter describes the applied methods to answer the questions of this thesis, as well as their limitations.

3.1 Literature research

Literature research is conducted to define the basis for the applied methods. The literature research includes:

- The political landscape in the energy area to describe the current trends and influences on the energy industry in Switzerland.
- An overview of today's energy demand and production portfolio, to define the actual state.
- The most impactful development scenarios for the Swiss energy industry. This allows to derive the general movements of future scenarios and sets a realistic perspective on scenarios that will be developed later in this thesis.
- To define the potential for energy storage, a comprehensive overview is created that presents the main characteristics of storage technologies.

Data acquisition

As part of the literature research, statistical data of the electricity production consumption from different sources is collected and compared. The following aspects are considered as crucial for the further processing of the data:

1. Data availability in the targeted timeframe.
2. Timeseries resolution, as a higher resolution can be used to downscale to a lower resolution, but not vice-versa.
3. Reliability in comparison with other sources.
4. Production information by production type.

Review of data sources

The ENTSO-E data for production, production type and demand are available in hourly resolution. The gross electricity production is around 25% lower than in all other considered sources. A deeper investigation shows differences to the other data sources, that cannot be explained with the defined assumptions. Hence the data quality of this data is viewed as questionable. The BFE data is only available in a monthly resolution and gives no insight about production types it is therefore not usable for further processing within this thesis. The Energy dashboard offers data sets on production and production type in daily resolution. Total produced electricity for January 2021 accounts to 5804 GWh. Consumption data is only available from December 2021 onwards. Swissgrid provides data for total produced electricity and gross consumed electricity available in 15 minutes resolution. Total produced electricity for 1.1.21 is 5613 GWh, which is in a comparable range to the Energy dashboard data. Production per type data is provided by Pronovo as well, but only for renewable energies and only from 2020 onwards.

Based on the data review, only the data from the Energy dashboard and Swissgrid fulfill the set data requirements. The energy dashboard is therefore considered the only valid source that provides production type information. As the Energy dashboard refers to Swissgrid data, the Swissgrid dataset is assumed to be more exact. Total production and gross consumption data is therefore further processed from the Swissgrid dataset. The electricity production difference of 209 GWh between the Energy dashboard and Swissgrid data presents an uncertainty and must be considered in the processing.

3.2 Quantitative analysis and model building

For the actual-state analysis, an electricity system model is created by averaging the production and consumption values of five years, resulting in the averaged 2017-2021 electricity model (avg17-21). For the model, general assumptions are taken:

- All relevant annual weather conditions are sufficiently represented in the observation period of five years.
- Over five years, any irregularities due to the Corona pandemic should smooth out.
- Relatively recent data should reflect current trends in the energy sector.
- The 2022 data is not used because it may still be incomplete.

To make the data sets comparable, data sets are only compared at the same time resolution. All years are normalized to 365 days, and the leap day of 2020 is deleted from the dataset. All daily records start at 00:00 and end at 23:59. Deviating raw data will be adjusted accordingly. The averaged electricity data will be projected to 365 days. To allow logical operations with the dates, the time stamps of 2021 will be used as dates for the averaged year.

The avg17-21 model will include the following elements:

- Averaged total electricity production, including the consummation of storage pumps and grid losses, processed from the Swissgrid data set.
- Averaged gross electricity consumption, demand data from the Swissgrid data.
- Averaged production profiles per production type, data from the Energy dashboard data.

The actual-state electricity balance results by subtracting the averaged production from the averaged consumption and quantifies a possible winter electricity gap.

Scenario developement

The future electricity consumption is derived from the EP2050+ model, scenario Zero Basis. The avg17-21 load curve is scaled up to the demand of 2050.
With the production profiles of avg17-21, different scenarios are developed by scaling the production profiles:

- A scenario with high autarky and minimal electricity shortage (Maximal Autarky Scenario MAS).
- A scenario with a neutral electricity balance (Neutral Balance Scenario NBS).

To set the scenario in perspective, the scenarios of established studies are modelled the same way.

Potential analysis for energy storage options

To estimate the potential for energy storage in the electricity segment, the Possible Winter Power Gaps of the scenarios are analyzed for their duration and magnitude. From this, it is derived which requirements a storage system must fulfill in order to cover the investigated winter electricity gaps. It will investigate which influence the storage scenarios have on the annual balance and how the requirements for surplus production change.

Economic impacts of the modelled scenarios

The LCOS values from the literature review are used to compare the expansion costs of the modeled scenarios with the respective storage costs.

4 Electricity system modelling

This section first describes the development of the average 2017-2021 model and its components. The model will then be applied to different scenarios and serves as an actual state analysis of today's electricity system in Switzerland. The first evaluation of production and consumption is conducted with the "Energieübersicht Schweiz 201X" datasets from Swissgrid. The Swissgrid datasets are advantageous because they offer production and demand data from one source and are considered the most reliable of the analyzed data sources.

4.1 Setup of the Average 2017-2021 electricity model

The avg17-21 model is generated according to the methodology in chapter 3.2. The idea of summarizing data over five years is to generate a representative model of the actual state of production and demand. As described in the data sources review, the gross production and consumption data is obtained from the Swissgrid data set. The following illustrations introduce the actual state according to the avg17-21 model.

Electricity production

The gross electricity production in the avg17-21 model is 64.4 TWh/a on average over the defined time scope. Figure 11 shows the electricity production over the course of one year.

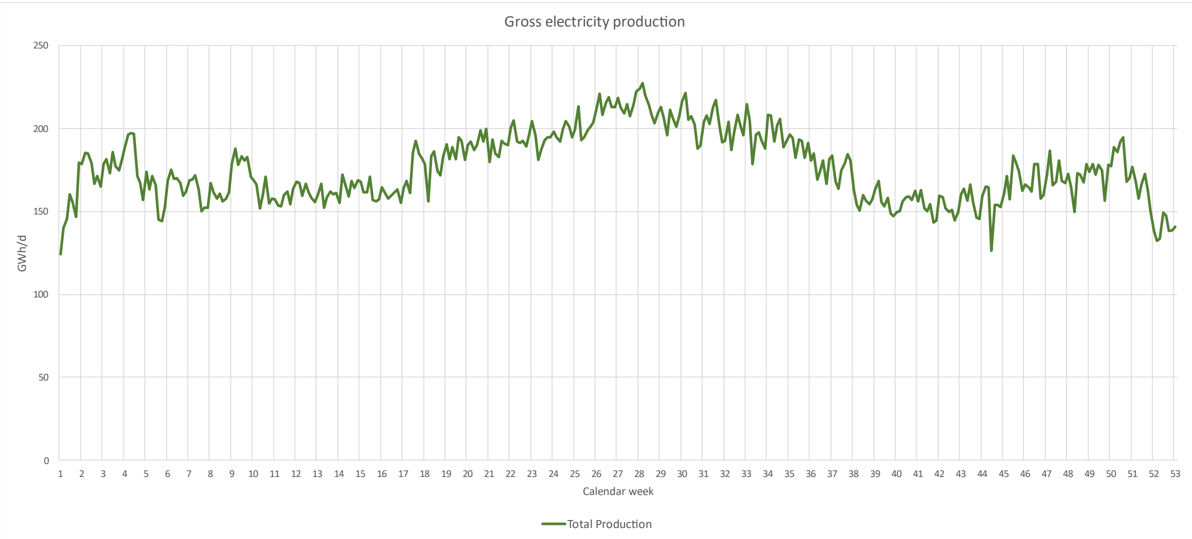

Figure 11 avg17-21 model, gross electricity production.
Data: (Swissgrid AG, 2022)

Production profile by production type

To gain further insights in the production profiles of the different production types, the electricity production by generation type is analyzed with data from the Energy dashboard, which provides information of the electricity production by source.
A comparison of the annual gross electricity production data of the Swissgrid (64.4 TWh) and Energy dashboard (67.0 TWh) data sets results in a difference of 2.6 TWh (3.9%). This difference cannot be explained by the provided background data and must be considered when the numbers of the different data sets are compared. Figure 12 displays the production profiles of the production portfolio in the avg17-21 model.

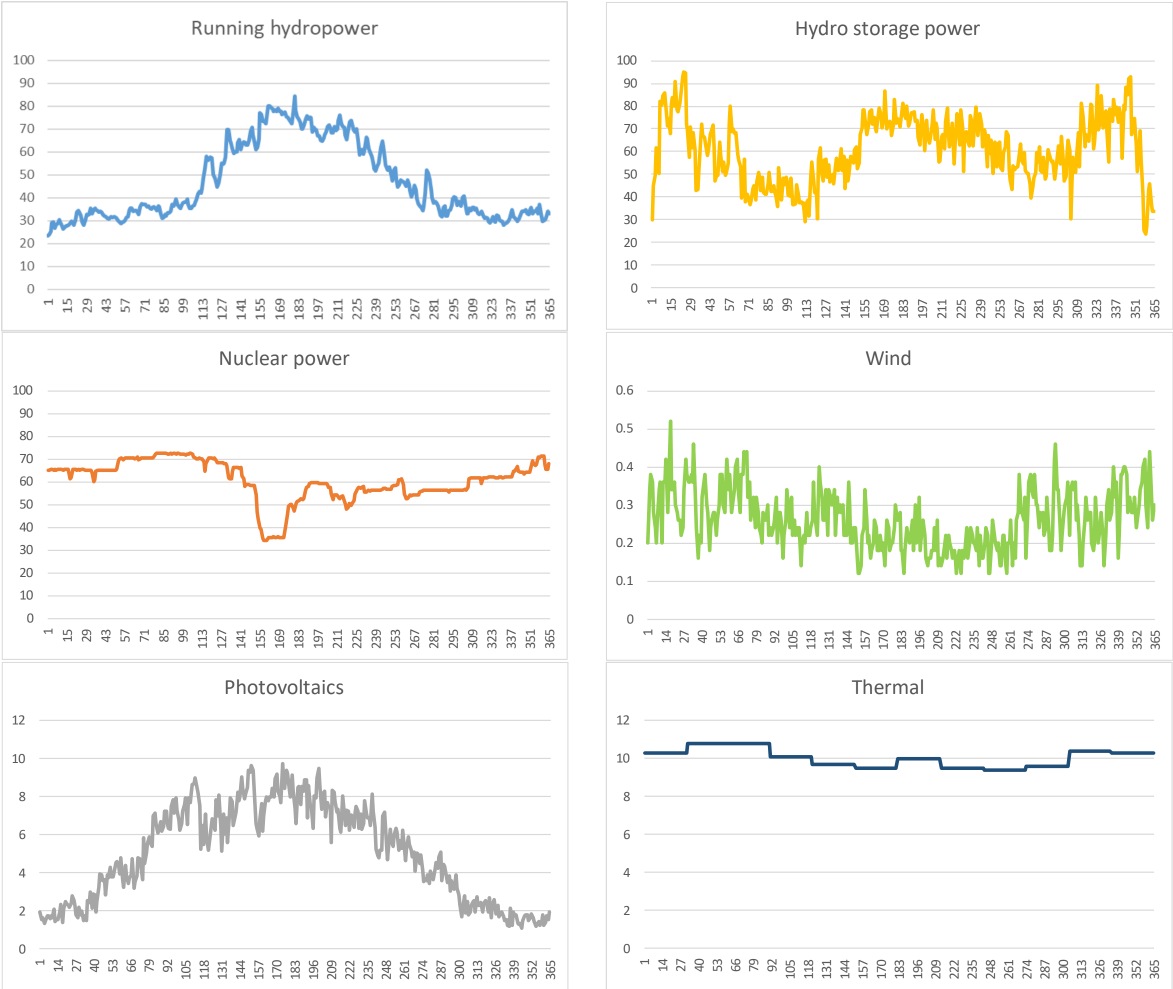

Figure 12 avg17-21 annual production profile per type in GWh/d.
Data: (opendata.swiss, 2023)

Running hydropower production is peaking from April to October, whereas hydro storage power production has two peak periods, one over the winter months and one in the middle of the year. Nuclear power produces a relatively constant baseload through the year, with a drop in June and July, while running hydro and photovoltaics are peaking. Wind power has the smallest annual production in the portfolio. It produces the bigger share of its capacity in the winter half-year. PV production has the biggest relative variance, with about five times higher production in the summer months than in the winter months. Thermal electricity production delivers a constant baseload power throughout the year, with only a minor reduction over the summer half-year. The detailed composition of the thermal category is not defined in the source.

Electricity consumption

Switzerland's gross electricity consumption in the avg17-21 model is 63.6 TWh/a. This includes grid and transmission losses, as the consumption of hydro storage pumps. The annual avg17-21 consumption is represented in Figure 13 in orange.

According to the research in chapter 2.2, the EP2050+ study assumes an annual electricity consumption of 84.4 TWh by 2050 (Prognos AG/TEP Energy GmbH/INFRAS AG, 2021). This is an increase by a factor of 1.33 compared to the annual consumption calculated in avg17-21. Scaling the avg17-21 consumption by this factor, the red graph results. The scaled graph correlates with the modelled consumption curve of the EP2050+ study, displayed in black.

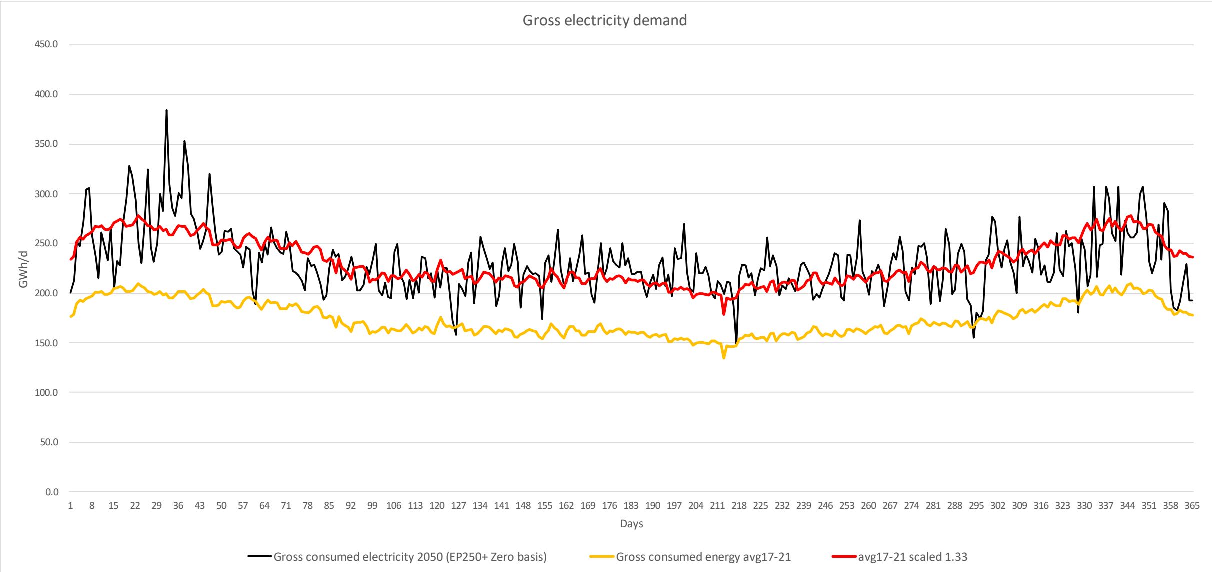

Figure 13 Comparison of modelled consumption curves with scale: GWh/d

Since the EP2050+ curve represents only one year, the spikes are much larger than those of the avg17-21 curve. Because the production curves are subject to the same smoothing, the scaled avg17-21 curve is used for modeling the scenarios.

Avg17-21 overall model

To show how production and consumption interact, the production quantities per type and the consumption curve are superimposed in Figure 14. The graph thus gives an initial indication of the times at which energy surpluses and deficits exist. The figure is the main illustration of the avg17-21 model, the resolution is in GWh/d. It must be noted that the production quantities per type are based on the energy dashboard data set, which states a higher value of the total electricity production as the Swissgrid data, which is used to generate the demand curve. The resulting difference between production and demand is therefore made smaller. This will be considered in calculations where both data sets are used together.

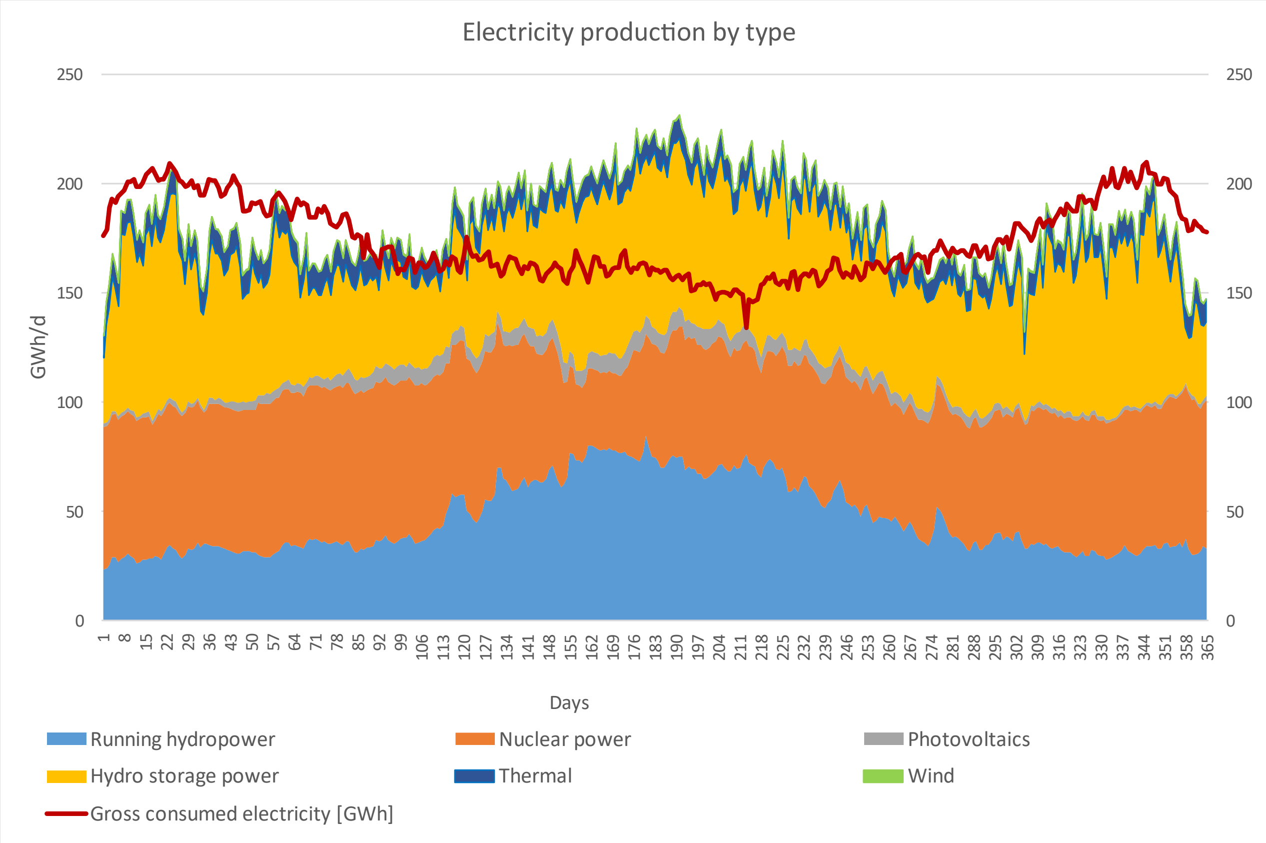

Figure 14 avg17-21 electricity model

The production capacities in the avg17-21 model are divided into the following shares in TWh/a: running water hydro: 17.0, nuclear power: 22.2, photovoltaics: 1.8, hydro storage power: 22.2, thermal: 3.7, wind: 0.1.

Electricity balance

The electricity balance is calculated by subtracting the gross electricity consumption from the total electricity production. The result is visualized in Figure 15, where the balance is represented by the yellow area. A negative balance indicates a shortage, a positive balance, a surplus of produced electricity.

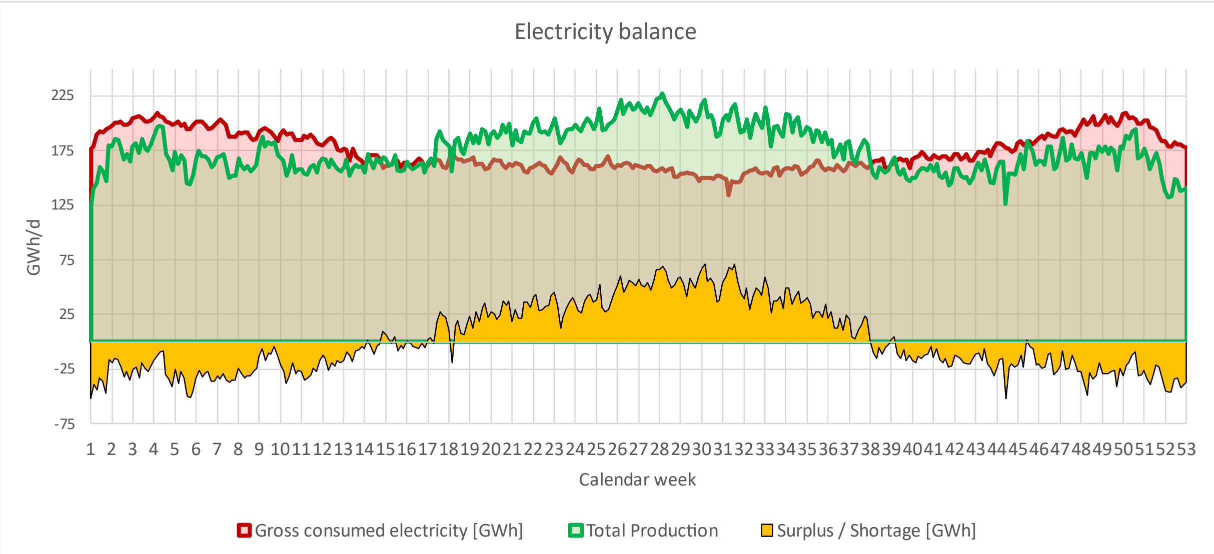

Figure 15 avg17-21 model, annual electricity balance in GWh/d scale.

Figure 15 shows that the year can be divided into a surplus and a shortage part, with little imprecision in the two transition zones. To clearly separate the two zones, the weekly balance of each calendar week is calculated from the data. According to this calculation, the start of the surplus period is in calendar week 18 and ends with CW 38, which means roughly late April to late September.
To investigate the characteristics of the surplus and shortage zones, the zones are shifted in the annual axis and resolved in GWh/d. This results in a 155 day surplus period and a 255 day shortage period. Figure 16 shows the two zones with the daily electricity balances and the average daily balances per zone.

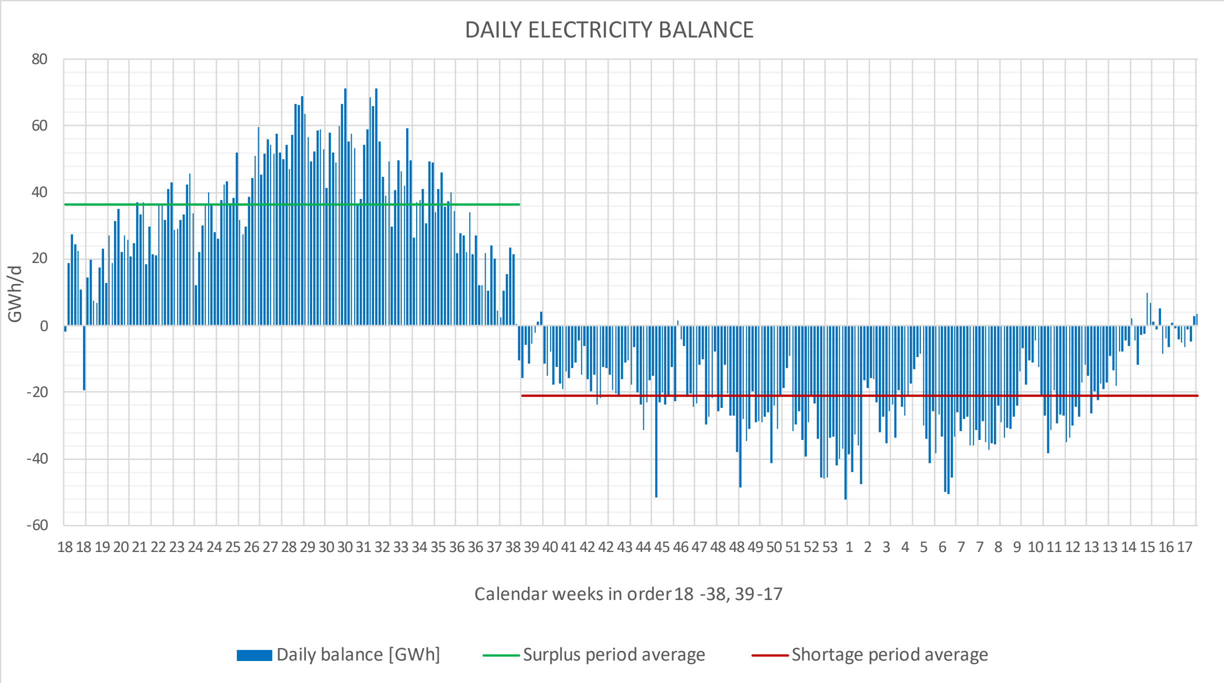

Figure 16 avg17-21 model, daily electricity balance

Table 10 summarizes the behavior of the electricity balance in the avg17-21 model over the year and within a defined shortage and surplus period.

Table 10 avg17-21 model, quantitative analysis of daily electricity balances

	Year		
Total electricity production	64.4		*[TWh]*
Total electricity balance	+1.1		
	Shortage period	Surplus period	
Period length	210	155	*[d]*
Total balance	-4606	5340	*[GWh]*
Average daily electricity balance	-21.1	+36.3	
Standard deviation	12.8	17.4	
Maximal daily balance	+9.9	+71.2	
Minimal daily balance	-52.3	-19.4	

The yearly balance is the difference between produced and consumed electricity and is plus 1.1 TWh.

4.2 Scenario implementation and results

In this section, the avg17-21 model is used as a basis to model the scenarios described in 3.2. For this purpose, the six avg 17-21 production profiles are scaled to new annual capacities and form the production portfolio of the scenario. In addition, the production profile of alpine photovoltaics is included for some scenarios. The scaled avg17-21 consumption curve is used to calculate the scenario's electricity balance and winter electricity gap. In the following, the results of the scenarios are presented with the assumptions made for them.

Energy Perspectives 2050+ scenario model

From the EP2050+ study, the Zero Basis scenario is used. It assumes a runtime of 50 years for the Swiss nuclear power plants. The study includes individual numbers for hydro storage power plants (19.02 TWh) and pumped hydro power plants (7.11 TWh). They are combined to hydro storage power production profile. The thermal production consists of biomass[3] (4.32 TWh) and others[4] (2.09 TWh). This input in TWh/a is used for the annual production portfolio: running water hydro: 18.55, nuclear power: 0, photovoltaics: 33.61, hydro storage power: 26.13, thermal, 6.41, wind: 4.32[5].

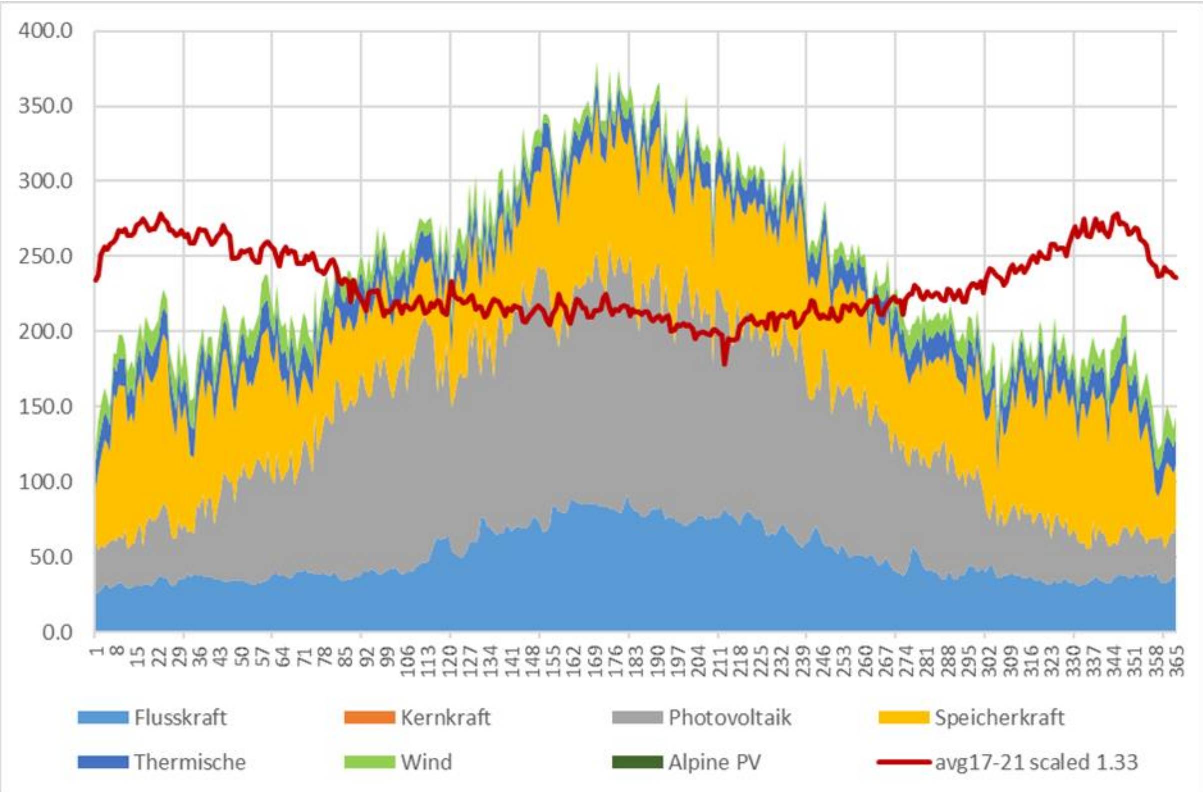

Figure 17 EP2050+ scenario visualisation, GWh/d

Figure 17 shows the EP2050+ production portfolio and the predicted electricity use for 2050. The portfolio leads to an electricity surplus between April and September and a shortage from October to March. The detailed results are presented in Table 11.

[3] Wood, biogas, sewer gas, biogenic waste
[4] Fossil powerplants (fuel to power and combined heat and power), geothermal
[5] (Prognos AG/TEP Energy GmbH/INFRAS AG, 2021)

Table 11 EP2050+ scenario results

	Year		
Total electricity production	89.0		*[TWh]*
Total electricity balance	+4.6		
	Shortage period	Surplus period	
Period length	180	185	*[d]*
Period balance	-10557	15127	*[GWh]*
Average daily electricity balance	-58.6	+165.8	
Standard deviation	29.3	43.9	
Maximal daily balance	-0.6	+2.0	
Minimal daily balance	-115.0	+165.8	

The results table shows that the shortage and surplus periods are equally long. The average surplus is higher than the average shortage, leading to a total surplus of 4.6 TWh.

PSI scenario model

The PSI study shows the extent to which different types of electricity production can be expanded under economic and ecological criteria. The resulting expansion potential until 2050 is used as input for the PSI Scenario. The PSI study assumes the following potentials in TWh/a: running water hydro: 17, nuclear power: 0, photovoltaics: 19, hydro storage power: 22.2, thermal: 6.9, wind: 4.3[6].
The study does not differentiate between running water and storage hydropower, but in big- and small-scale hydropower, which can’t be matched to the production profiles. As the sum of small- and big-scale matches witch the total hydropower production from the avg17-21 model, the same capacities are adopted for the PSI scenario. The thermal production consists of Wood Combined Heat and Power (CHP), biogas and deep geothermal.

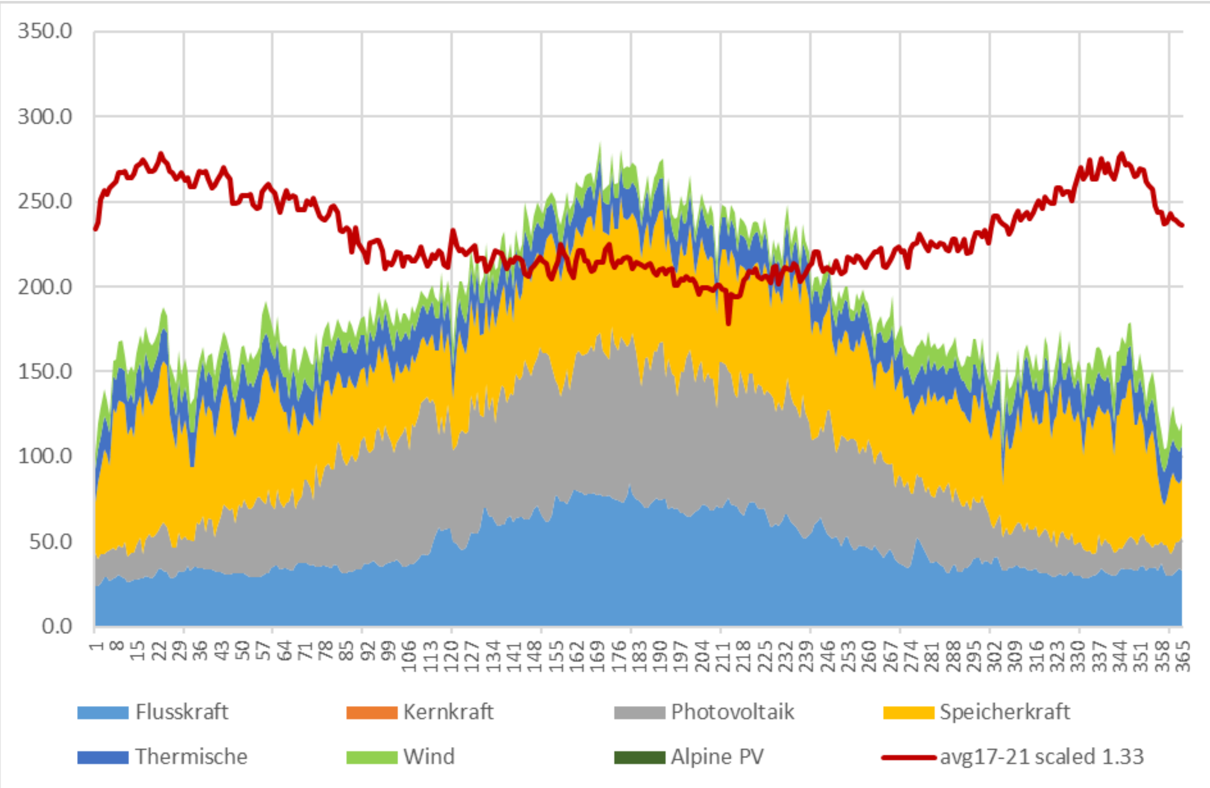

Figure 18 PSI scenario visualisation, GWh/d

6 (Hirschberg, 2017)

Figure 18 shows the modelling result with the PSI input data. The period between May and September has a positive electricity balance. The results are presented in Table 12.

Table 12 PSI scenario results

	Year		
Total electricity production	69.4		*[TWh]*
Total electricity balance	-15.0		
	Shortage period	Surplus period	
Period length	257	108	*[d]*
Period balance	-18913	+3890	*[GWh]*
Average daily electricity balance	-73.6	+36.0	
Standard deviation	36	17.0	
Maximal daily balance	-0.2	+71.8	
Minimal daily balance	-132.7	+0.7	

At 257 days, the shortage period in the PSI scenario is longer than the surplus period. The overall balance is also negative at -15 TWh.

Maximum Autarky Scenario model

The Maximum Autarky scenario is not study-based; it is used to explore what level of production expansion would be required to achieve a consistently self-sufficient power supply. The individual production profiles were scaled in a try-and-error process to bring the portfolio as close as possible to the consumption curve and at the same time keep the surplus as low as possible.
To achieve this, it was necessary to scale the profiles with higher production in the winter months to compensate for the PV and running hydro peaks during summer. Thermal is scaled up by 450% to replace nuclear power. The conventional PV production is left untouched, but the alpine PV profile (Section 2.3) is expanded because of its anti-cyclic profile. Wind has a similar profile and was expanded by over 12’000%. The scenario portfolio is composed in the following TWh/a shares: running water hydro: 17, photovoltaics: 2, hydro storage: 22.2, thermal: 20, wind: 12, alpine PV: 20.

Figure 19 shows the resulting MAS model. The shortage period is only short from November to March. Table 13 summarizes the results. Despite a comparatively balanced annual production, the scenario has 106 shortage days. This is due to the framework condition that the annual surplus should be kept as small as possible. Of all the scenarios examined, the MAS has the smallest mean value and the smallest standard deviation for the average daily shortage.

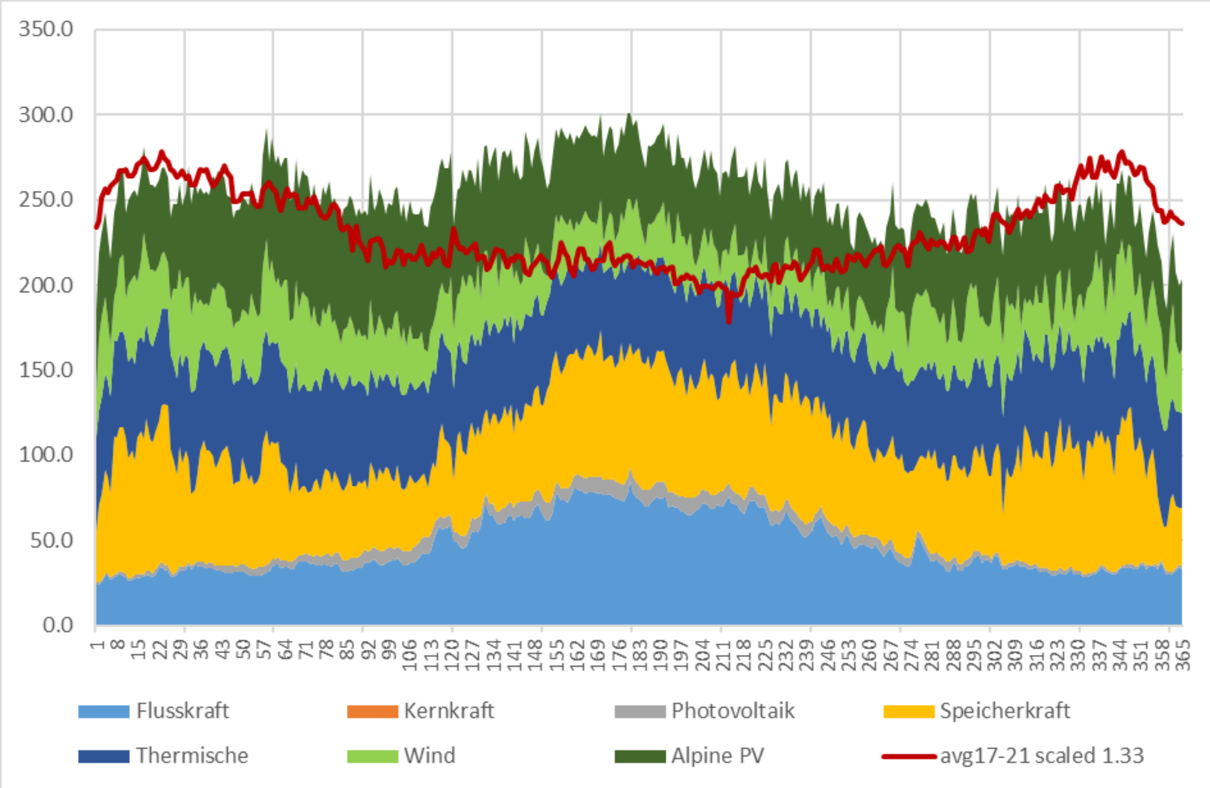

Figure 19 MAS scenario visualisation, GWh/d

Table 13 MAS scenario results

	Year		
Total electricity production	93.2		*[TWh]*
Total electricity balance	+8.8		

	Shortage period	Surplus period	
Period length	106	259	*[d]*
Period balance	-1584	+10371	*[GWh]*
Average daily electricity balance	-14.9	+40.0	
Standard deviation	12.0	26.1	
Maximal daily balance	-0.2	+88.6	
Minimal daily balance	-52.0	+0.7	

Neutral Balance Scenario model

For the NBS, the production profiles are scaled until the annual balance is zero. This means that over the year the same amount of electricity is produced as consumed. The following assumptions were made for the production portfolio: Hydropower is expanded only slightly and mainly in hydro storage. PV is expanded similarly to the EP2050+ scenario, but partly as alpine PV. The remaining expansion potentials are based on the EP2050+ scenario. This result in the following production portfolio in TWh/a: running water hydro: 18, nuclear power: 0, conventional photovoltaics: 22, hydro storage: 26, thermal: 6, wind: 4.4, alpine PV: 8. This input leads to the model shown in Figure 20, the results are summarized in Table 14.

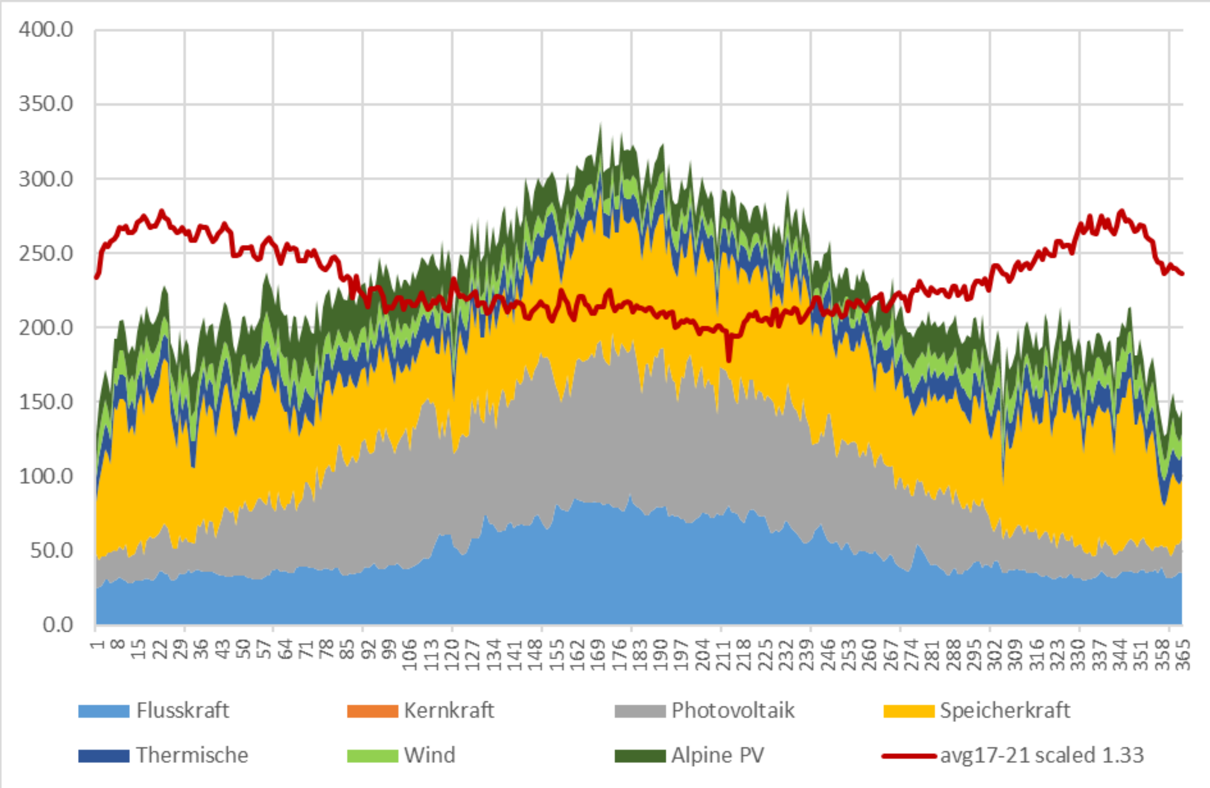

Figure 20 NBS scenario visualisation, GWh/d

The results table shows that the annual balance is not exactly balanced by 14 GWh. This deviation can be explained by the input in TWh and the evaluation in GWh. The surplus period is 17 days shorter and therefore shows on average higher daily deviations than the shortage period.

Table 14 NBS scenario results

		Year	
Total electricity production		84.4	*[TWh]*
Total electricity balance		0	
	Shortage period	Surplus period	
Period length	191	174	*[d]*
Period balance	-10323	+10237	*[GWh]*
Average daily electricity balance	-54.0	+58.8	
Standard deviation	26.4	33.5	
Maximal daily balance	-1.6	+124.2	
Minimal daily balance	-109.8	+0.4	

4.3 Winter electricity gap

All scenarios examined show an electricity shortage in the winter months. From the model representations in daily scaling, it is evident that the days with electricity shortage occur together. There are some exceptions in the transitions and in the MAS scenario. From this it is derived that the year can be divided into two continuous shortage and surplus periods. Figure 21 shows the duration curves of the energy balances of the scenarios. The graph shows the shares of positive and negative days per year, as well as how many days in the year the energy balance remains at a certain level. A completely horizontal curve would mean that the balance is the same the whole year. The steeper the curve, the greater the variance in the electricity surplus or shortage.

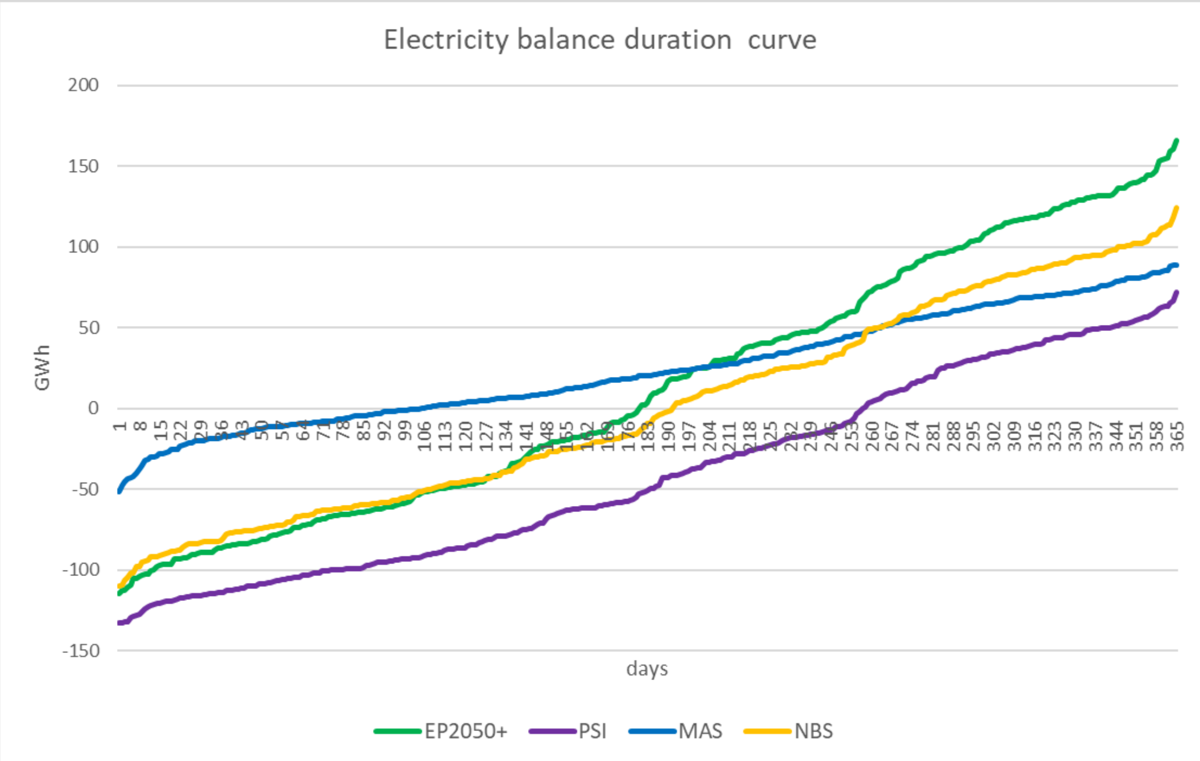

Figure 21 Electricity balance duration curve, scenario comparison

The area below the zero line up to the scenario balance duration curve represents the total electricity shortage. Table 15 gives an overview of the electricity shortage in each of the scenarios examined:

Table 15 Electricity shortage in the examined scenarios

	EP2050+	PSI	MAS	NBS
Period length [d]	180	257	106	191
Period balance [GWh]	-10557	-18913	-1584	-10323
Average daily electricity balance [GWh]	-58.6	-73.6	-14.9	-54.0

The shortage periods last between 106 and 257 days, the electricity shortage is between 1.6 and 19 TWh. In average over all scenarios, a shortage day lacks 50.3 GWh, resulting in the need for an average power output of 2 GW over the whole shortage period. This is roughly equivalent to twice the output of the Gösgen nuclear power plant (Kernkraftwerk Gösgen, 2023). The described electricity shortage can be compensated in four strategic directions: importing the shortage electricity, expanding production capacities, use of electricity storage technologies to use surplus energy from the summer month during the shortage period or reducing the electricity demand with energy efficiency measures and sectoral coupling.

4.4 Potential for energy storage

This section describes the options for covering the winter power gap with energy storage and their impact on the energy system. The potential analysis is set at the system level and does not address the peculiarities of specific technologies. It is assumed that energy is stored and discharged in the form of electricity. This neglects the possibilities of sector coupling for simplification.

The most important property of a system-level energy storage device is round trip efficiency. Values for common energy storage technologies are listed in section 2.4. In the energy scenario modelling in section 4.2, no new storage technologies were considered, and the losses of hydro storage are being neglected. If storage technologies are now to be deployed on a large-scale, round-trip efficiency has an enormous impact on the electricity balance, because the losses of the energy storage portfolio must be compensated with additional electricity production.

Based on the energy gaps described in 4.3, it can be deduced which characteristics energy storage technologies must have to cover the winter electricity gap:

- Long storage duration
- Low self-discharge rate
- High storage capacity
- Few discharge cycles per year

Figure 11 shows that only a few technologies currently meet these requirements:

- Mechanical storage such as pumped hydro, gravitational storage, or compressed air storage
- Chemical storage, such as power to hydrogen or methane
- Electrochemical storage, for example lithium-ion batteries or redox flow batteries

The literature review in section 2.4 shows that currently only the first two of the above-mentioned technology classes are considered for long-term storage.
In the following table, the required charging energy including round-trip efficiency is calculated to cover the entire winter electricity gap with a storage system. A gigantic storage portfolio is assumed, one third of which consists of PHS and two thirds of PtH. The average values of the range of round-trip efficiency values are taken from the literature: 76% for PHS and 39% for PtH (Sterner Michael, 2019). This results in a round-trip efficiency of 58% for the assumed storage system.

Table 16 Required charging electricity to compensate the winter electricity gap

	[GWh]		
	Model shortage	Model surplus	Required charging electricity
EP2050+	10557	15127	18360
PSI	18913	3890	32892
MAS	1584	10371	2755
NBS	10323	10237	17953

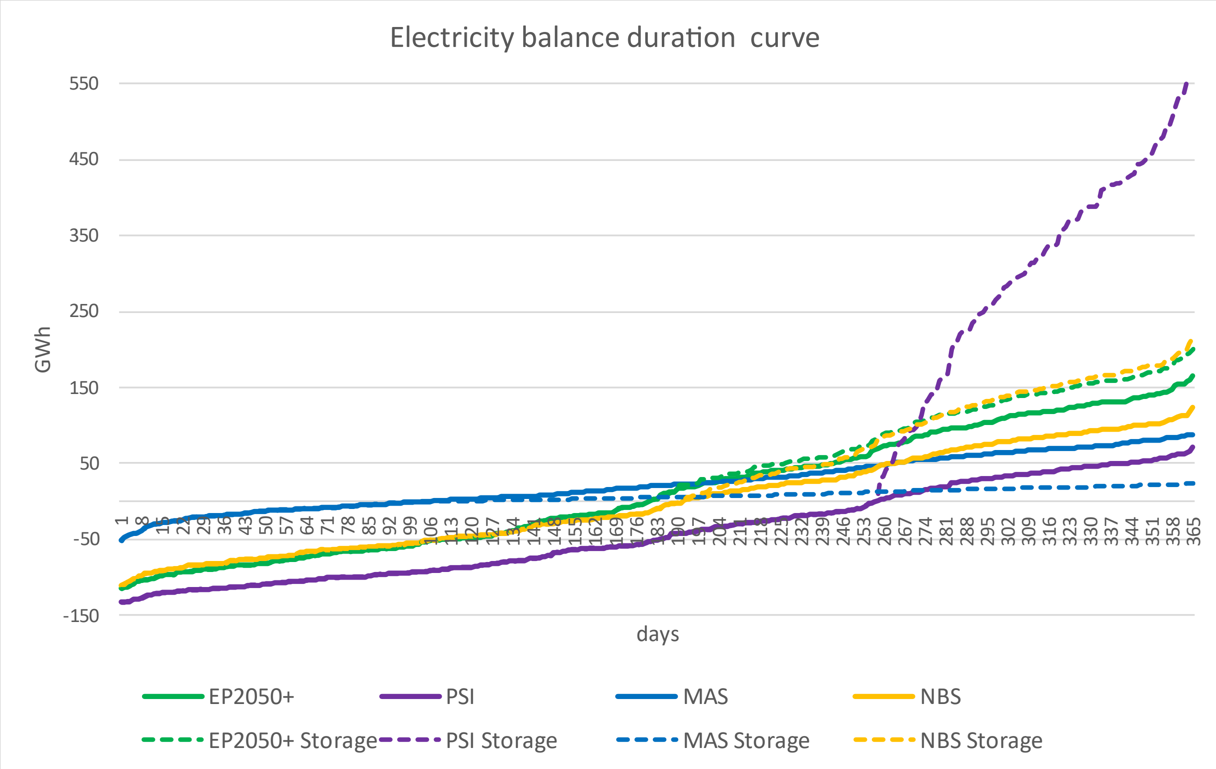

Figure 22 Electricity balance duration curve, impact of storage round-trip efficiency on the electricity demand

The results show that only the MAS scenario has a big enough summer electricity surplus to compensate for the winter electricity gap with a storage with 58% efficiency. This is also visualized in Figure 22, where the dotted lines indicate the required summer surplus in the electricity balance load curve. The calculation shows that the lower the round-trip efficiency of the storage portfolio is, the steeper gets the duration curve in the balance positive area.

To date, the author of this thesis is not aware of any major, politically supported movements for the long-term storage of electricity. Also, the EP2050+ study does not further address this option.

4.5 Economical aspects of portfolio expansion and storage

In this section, the costs of the storage portfolio assumed in 4.4 are calculated and compared with the expansion costs of the four scenarios. For this purpose, the Life Cycle Cost of Storage (LCOS) is taken from literature. For the storage technologies used, these are 0.4 CHF/kWh for PtH and 1.4 CHF/kWh for PHS (Jülch, 2016), with an exchange rate of 1 CHF to 1 Euro.
These are compared with the Levelized Cost of Energy (LCOE) in CHF/kWh of the production types from the PSI study. These are for newly built plants in Switzerland in 2035: Running hydro 0.21, PV 0.13, PHS 0.21, Thermal 0.34, Wind 0.14, Alpine PV 0.13 (Hirschberg, 2017). In each case, the average values of the specified price ranges are indicated. Uncertainties exist for PV and Alpine PV. Due to a lack of information, their LCOEs were equated. Another uncertainty is the discrepancy between the LCOS and LCOE of PHS when comparing the two sources. For the sake of simplicity, the data are taken as they are, assuming that the LCOE is based on today's economically oriented use of the PHS and the LCOS reduces their use to storage.

Figure 23 shows expansion costs of production capacities in comparison to the actual state, avg17-21 model and the costs of compensating the whole winter electricity gap (required charging electricity from 4.4) with the 1/3 PHS 2/3 PtH storage system. The systems LCOS is 0.73 CHF/kWh.

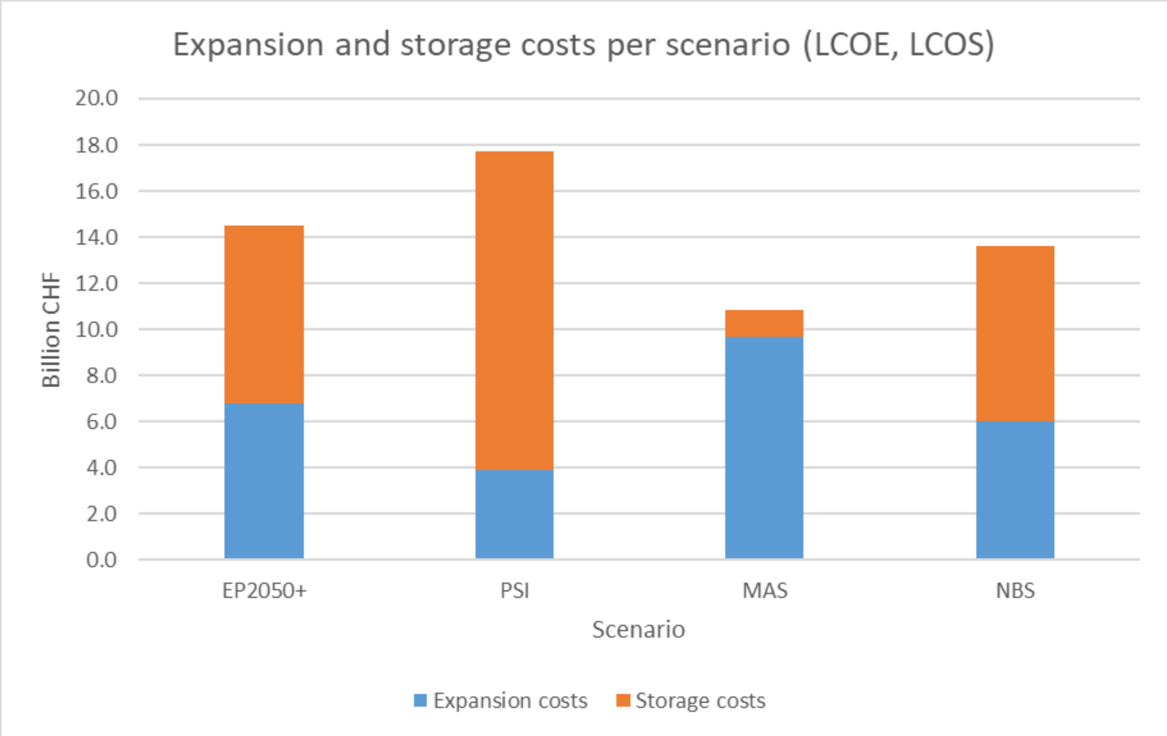

Figure 23 Expansion and storage costs per scenario

The scenario with the highest investment in the electricity production capacity has the lowest storage costs and the lowest overall system costs. The difference of production LCOE to the storage LCOS has a huge influence on the result.

5 Discussion of results

This chapter summarises the results of this work and puts them in perspective.

Actual state of electricity system and winter electricity gap

For the actual state analysis of the Swiss energy system, data on the years 2017 to 2021 were combined to create a representative data set representing the typical annual patterns of electricity production and consumption.

Analysing these patterns, the current production portfolio of run-of-river power, pumped storage power plants, nuclear power plants, wind power plants, photovoltaics and thermal power plants produces 64.4 TWh of electricity per year in Switzerland. This compares with an annual total electricity consumption of 63.6 TWh. The consumption values in the winter months are between 10 and 20 percent higher than in the summer months. Due to the higher production in summer, the annual electricity balance is +1.1 TWh. As electricity production and consumption are not evenly distributed, the year can be divided into two phases:

- A surplus period from April to September with an overproduction of 5340 GWh.
- A shortage period from October to March, with an overconsumption of 4606 GWh.

The shortage of electricity in the winter half-year is colloquially referred to as the winter electricity gap. The results of the actual state analysis are considered reliable, so Swissgrid's data basis is very solid. However, the results are influenced by the fact that they were calculated from a data set that represents the mean value from five consecutive years. The idea behind this is to compensate for exceptional occurrences such as extreme weather situations or the corona pandemic and to create a model that represents an assumed normal case. The fluctuations in the data are thus smoothed out. One consequence of this is that the maximum values occurring in the model are smaller than the occurring ones. This is visible in Figure 24, which shows the current balances of the individual years and the curve of the mean value.

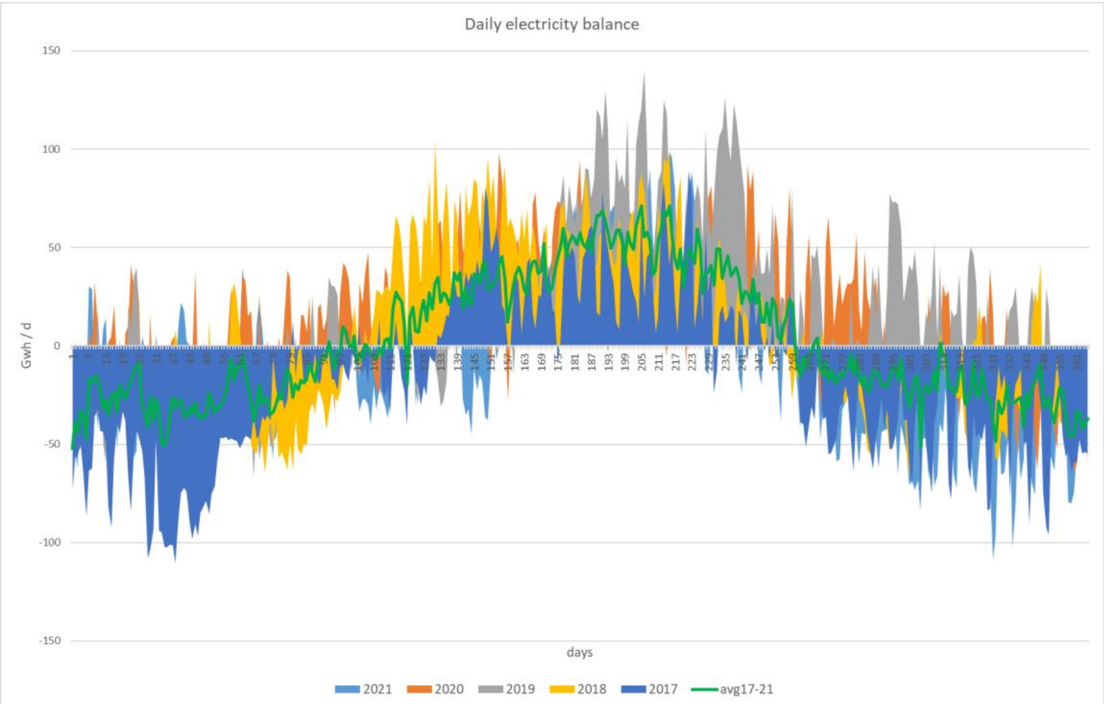

Figure 24 Daily electricity balance of the source data and the avg17-21 curve

The resulting avg17-21 model serves as a basis to develop future scenarios. The results of those are summarized and discussed in the next section.

Scenario results

Based on the literature research, an electricity consumption of 84.4 TWh is assumed until 2050. To cover this demand, the current production profiles were scaled according to four scenarios. In addition, a profile for alpine PV was added to the existing PV production profile. All scenarios assume a completed phase-out of nuclear energy by 2050. The expansion scenarios delivered the following results:

Energy Perspectives 2050+ scenario, EP2050+
In the EP2050+ scenario, the omitted nuclear energy is mainly compensated with a huge expansion of PV to 34 TWh. In addition, wind and thermal power sources are expanded. The resulting portfolio is highly cyclical and results in a winter electricity gap of 11 TWh, with an annual production of 89 TWh and an annual balance of +5 TWh. With the wide scope and the depth of its data, the scenario is considered reasonable.

Potentials, costs, and environmental impacts of electricity plants, PSI
The PSI scenario is very similar in composition to the EP2050+ scenario. However, all expansions are assumed to be lower. According to the scenario, PV is expanded to 19 TWh. Thermal and wind are estimated at 7 and 4 TWh, respectively, which is roughly in line with the EP2050+ model. the two hydropower categories are considered exhausted and left at the current level. The resulting portfolio has the largest winter electricity gap of all scenarios at 19 TWh. The annual production of 69 TWh is only 5 TWh larger than today and leads to a negative annual balance of -15 TWh. The PSI scenario is five years older than the EP2050+ study and is based on a politically different starting position, which may be one reason for the lower potential assumptions. From today's perspective, the assumptions seem too low.

Maximal Autarky Scenario, MAS
This scenario is not based on a previous study and aims to align the production curve as much as possible with the consumption curve without generating an extreme annual surplus.
For this purpose, the production types that produce more electricity in winter or have a uniform yearly distribution are particularly scaled up. PV is scaled up to 22 TWh, but most of it as alpine PV (20TWh), which has a counter-cyclical production profile. This is also true for wind power, which is expanded to 12 TWh. To compensate for the loss of base load from nuclear power plants, thermal power sources are scaled up to 20 TWh. Because hydropower is subject to strong political conditions, it was left at the current level.
This results in a relatively balanced annual production curve with the smallest winter electricity gap of 1.6 TWh of the scenarios investigated. The total amount of electricity produced of 93 TWh is the largest in comparison, with an annual balance of +8.8 TWh. The assumptions for this scenario are considered unrealistic. It shows what would be needed for near self-sufficiency. However, the possibilities of storage technologies are neglected.

Neutral Balance Scenario, NBS
Like the MAS scenario, the NBS is also not based on a study. The NBS aims for an annual balance of zero. This can be used to show how long the surplus and shortage periods will be if they are to cancel each other out exactly. For this purpose, the production profiles including alpine PV were scaled to 84.4 TWh. This results in a portfolio that is surprisingly like EP2050+, only with about 5 TWh less surplus in summer, which can also be seen from the duration balance profiles in 4.3. The shortage period is 191 days and is completely compensated by the 174 days surplus period. The total production is 84.4 TWh with an annual balance of zero.

The extent of the expansion in the scenarios can be shown with some approximate calculations: For the additional capacity of 30 TWh PV, about 158 km2 of solar panels are needed. This is based on an average capacity of 190 kWh/m2 (Industrielle Werke Basel, 2023). This area is approximately comparable to the area of Lake Lucerne and Lake Thun together and is about 0.4% of Switzerland's surface. Compared to the fact that about 5% of the Swiss surface area is building zone, the required area seems to be available. A study of the BFE in 2018 estimated the potential for PV in Switzerland only on building roofs to about 50 TWh/a (Bundesamt für Energie F, 2018). As the study does not include freestanding or alpine PV, the expansion potential of 39 TWh is considered a realistic target.

To expand the wind power capacity to the targeted 4.3 TWh according to the EP2050+ study, about 1200 additional wind plants must be constructed in addition to the existing 40 plants. This assumes an average capacity of 3.5 GWh per plant, which corresponds to the average output of today's plants (Bundesamt für Energie G, 2020). Considering the great resistance from the population against wind power, the feasibility of this goal is questionable if the political and social framework conditions do not change.

For the remaining production types, it is more difficult to make an estimate because the external influences are even greater. Basically, it can be said that the development of the Swiss energy landscape is mainly dependent on political decisions. In principle, Switzerland offers the potential for a mostly independent energy supply. It is up to the politicians, and thus the population, to decide which expansion of the energy supply, with all its effects on the environment, should be implemented.
When comparing the scenarios, it becomes apparent that the extreme expansion of PV leads to an enormous peak in summer production. For the security of supply, it is therefore favourable to expand counter-cyclical production types such as wind, PHS, alpine PV or thermal as well, in order to achieve a more even annual distribution.

Storage Potential and ecocomical indicators

Depending on the scenario, the resulting winter electricity gap is between 1.6 and 19 TWh. This shortage period can be covered by imports, expanded generation capacity, or energy storage. Due to the losses during storage and discharge, the surplus energy required in summer increases by the factor of round-trip efficiency. If the winter electricity gap could be completely covered with energy stored in summer, this would mean a degree of self-sufficiency of 100% in the electricity sector. An example calculation with an assumed electricity storage with 58% round-trip efficiency and capacity for the entire winter electricity gap showed that only the MAS scenario can achieve complete self-sufficiency. In the other scenarios, the winter electricity gap with assumed storage losses exceeds the oversupply in summer. For a long-term storage system, the following technologies are currently being considered: PHS, PtX, battery storage systems, compressed air storage or alternative storage systems based on gravity.

A comparison between the scenarios shows that the expansion of production capacities leads to a more cost-efficient energy system than the expansion of storage technologies. However, this result is strongly dependent on the assumptions made regarding expansion and storage costs. To estimate the costs of production expansion in the scenarios, a projection of the expansion costs was made with the LCOE of each production type. Depending on the scenario, the expansion costs amount to between 3.9 and 9.7 billion Swiss francs. Because the more favourable scenarios require more energy storage, the storage costs were calculated for each scenario. For this, a storage system with two thirds PtH and one third PHS was assumed, with a LCOS of 0.58 CHF/kWh. The storage costs to cover the winter electricity gap are between 1.2 and 13.9 billion Swiss francs.
Assuming that Switzerland's entire electricity supply is to be covered by its own production and storage facilities, the system costs result from expansion costs compared to today for production and

storage facilities. These amount to 14.5 billion CHF for the EP2050+ scenario, 17.7 for the PSI scenario, 10.9 for the MAS scenario and 13.6 billion for the NBS scenario.

It must be added that a purely economic view does not do justice to the storage systems. They offer advantages that must also be considered in a more complex comparison. For example, the intelligent use of storage systems can increase the degree of self-sufficiency with lower capacity expansion in production, which reduces the impact on the environment.

5.1 Limitations of research

This section describes the limitations of the methodology used and what misconceptions are possible as a result.

Data availability and quality

The result of any modeling is strongly dependent on the quality of the input data and the assumptions made. During the data research for this thesis, it became apparent that the data on energy supply is very difficult to interpret.
On the one hand, there are several sources for all data, some of which contradict each other. The general conditions are not always transparent, which makes comparisons difficult. During the research, it also became apparent that the energy sector is highly politicized and that different players in the electricity market interpret facts very differently, which complicates the scientific use of the data.

Reliability of production profiles

By averaging the production and consumption data for the actual state analysis from five years, the extreme values are smoothed out. This leads to the assumption that the profiles created are representative for an average year. This means that the data can be used to plan a standard load case, but reserves must be built into the system for any extreme events.

The scenarios assume that the production profiles will remain the same until 2050. If these change significantly in the future, the results of the scenarios are less reliable. For solar energy, the profile will change with the installation of alpine PV, which is considered with a separate profile in the model.

Effects of different evaluation scopes

For the modeling, a daily resolution of the production and consumption values was chosen. This decision was made because the only reliable source of data on the individual production types is in daily resolution. Swissgrid provides the load data in 15-minute resolution, but without information on the production type. A sample analysis in hourly resolution of calendar week 12 shows that even in the shortage days individual hours show a positive balance. This is visible in Figure 25.

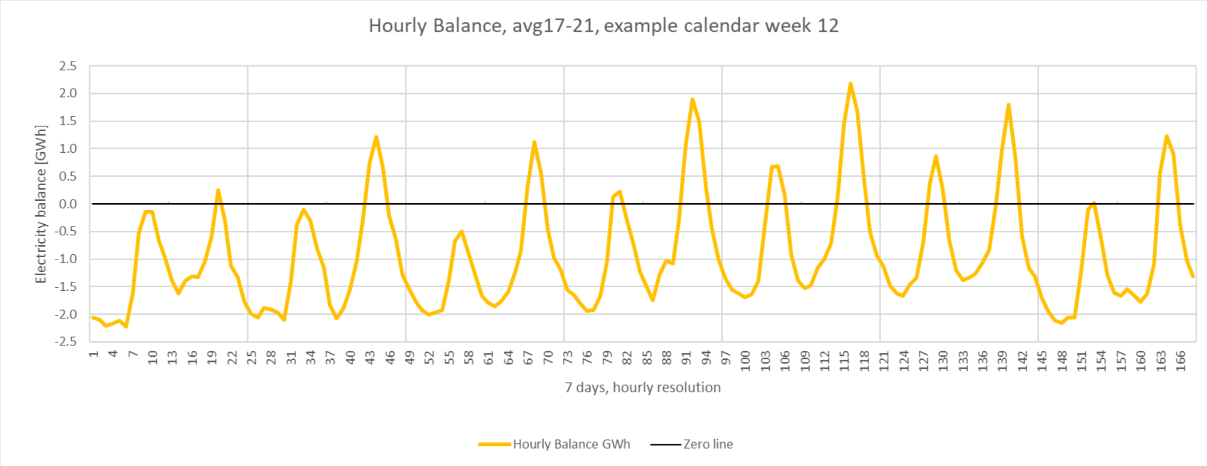

Figure 25 avg17-21 model, electricity balance in hourly scope, for CW 12

For the evaluation of the winter electricity gap, a daily resolution is sufficient. For the design and operation of a storage system however, short power surpluses in the shortage period can also be of importance, which are neglected in the daily resolution.

Simplifications for storage potentials and economical assessment

The estimate of excess energy is directly dependent on the assumptions made for round-trip efficiency, and the estimates of expansion and storage costs are directly dependent on the assumed LCOE and LCOS values. These considerations should be regarded as an initial estimate of the relative ratios.

5.2 Future research

The model developed in this work provides a solid data basis. The model could be further developed in the following aspects:

1. The scenarios were chosen relatively arbitrarily. In a further development, the production portfolio could be optimized according to economic or other framework conditions.
2. The energy balance needs to be evaluated more precisely. Thus, like the production portfolio, a storage portfolio can be created. This should be designed with different response times and capacities to cover the winter electricity gap.
3. The required charging energy and the delivered power of the storage portfolio can be integrated into the model of production and consumption.
4. The influence of sector coupling was neglected in this thesis. The possible optimization of the consumption curve by means of sector coupling should be further investigated.

6 Conclusions

This thesis provides a quantitative overview of electricity production and consumption in Switzerland. Using a model that averages electricity data from 2017-2021, an actual state analysis is performed. The model shows that the electricity balance of Switzerland is positive over one year, with 1.1 TWh surplus per year. However, there is a winter electricity gap of 4.6 TWh, which is currently covered by imports from abroad.

For the model, the characteristic production profiles of the Swiss production portfolio were determined. Today, this consists of run-off hydropower, nuclear power, pumped storage hydro, photovoltaics, thermal power and wind.

The federal government's energy strategy aims, among other things, to phase out nuclear power and switch electricity production in Switzerland to renewable energy sources. The implementation of this process is subject to strong political influences because various interest groups want to play a role in shaping the energy system.

Four scenarios are modelled from the calculated production profiles to investigate the impact of the expansion of renewables on the winter electricity gap. It has been shown that the massive expansion of conventional PV plants does not contribute to closing the winter electricity gap. The production portfolio must be supplemented with PV at alpine locations and wind power plants, which, according to the profiles determined, generate more electricity in winter than in summer. Sustainable thermal energy sources would have the potential to replace the base load of nuclear power plants. However, the studies examined see only little expansion potential for this.
While run-of-river power plants have a similar peak as PV in summer, pumped storage power plants have the potential to generate more electricity in winter. However, the studies examined estimate the expansion potential of hydropower at only a few terawatt hours per year.

This study examines the interaction of production types and shows how the winter electricity gap changes in the four expansion scenarios. From the results, a requirement profile for an energy storage system can be derived, with which the winter electricity gap can be covered. Depending on the scenario, the storage system requires a capacity of between 2 and 19 TWh and only performs only a few discharge cycles per year.

The round-trip efficiency of the storage system has a decisive influence on the energy system because the losses increase the necessary energy to charge the storage. As things stand today, a handful of technologies can be considered for such an application, but many research projects are underway. If Switzerland wants to reduce its independence from foreign electricity, a storage portfolio like the production portfolio will be necessary in the future to compensate for the lack of flexibility of renewables.

The electricity consumption in Switzerland will grow in the future. However, as the inefficient fossil fuels are replaced, the total energy consumption will decrease. The energy transition offers Switzerland enormous opportunities for the environment, but also for the economy, the workforce and the research location. Technologically, all the necessary means for the energy transition are available; what is critical are the political decisions. We should use our influence in all areas and tackle the opportunities of change.

This study provides the methodology and a solid data basis for further optimization tasks of the electricity system in Switzerland.

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Appendix

Agreed scope of Work

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Lucerne University of Applied Sciences and Arts
HOCHSCHULE LUZERN
Engineering and Architecture

Energy Systems Engineering

Bachelor Thesis Agreed Scope of Work

Student name: Raffael Balzarini
Tel.: 079 852 08 76
E-mail: raffael.balzarini@stud.hslu.ch

The student is responsible for the definition of the scope of work. It must be reviewed and signed by the coach and the industry partner and prior to its submission.

1. Project title

Expansion of renewable energies and energy storage on the winter energy supply

2. Technical theme

Renewable energies, energy storage, energy systems, systems modelling

3. Background

The "Winterstromlücke" in Switzerland is an important issue for Switzerland's energy system in the future. In combination with the goal of net-zero emissions by 2050, which creates incentives for the expansion of renewable energies and the electrification of the heat and mobility sectors, the question arises how different renewable technologies such as photovoltaics, wind power, and the increased use of heat pumps and electric vehicles will affect the winter electricity gap. Will the deployment of a particular technology help reduce the gap or will the gap widen? One solution to the winter power gap currently under discussion is seasonal energy storage. Together with the expansion of renewable energy, this raises the question of the energy potential that can be shifted from summer to winter.

4. Project aim

The target of this project is to perform a situation analysis of Switzerland`s energy supply and demand today and in the future and determine the potential for energy storage options.

5. Project objectives

1. Creating a situation analysis of Switzerland`s energy supply and demand (electricity portfolio and heating energy).
2. Defining possible scenarios in the development of energy supply and demand until 2050.
3. Determining the potential for energy storage within the evaluated system of supply & demand.
4. Evaluating the system by variating different technologies. Are there synergies? Are there elements in the system, that can influence the system disproportional? How should the system look to deliver a secure energy supply over the year?

Page 2 of 3
Agreed Scope of Work

Hochschule Luzern
Engineering and Architecture

6. Project classification *(choose one option)*

- ☒ Open with internet selection (content visible to all)
- ☐ Open without internet selection (title and abstract visible to all, content accessible for users with HSLU account)
- ☐ Internal (title and abstract visible to users with HSLU account, content only accessible for authorized persons)
- ☐ Confidential (visible only for authorized persons)

7. Agreed industrial deliverables

- Academic Report
- Energy system simulation
- (Optional, if time allows: interactive simulation platform to analyse different scenarios)

The industrial deliverables must be provided to the industry partner in the form requested.

8. Academic deliverables

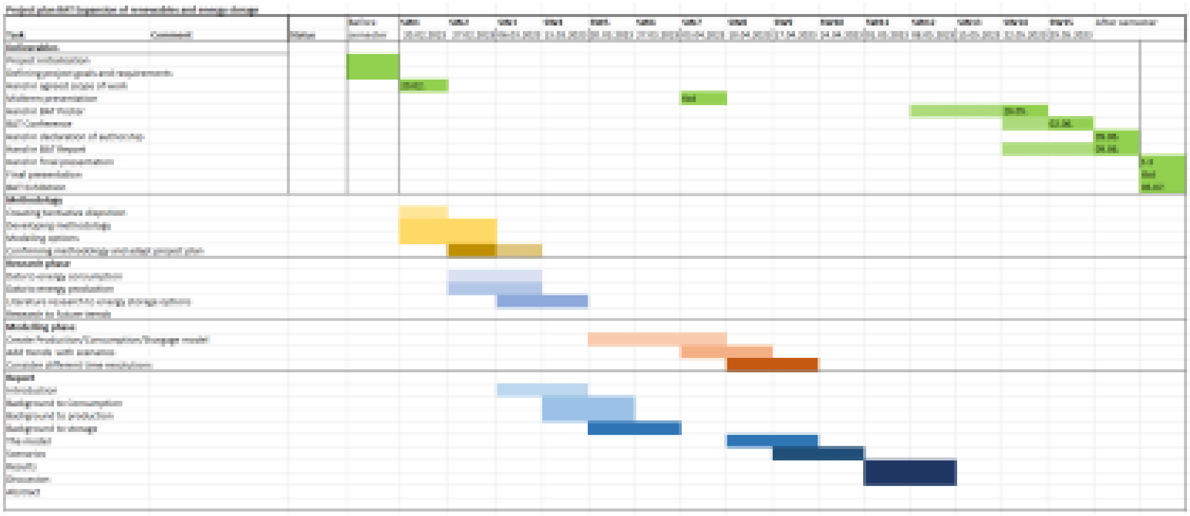
The following documents are to be submitted electronically on elearning.hslu.ch:

- BAT Agreement (pdf) >> Remove in case of T&A internal projects & startups (i.e. founded within the last 5 years or up to kCHF 700 turnover)
- Report (pdf) and appendices/relevant documents such as presentations, measurement data, programs, evaluations, calculations, excel sheets, etc. The first page of the report must be the official title page.
- Declaration of authorship (pdf)
- Poster (pdf and ind)
- Release confirmation for the poster (pdf) >>Remove in case of T&A internal project
- Final presentation (ppt/pdf)

The detailed documentation requirements, submission dates and instructions for the submission can be found on elearning.hslu.ch.

Failure to deliver the documents on the required dates will cause the project to be graded as "F".

9. Project milestone schedule



10. Additional comments

All documents provided by the client have to be handled in a confidential manner.

Page 3 of 3
Agreed Scope of Work

Hochschule Luzern
Engineering and Architecture

11. Industry partner

Firm: CC Business Engineering
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13. Expert

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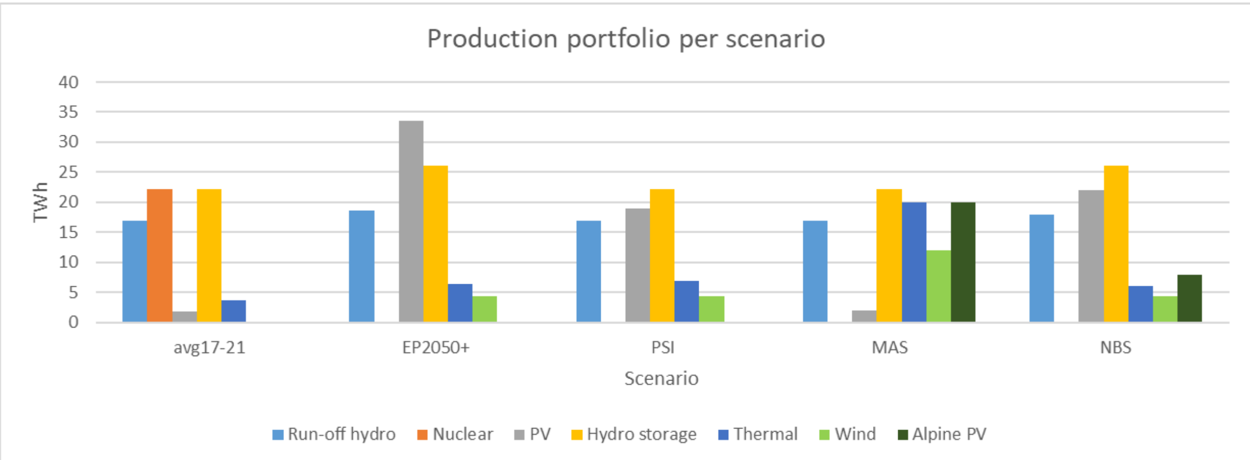
E-mail: orlando.gehrig@swisspower.ch

14. Signatures

Raffael Balzarini

Coach | Student | Industry Partner

Scenario numerical input tables



ScenarioProduction portfolio [TWh]											
Scenario	Run-off hyd	Nuclear	PV	Hydro stor	Thermal	Wind	Alpine PV	Expansion costs	Storage costs	Total import	System cost
avg17-21	17	22.2	1.8	22.2	3.7	0.1	0				
EP2050+	18.55	0	33.61	26.13	6.41	4.32	0	6.8	7.7	3.61	14.5
PSI	17	0	19	22.2	6.9	4.3	0	3.9	13.9	6.48	17.7
MAS	17	0	2	22.2	20	12	20	9.7	1.2	0.54	10.9
NBS	18	0	22	26	6	4.4	8	6.0	7.6	3.53	13.6

Expansion costs: LCOE of expanding from avg17-21 to the scenario.
Storage costs: Total LCOS to cover the complete winter electricity gap with storage.

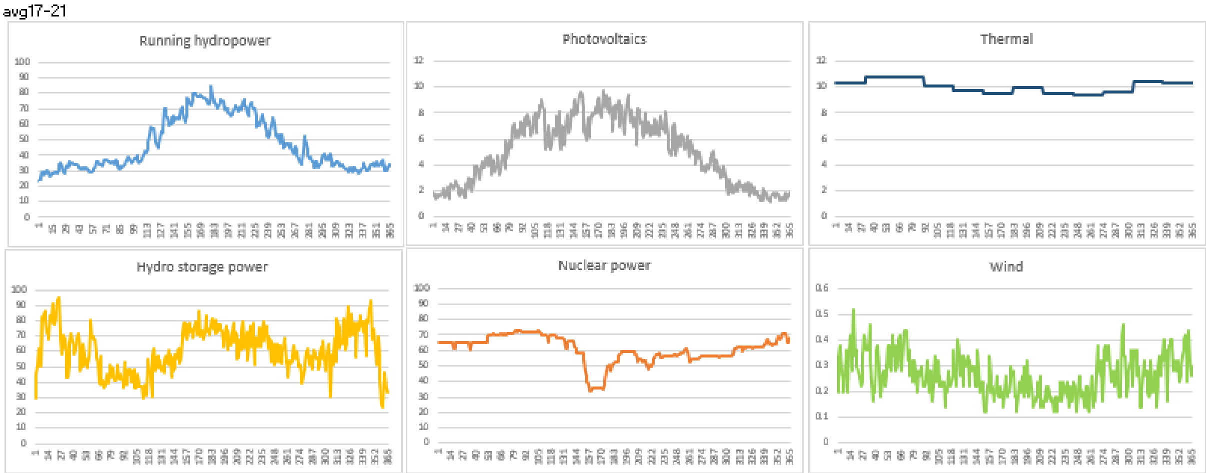
Import costs: Total costs of covering the winter electricity gap with imported electricity at a price of 34 RP/kWh (2022).

Required expansion compared to avg17-21 [TWh]								
	Scenario	Run-off hyd	Nuclear	PV	Hydro stor	Thermal	Wind	Alpine PV
	EP2050+	1.55	0	31.81	3.93	2.71	4.22	0
	Costs	325500000	0	4.14E+09	8.25E+08	9.08E+08	5.7E+08	0
	PSI	0	0	17.2	0	3.2	4.2	0
	Costs	0	0	2.24E+09	0	1.07E+09	5.67E+08	0
	MAS	0	0	0.2	0	16.3	11.9	20
	Costs	0	0	26000000	0	5.46E+09	1.61E+09	2.6E+09
	NBS	1	0	20.2	3.8	2.3	4.3	8

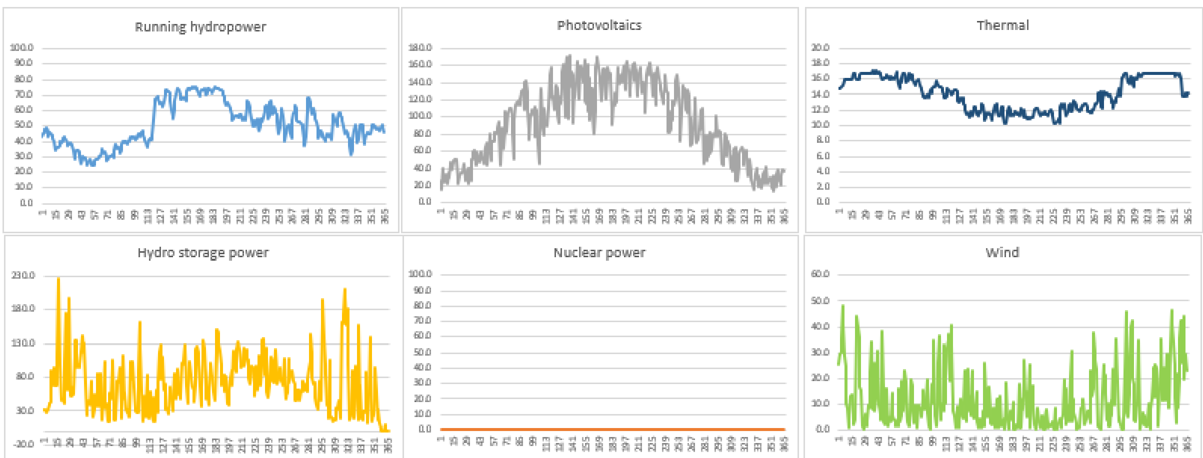
LCOE		Run-off hyd	Nuclear	PV	Hydro stor	Thermal	Wind	Alpine PV
[CHF/kWh]		0.21	0	0.13	0.21	0.34	0.135	0.13
For new build plant in CH								

Comparison of avg17-21 and EP2050+ production profiles

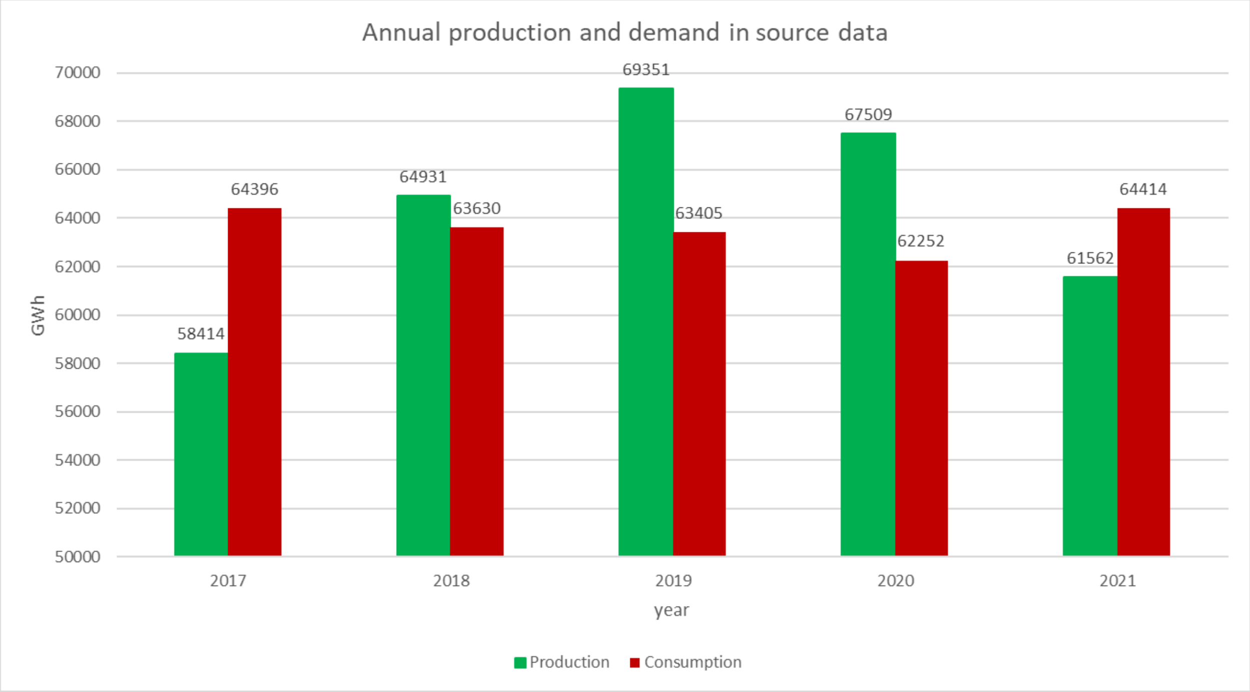
avg17-21



EP2050+



Comparison of production and consumption variance in averaged data

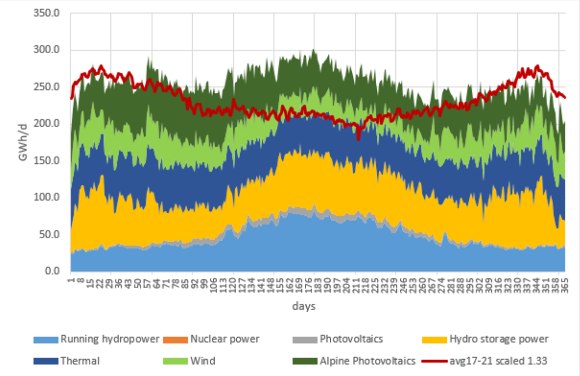


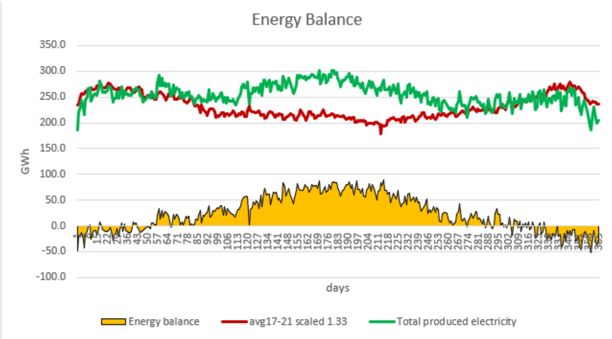
Interactive energy system model: Screenshot and explanation

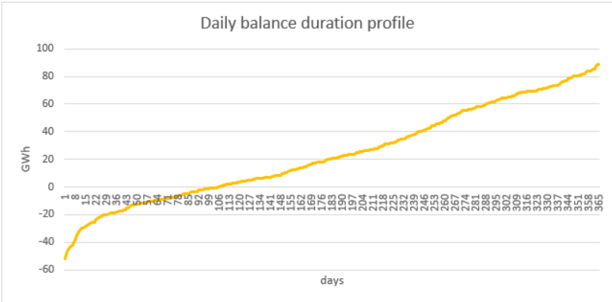
The file "Switzerland electricity simulation.xlsx" is used to model different scenarios and generates automated results.

Enter input in the orange fields

	Flusskraft	Kernkraf	Photovoltail	Speicherkraf	Thermisch	Wind	Alpine PV
	TWh/a	TWh/a	TWh/a	TWh/a	TWh/a	TWh/a	TWh/a
avg17-21	17.0	22.2	1.8	22.2	3.7	0.1	0.0
Scenario capacity	17.0	0	2.0	22.2	20	12	20
new TWh/a	0.0	-22.2	0.2	0.0	16.3	11.9	20.0
change	0%	-100%	9%	0%	446%	12473%	100%







Scenario results, yearly evaluation		
Total electricity production	93.2	[TWh]
Total electricity balance	8.8	[TWh]
Surplus period		
Number of surplus days	259	[d]
Total surplus	10371	[GWh]
Average daily electricity balanc	40.0	[GWh]
Maximal daily balance	88.6	[GWh]
Minimal daily balance	0.7	[GWh]
Standard deviation	26.1	[GWh]
Shortage period		
Number of shortage days	106	[d]
Total shortage	-1584	[GWh]
Average daily electricity balanc	-14.9	[GWh]
Maximal daily balance	-0.2	[GWh]
Minimal daily balance	-52.0	[GWh]
Standard deviation	12.0	[GWh]

Scenario data							
avg17-21	17	22.2	1.8	22.2	3.7	0.1	0
EP2050+	18.6	0.0	33.6	26.1	6.4	4.3	0
PSI	17.0		19	22.19	6.9	4.3	0
Max autar	17.0	0	2	22.2	20	12	20
balanced	18	0	22	26	6	4.4	8

Data sources – used and processed data

All processed data and generated plots are available in the “Production and demand daily.xlsx” file.

Sheet	Title	Content
1	01 Overall plot	Combined Production and Demand diagrams - avg17-21 model
2	02 Production plot	avg17-21 production, production profiles and comparison to EP2050+ profiles
3	03 Demand plot	Demand plot, demand scaled and compared to EP2050+
4	04 Gap plot	Electricity balance for year, months and weeks
5	05 Hourly resolution balance	Plot of 1 chosen calendar week, electricity balance on hourly resolution
6	06 Energy Balance	Energy balance, daily values to weekly and monthly overview
7	07a Gap by day	Electricity gap daily, rearranged data from sheet 7
07a	07 Gap by year	Production and Consumption Values 17-21 in comparison, hourly resolution for balance calculation
8	08 Total production	avg17-21 production data, Swissgrid source
9	09 Production by type	avg17-21 production profile, energy dashboard source
10	10 Total consumed	avg17-21 gross-consumed electricity
11	11 End-consumed	avg17-21 end-consumed electricity
12	Input data for "Switzerland electricity system simulation	
13	RAW Total consumed	Source data gross consumed electricity
14	RAW End-consumer	Source data end consumed energy
15	RAW Total produced	Source data produced electricity
16	RAW Production by type	Source data electricity production by source

Example: sheet 09

G7 =SUMIFS($C$7:$C10956;$E$7:$E10956;$F7;$B$7:$B10956;G$6)/5

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
						Running hydro	Nuclear powe	Photovoltaics	Hydro storage pc	Thermal	Wind	Sum [TWh]			
					Sum TWh	17.0	22.2	1.8	22.2	3.7	0.1	67.0			
ogd104_stromproduktion_swissgrid					Sum GWh	17037	22165	1834	22190	3661	95	Production [GWh]			
Schaltjahr - 29.02.2020 gelöscht					Days 1-365	GWh	GWh	GWh	GWh	GWh	GWh	GWh			
Datum	Energietraeger	Produktion_GWh	Datum	Nr of day in year		Flusskraft	Kernkraft	Photovoltaik	Speicherkraft	Thermische	Wind	Summe		"Date"	Calendar week
01.01.2017	Flusskraft	15.7	01.01.2017	1	1	23.6	64.82	1.94	29.74	10.3	0.2	130.6		01.01.2021	1
01.01.2017	Kernkraft	41.8	01.01.2017	1	2	24.08	64.94	1.54	44.86	10.3	0.34	146.1		02.01.2021	1
01.01.2017	Photovoltaik	1.9	01.01.2017	1	3	25.42	65.28	1.64	49.62	10.3	0.38	152.6		03.01.2021	2
01.01.2017	Speicherkraft	34.8	01.01.2017	1	4	29.12	65.26	1.32	61.58	10.3	0.36	167.9		04.01.2021	2
01.01.2017	Thermische	10.3	01.01.2017	1	5	29.32	65.22	1.46	56.74	10.3	0.28	163.3		05.01.2021	2
01.01.2017	Wind	0.1	01.01.2017	1	6	26.8	65.3	1.72	50.2	10.3	0.24	154.6		06.01.2021	2
02.01.2017	Flusskraft	17.8	02.01.2017	2	7	28.34	65.2	1.72	82	10.3	0.2	187.8		07.01.2021	2
02.01.2017	Kernkraft	41.8	02.01.2017	2	8	28.86	65.24	1.58	80.62	10.3	0.26	186.9		08.01.2021	2
02.01.2017	Photovoltaik	1.4	02.01.2017	2	9	30.5	65.26	1.72	84.5	10.3	0.34	192.6		09.01.2021	2
02.01.2017	Speicherkraft	57	02.01.2017	2	10	29.46	65.26	1.64	86.04	10.3	0.36	193.1		10.01.2021	3
02.01.2017	Thermische	10.3	02.01.2017	2	11	28.22	65.32	2.1	80.66	10.3	0.2	186.8		11.01.2021	3
02.01.2017	Wind	0.1	02.01.2017	2	12	26.44	65.1	1.44	71.18	10.3	0.36	174.8		12.01.2021	3
03.01.2017	Flusskraft	19.4	03.01.2017	3	13	27	65.26	1.58	74.46	10.3	0.36	179.0		13.01.2021	3
03.01.2017	Kernkraft	41.8	03.01.2017	3	14	27.88	65.28	1.52	67.9	10.3	0.42	173.3		14.01.2021	3
03.01.2017	Photovoltaik	1.7	03.01.2017	3	15	27.94	65.32	1.94	81.04	10.3	0.28	186.8		15.01.2021	3
03.01.2017	Speicherkraft	79.5	03.01.2017	3	16	28.28	65.28	2.32	83.82	10.3	0.36	190.4		16.01.2021	3
03.01.2017	Thermische	10.3	03.01.2017	3	17	28.76	61.14	1.38	80.02	10.3	0.52	182.1		17.01.2021	4
03.01.2017	Wind	0.2	03.01.2017	3	18	29.64	61.7	2.08	90.74	10.3	0.34	194.8		18.01.2021	4
04.01.2017	Flusskraft	21.6	04.01.2017	4	19	29.24	65.26	2.46	78.44	10.3	0.34	186.0		19.01.2021	4
04.01.2017	Kernkraft	41.8	04.01.2017	4	20	28.1	65.36	2.36	77.52	10.3	0.36	184.0		20.01.2021	4
04.01.2017	Photovoltaik	1.1	04.01.2017	4	21	30.12	65.32	2.26	81.32	10.3	0.3	189.6		21.01.2021	4
04.01.2017	Speicherkraft	85.3	04.01.2017	4	22	33.7	65.22	2.2	84.84	10.3	0.28	196.5		22.01.2021	4
04.01.2017	Thermische	10.3	04.01.2017	4	23	34.56	65.32	2.4	92.98	10.3	0.26	205.8		23.01.2021	4
04.01.2017	Wind	0.4	04.01.2017	4	24	33.22	64.94	2.76	94.92	10.3	0.26	206.4		24.01.2021	5
05.01.2017	Flusskraft	20.7	05.01.2017	5	25	32.44	65.3	2.54	94.76	10.3	0.22	205.6		25.01.2021	5
05.01.2017	Kernkraft	41.7	05.01.2017	5	26	29.48	65.34	2.22	72.16	10.3	0.24	179.7		26.01.2021	5
05.01.2017	Photovoltaik	1.1	05.01.2017	5	27	28.26	65.3	1.76	69.12	10.3	0.34	175.1		27.01.2021	5
05.01.2017	Speicherkraft	77.1	05.01.2017	5	28	30.04	65.18	1.62	57.4	10.3	0.42	165.0		28.01.2021	5
05.01.2017	Thermische	10.3	05.01.2017	5	29	32.76	65.18	2.18	70.88	10.3	0.38	181.7		29.01.2021	5
05.01.2017	Wind	0.3	05.01.2017	5	30	32.4	65.16	1.78	61.62	10.3	0.36	171.6		30.01.2021	5
06.01.2017	Flusskraft	18.4	06.01.2017	6	31	32.88	64.98	2	68.32	10.3	0.36	178.8		31.01.2021	6
06.01.2017	Kernkraft	41.8	06.01.2017	6	32	35.58	65.1	1.5	61	10.8	0.38	174.4		01.02.2021	6
06.01.2017	Photovoltaik	2	06.01.2017	6	33	33.26	64.18	1.74	42.72	10.8	0.36	153.1		02.02.2021	6
06.01.2017	Speicherkraft	60.9	06.01.2017	6	34	34.96	60.16	1.48	43.44	10.8	0.46	151.3		03.02.2021	6
06.01.2017	Thermische	10.3	06.01.2017	6	35	35.46	60.84	2.52	51.48	10.8	0.32	161.4		04.02.2021	6
06.01.2017	Wind	0.3	06.01.2017	6	36	34.72	64.66	2.42	65.74	10.8	0.24	178.6		05.02.2021	6
07.01.2017	Flusskraft	19.1	07.01.2017	7	37	34.32	64.88	2.96	71.94	10.8	0.16	185.1		06.02.2021	6
07.01.2017	Kernkraft	41.8	07.01.2017	7	38	33.86	65.12	2.12	67.14	10.8	0.22	179.3		07.02.2021	7
07.01.2017	Photovoltaik	1.5	07.01.2017	7	39	34.02	65.04	2.9	66.26	10.8	0.2	179.2		08.02.2021	7
07.01.2017	Speicherkraft	68	07.01.2017	7	40	33.58	65.02	2.84	63.44	10.8	0.32	176.0		09.02.2021	7
07.01.2017	Thermische	10.3	07.01.2017	7	41	32.76	64.94	1.94	58.14	10.8	0.36	168.9		10.02.2021	7
07.01.2017	Wind	0.1	07.01.2017	7	42	32.3	65.12	2.52	60.58	10.8	0.38	171.7		11.02.2021	7
08.01.2017	Flusskraft	18.5	08.01.2017	8	43	31.86	65.12	3.22	67.58	10.8	0.3	178.9		12.02.2021	7
08.01.2017	Kernkraft	41.7	08.01.2017	8	44	31.18	65.14	3.92	68.54	10.8	0.28	179.9		13.02.2021	7
08.01.2017	Photovoltaik	0.9	08.01.2017	8	45	30.68	65.1	3.88	71.58	10.8	0.18	182.2		14.02.2021	8
08.01.2017	Speicherkraft	55.5	08.01.2017	8	46	31	65.06	3.58	62.5	10.8	0.24	173.2		15.02.2021	8
08.01.2017	Thermische	10.3	08.01.2017	8	47	31.72	64.84	3.64	47.2	10.8	0.26	158.5		16.02.2021	8
08.01.2017	Wind	0.2	08.01.2017	8	48	31.6	65.12	2.82	50.02	10.8	0.28	160.6		17.02.2021	8
09.01.2017	Flusskraft	20.3	09.01.2017	9	49	31.68	65.02	3.9	49.56	10.8	0.28	161.2		18.02.2021	8
09.01.2017	Kernkraft	41.7	09.01.2017	9	50	31.56	64.98	3.72	64.28	10.8	0.22	175.6		19.02.2021	8
09.01.2017	Photovoltaik	1.8	09.01.2017	9	51	31.24	65.42	4.26	58.12	10.8	0.26	170.1		20.02.2021	8
09.01.2017	Speicherkraft	111.6	09.01.2017	9	52	30.18	69.36	3.8	51.1	10.8	0.3	165.5		21.02.2021	9
09.01.2017	Thermische	10.3	09.01.2017	9	53	29.5	69.98	3.8	55.28	10.8	0.38	169.7		22.02.2021	9
09.01.2017	Wind	0.1	09.01.2017	9	54	28.82	70.28	4.02	49.48	10.8	0.38	163.8		23.02.2021	9
10.01.2017	Flusskraft	21.7	10.01.2017	10	55	29.32	70.2	4.52	50.78	10.8	0.3	165.9		24.02.2021	9
10.01.2017	Kernkraft	41.7	10.01.2017	10	56	29.32	69.7	4.58	55.16	10.8	0.28	169.8		25.02.2021	9
10.01.2017	Photovoltaik	0.7	10.01.2017	10	57	30.1	70.5	4.3	72.14	10.8	0.36	188.2		26.02.2021	9
10.01.2017	Speicherkraft	117	10.01.2017	10	58	31.46	70.48	3.92	80.16	10.8	0.42	197.2		27.02.2021	9
10.01.2017	Thermische	10.3	10.01.2017	10	59	31.66	70.42	4.76	68.7	10.8	0.34	186.7		28.02.2021	10
10.01.2017	Wind	0.2	10.01.2017	10	60	34.72	70.44	3.62	70.1	10.8	0.38	190.1		01.03.2021	10
11.01.2017	Flusskraft	22	11.01.2017	11	61	35.6	70.44	3.24	67.78	10.8	0.28	188.1		02.03.2021	10
11.01.2017	Kernkraft	41.7	11.01.2017	11	62	35.62	70.46	4.36	68.16	10.8	0.3	189.7		03.03.2021	10
11.01.2017	Photovoltaik	1.5	11.01.2017	11	63	34	70.38	3.82	58.6	10.8	0.34	177.9		04.03.2021	10

04 Gap plot | 05 Weekly Gap | 06 Energy Balance | 07 Gap by year | 07a Gap by day | 08 Total production | 10 Total consumed | 09 Production by type | 11 End-cons