ETH zürich

ETH Library

Security of Electricity Supply in Switzerland

What can demand-side flexibility in the industry sector contribute?

Master Thesis

Author(s):
Federer, Lukas

Publication date:
2022-08-24

Permanent link:
https://doi.org/https://doi.org/10.3929/ethz-b-000595391

Rights / license:
In Copyright - Non-Commercial Use Permitted

This page was generated automatically upon download from the ETH Zurich Research Collection.
For more information, please consult the Terms of use.

SECURITY OF ELECTRICITY SUPPLY IN SWITZERLAND

What can demand-side flexibility in the industry sector contribute?

Master's thesis

MAS ETH in Applied Technology
Supervisor: Dr. Christian Schaffner
Advisor: Dr. Marius Schwarz
24.08.2022

ETH zürich

Lukas Federer
08-058-547

Content

Abstract

This thesis investigates how and to what extent the flexibility of the Swiss industry can contribute to security of electricity supply in a winter shortage scenario in 2030. A mixed methods approach is used to bring an individualistic company perspective and the systemic perspective together and to give a broad overview of the topic. Evidence from a literature review, anecdotal evidence from semi-structured interviews with industry stakeholders and a system modelling analysis with the Nexus-e platform produce a wide spectrum of insights: Defining industry flexibility is complex and the realizable potential may be small. Industry companies and other stakeholders name many limitations to leveraging more flexibility potential, either technical or socio-economic. Lastly, the Nexus-e analysis indicates that industry flexibility may contribute to security of supply winter shortage situations via load shedding, but never to the extent that additional generation capacities (gas power plants) can be fully replaced. According to these findings, this thesis concludes that electricity flexibility from industry consumers is unfortunately no panacea for a winter scenario with a structural electricity deficit over longer periods of time. Flexibility can only be part of a mix of measures that increases seasonal resilience of the Swiss electricity system. To foster industry flexibility measures and to find its optimal role in the electricity system of the future, further research and policy action is advisable.

List of Figures

1. Introduction

1.1 Motivation

Historically, electrification in Switzerland has been closely linked to the development of industry sites and industrial production. In its infancy, the Swiss electricity system, meaning power plants and grids, was in large parts built by private sector companies.[1] In many cases, these companies were not mainly electricity companies or utilities, but rather large industry consumers who aimed to secure their own energy supply. There are numerous interesting examples of this: In the canton of Wallis, the chemical company Lonza started operating in 1897 after it received the usage rights to build hydro power plants in order to satiate the energy hunger of its carbide production.[1] Over decades, the abundance of cheap, secure electricity helped Lonza to grow into an international corporation. The company ultimately built and owned a large portion of the electricity production and distribution in the canton of Wallis. Beginning in the Eighties and Nineties of the 20th century, these assets were gradually sold to the public sector and foreign investors, as electricity was no longer a scarce and expensive production factor, but had become a relatively cheap, internationally traded commodity.[2][3] In a similar fashion, the electrical engineering company Brown Boveri & CIE (later ABB) helped to finance and build a large hydro power plant on the river Limmat before establishing its main production facilities in Baden in 1891.[5]

As these anecdotes indicate, access to electricity was once a key success factor for the development of the industrial sector in Switzerland. With structural changes in the economy during the 20th century, most notably the commoditization of electricity and the integration of the European grid, but also the slow decline of primary industries in Europe and the emergence of the service sector, manufacturing companies in Switzerland became less and less worried about the availability and price of their electricity. It was only after the energy crises in the 1970s that demand-side measures for grid and system stability and energy efficiency became relevant considerations.[6][7] The issue of decarbonization and the transition towards clean energy later emphasized the focus on these topics. In addition, it became clear that the volatility of production in a carbon-free electricity system without a reliable base load would require a great deal of demand-side measures.[2] The implications for the industrial sector in Switzerland today are twofold: On the one hand, the future electricity supply will no longer unilaterally serve demand, but demand will also have to contribute to system and grid stability. This will likely make prices and availability more volatile and raise questions about how manufacturing companies can secure their supply as well as control their energy costs. On the other hand, the uncertainties may also open up new opportunities. Industry sites and other large and small consumers may offer demand flexibility on the market and thus contribute to both system and

[2] For example, Moura & de Almeida (2010) [8] explain this for market integration of wind power.

grid stability. This, in turn, could result in far-reaching implications for production set ups and business models in the industry sector. Ultimately, from the perspective of Swiss companies, electricity at the beginning of the 21st century seems to be back to what it was for the industry in the 19th century: Not a minor consideration or a commodity, but rather a key concern for site selection and business continuity.

1.2 Relevance of electricity flexibility

With the increasing deployment of renewable energy sources and the shift towards a carbon-free energy consumption, demand side integration and especially demand response become increasingly important tools to address the resulting challenges for electricity systems and grids. The International Renewable Energy Agency IRENA "suggests that by 2050, globally around 61% of electricity could be supplied by variable renewable energy sources like solar and wind power."[9] Moreover, the International Energy Agency IEA estimates, that in a Net Zero Emissions by 2050 scenario, 15% of average annual electricity demand will have to be shiftable and that therefore, demand side integration, demand side management and demand response become crucial.[10]

In the literature, flexible loads are mentioned as an important demand side resource.[11] Flexibility is defined in different ways, depending on the perspective. From a systemic viewpoint, demand side flexibility "refers to the portion of demand in the system (including via electrified heat and transport) that can be reduced, increased or shifted within a specific duration"[9], meaning that it includes power capacities (portion of demand) as well as an amount electricity (duration). Fattahi Meyabadi & Deihimi (2017) [57] mention flexibility in their general framework of demand side management. They make the neat distinction between strategic electricity load management, which aims to avoid electricity shortages, and dynamic electricity load management, which aims to deal with peak load and even out consumption. From the perspective of the individual consumers, energy flexibility means something different. One source describes it as "the deviation to the planned consumption, generation and use of storage, in response to price signals or instruction, on residential, commercial or industrial sites"[12]. More specifically for the industry sector – the relevant viewpoint in the context of this thesis - flexibility can be defined as "the ability of a production system to adapt quickly and in a process-efficient way to changes in the energy market"[13]. So, in addition to the technical factors (*what* and *how much* demand can be shifted, increased or reduced), industry consumers care about the security of energy supply, adaptability to market conditions and business continuity when thinking about flexibility. This thesis will address both views, the systemic one and the individualistic one (companies) as they are not mutually exclusive and tend to have a certain overlap.

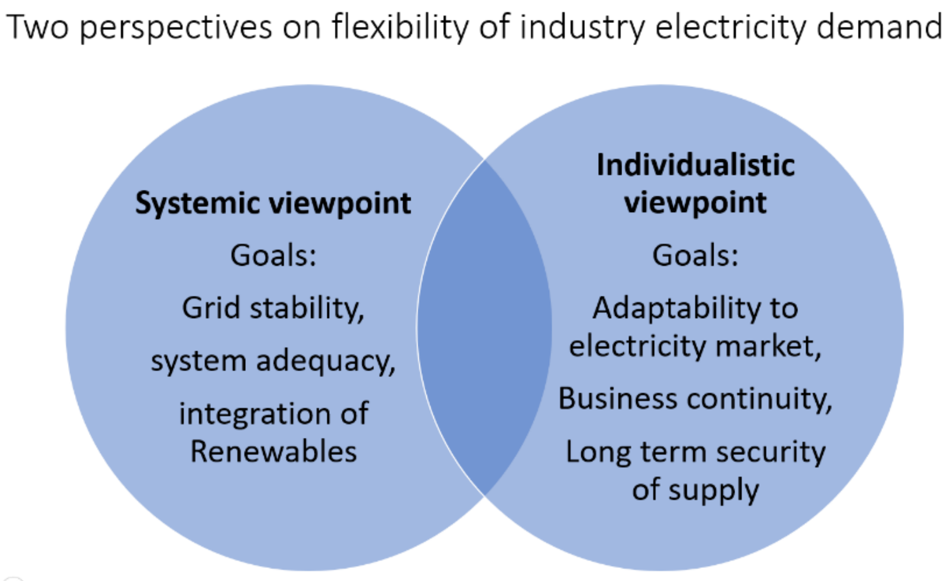


Figure 1: Two perspectives on flexibility of industry electricity demand.

From the systemic viewpoint, flexibility and other demand side resources ultimately serve the purpose of maintaining grid stability, meaning the balancing between consumption and generation as indicated by the grid frequency and the power flows.[14] In this regard, flexibility contributes to system adequacy, i.e. "the ability of a power system to supply the load in all the steady states in which the power system may exist considering standards conditions."[15] With the imperative of decarbonization and more volatile generation patterns from Renewables, system adequacy is increasingly becoming a challenge.

When it comes to flexibility, there are also different timescales to consider. Peak load can occur during milliseconds, seconds or minutes while electricity shortages may happen over hours, days, weeks, months or even years. Time scales up to 15 minutes are covered by ancillary services of the grid operators (primary, secondary and tertiary stages).[16] These short timeframes are important but are not the main focus of this thesis. Instead, this thesis will focus on longer durations, which is less about peak load and more about providing enough electricity to avoid lasting shortages, a particularly important consideration for the future of the Swiss electricity system: balancing between day and night and more importantly between summer and winter season. Such scenarios imply load shifting or shedding over hours, days, weeks, months or years.

The 2050+ energy perspectives, published by SFOE, estimate that electricity production from photovoltaics may increase to 33.6 TWh per year by 2050 (more than half of an estimated yearly consumption of 62.2 TWh).[17] These capacities will be subject to considerable seasonal volatility. During the winter months, the volatility will have to be compensated with hydro power generation or other base load generation capacities, complemented by seasonal storage such as hydrogen, with increased energy efficiency and last but not least with flexibility options. This thesis will distinguish flexibility options from industry consumers for short durations and for longer durations and will focus on the latter. There are however interdependencies between the two and the transition is not clear-cut.

Distinction between time horizons for flexible industry electricity demand in this thesis	
Short durations	**Longer durations**
▪ Cause: Peak Load ▪ Durations: Up to 15 minutes ▪ Instruments: Ancillary services to stabilize the grid	▪ Cause: electricity shortages ▪ Durations: hours, days, months, years ▪ Instruments: Load shifting or shedding to reduce demand

Figure 2: Distinction between time horizons for flexible industry electricity demand in this thesis.

Historically, Switzerland is a net exporter of electricity. In the winter season however, it has imported an average of about 4.5 TWh over the past years with a peak 9.7 TWh in the winter of 2016/2017.[18] A lack of sufficient generation capacities, political woes with the EU and insufficient export capabilities in our neighboring countries may become a serious threat to Switzerland in future winters. This was shown in a recent system adequacy study conducted by the Federal Electricity Commission (ElCom) and Swissgrid.[19] Moreover, SFOE, in an addendum the 2050+ energy perspectives, argue that the Swiss import deficit in winter could amount to as much as 16 TWh until 2035 under unfavorable conditions.[20] Flexibility options will play an important role in dealing with these future challenges.

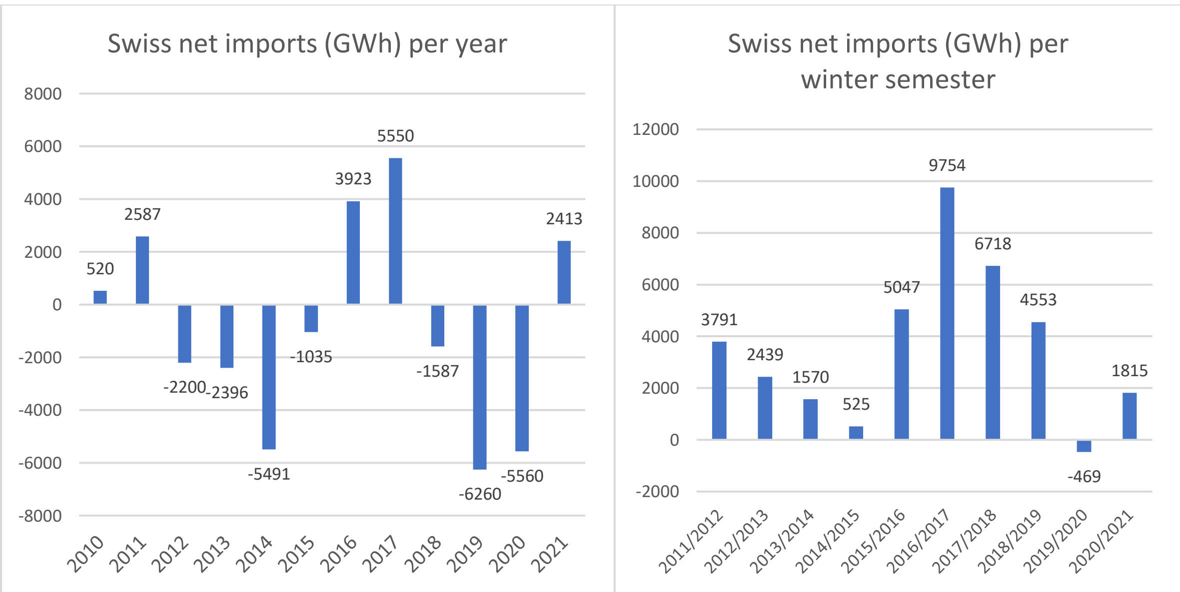


Figure 3: Swiss net imports (GWh) per year and Swiss net imports (GWh) per winter semester, based on [18].

1.3 Swiss industry demand

The electricity demand of the Swiss industry sector is assessed differently in different sources. According to the main energy and electricity statistics by SFOE, in 2021, the industry and manufacturing sector was responsible for 19.4% of final energy consumption (153'430 TJ) and 30% (16.7 TWh) of electricity consumption in Switzerland.[18][21] Other sources estimate electricity consumption of the industry sector at 13.4 TWh.[3] While these shares are still significant, they have slowly declined over the past decades, as the following graph shows for electricity:

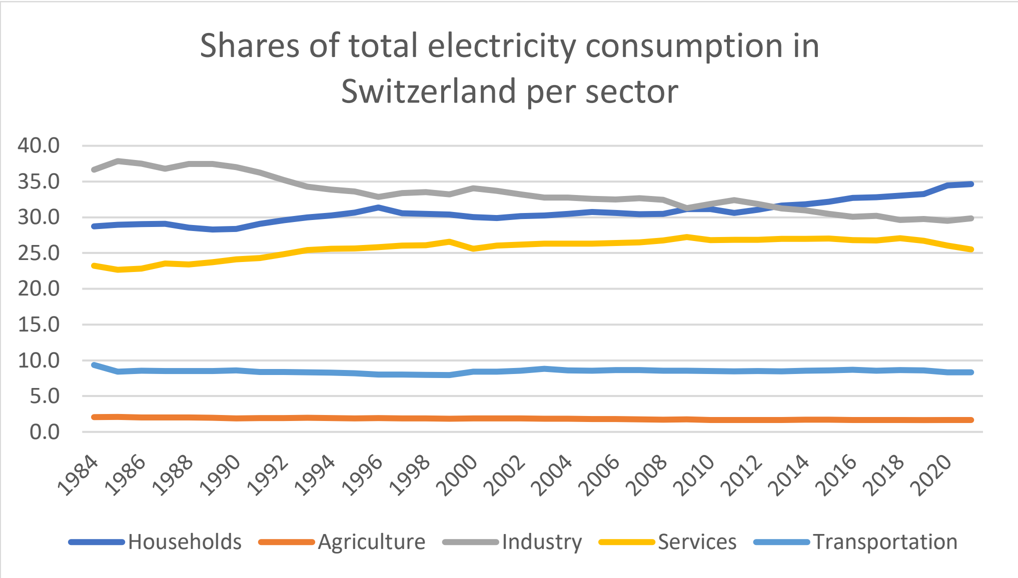
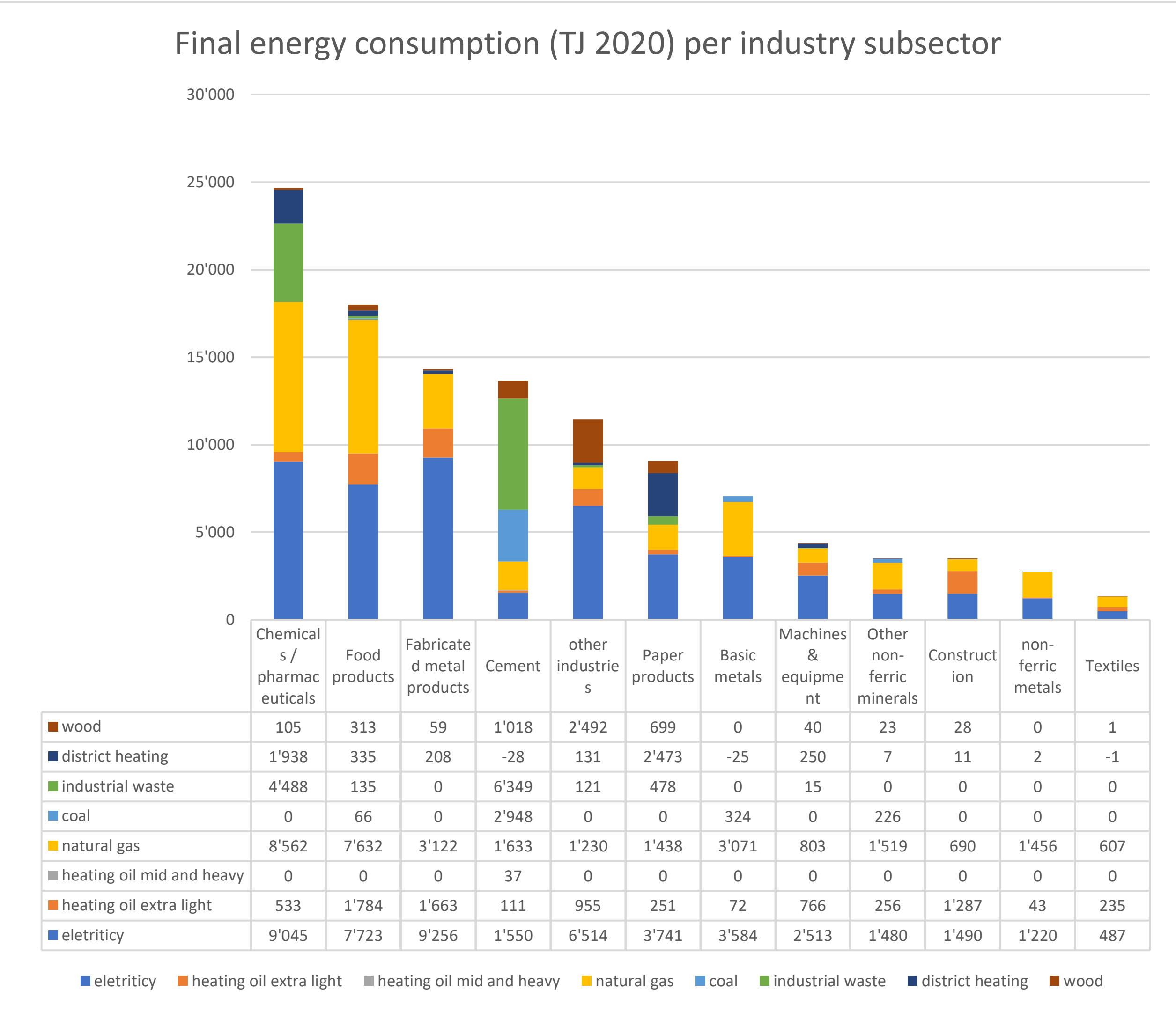


Figure 4: Shares of total electricity consumption in Switzerland per sector, based on [18].

This is in line with two well-known trends: On the one hand, industry consumers are becoming more and more energy efficient. Over the past years, energy consumption per GDP has continually decreased and the energy intensity of the Swiss economy is generally significantly lower than the OECD-average.[23] On the other hand, the overall economic contribution of the industry sector has decreased in favor of the tertiary sector (services). This development is in line with the long-term structural changes that can be observed in almost all developed economies. Emerging countries such as China or India on the other hand still have significantly higher energy intensity because of their higher share of (heavy) industry.[24] Low energy intensity and low output share of industry are properties of the Swiss economy will be relevant for the following analysis because they have direct implications on the electricity flexibility potential.

[3] SFOE uses two different methodologies for assessing overall industry demand. The numbers used in this thesis are based on a representative sample of 13'000 companies and production facilities which are extrapolated for 19 subsectors of industry and services. This approach does not fully consider self-produced electricity from other energy sources.[22] It is however more practical for the purpose of this thesis, because it allows a look at specific subsectors. The second approach (as used in [21]) is based on data from several hundred utilities. It therefore represents the view of the energy suppliers more than that of the consumers.

This thesis builds on the classification of the industry sector into twelve subsectors used by SFOE.[22] Figures 5 to 7 show the total energy consumption of these subsectors in Terajoules as well as the electricity-share of their energy consumption in percent. The chemical and pharmaceutical industry is evidently the biggest energy consumer in the Swiss industry sector, but it also has one of the lower shares of electricity consumption. The subsectors with relatively high overall energy demand and high shares of electricity demand are basic metals, fabricated metal products and machines & equipment.



	Chemicals / pharmaceuticals	Food products	Fabricated metal products	Cement	other industries	Paper products	Basic metals	Machines & equipment	Other non-ferric minerals	Construction	non-ferric metals	Textiles
wood	105	313	59	1'018	2'492	699	0	40	23	28	0	1
district heating	1'938	335	208	-28	131	2'473	-25	250	7	11	2	-1
industrial waste	4'488	135	0	6'349	121	478	0	15	0	0	0	0
coal	0	66	0	2'948	0	0	324	0	226	0	0	0
natural gas	8'562	7'632	3'122	1'633	1'230	1'438	3'071	803	1'519	690	1'456	607
heating oil mid and heavy	0	0	0	37	0	0	0	0	0	0	0	0
heating oil extra light	533	1'784	1'663	111	955	251	72	766	256	1'287	43	235
eletriticy	9'045	7'723	9'256	1'550	6'514	3'741	3'584	2'513	1'480	1'490	1'220	487

Figure 5: Final energy consumption (TJ 2020) per industry subsector, based on [22].

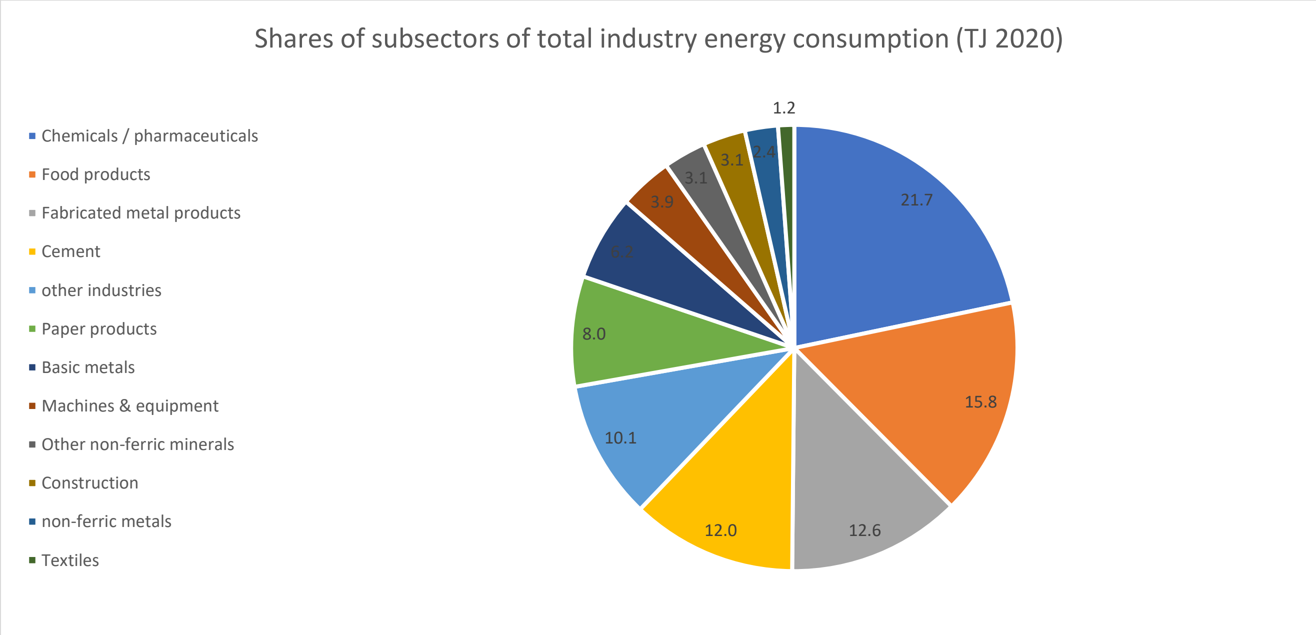


Figure 6: Shares of subsectors of total industry energy consumption (TJ 2020), based on [22].

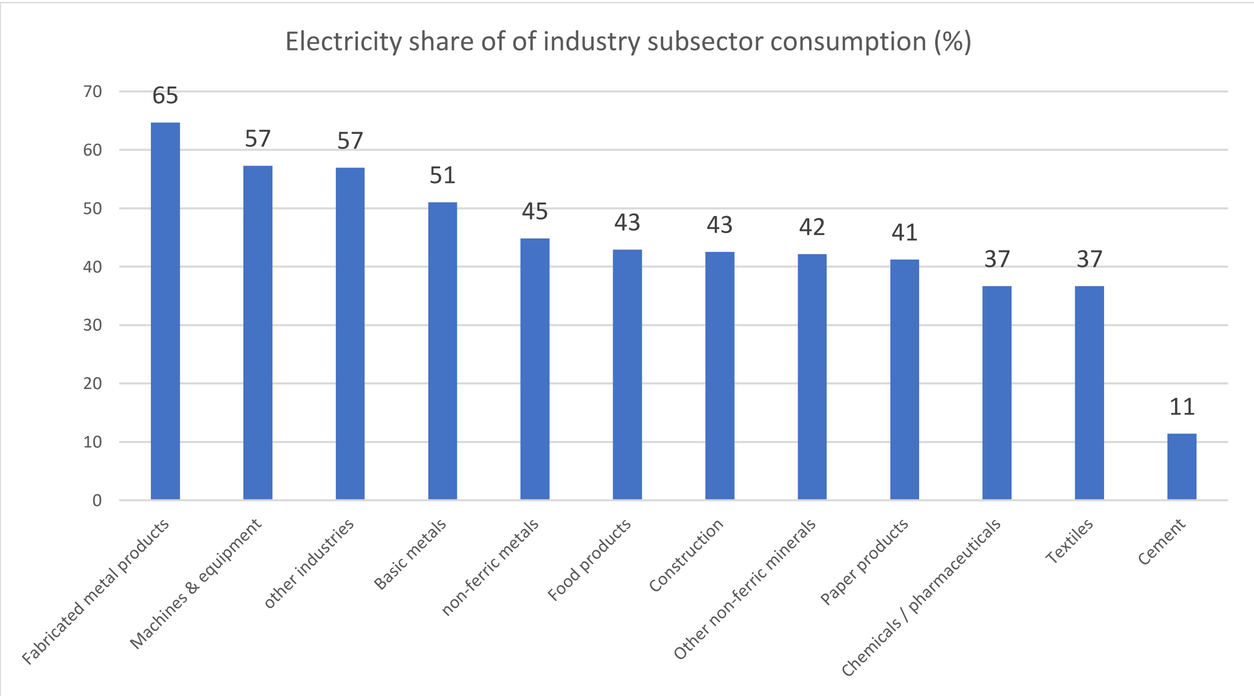


Figure 7: Electricity share of industry subsector consumption (%), based on [22].

1.4 Current policy discussion

The current baseline of the Swiss energy policy is set by the 2050 energy strategy, which has been in place since 2018. The strategy aims to decarbonize Swiss energy production and replace nuclear power plants by 2050, which, as of 2021, provide 28.9% of total Swiss electricity generation.[18] So far, the strategy has relied on increasing energy efficiency, increasing the share of Renewables (mainly photovoltaics and wind) and investing in electricity grids.[25]

Switzerland has had a structural electricity generation deficit during winter for many years. To this day, the 2050 energy strategy has not changed this situation, all the while the import capabilities of Switzerland have worsened due to the complicated bilateral relations with the EU. SFOE has stated that without a bilateral agreement on electricity market, Switzerland will not be able to further develop Flow Based Market Coupling (FBMC) with the EU and Redispatch cost will increase significantly. By 2025, when 70% of European grid capacity will be reserved to the EU single market participants, this could lead to severe issues with security of supply.[26] Recently, ElCom has also reinforced its standpoint, that security of supply is structurally jeopardized and that an insufficient electricity supply in the winter of 2022/2023 is not unlikely.[27] SFOE has also argued that the high production deficit in winter will persist past 2040, especially if the runtime of the remaining nuclear power plants in Switzerland is not maximized to 60 years or other options are leveraged very fast.[20] This last analysis also touches on demand side flexibility options as a mitigation strategy, but does not investigate it any further.

Security of electricity supply is a big strategic energy risk for Switzerland. The Federal Office for Civil Protection even claims that electricity shortages are the most likely and potentially most damaging risk scenario for Switzerland overall.[28] In reaction to this structural problem and the aftermath of the Russian attack on Ukraine, the Federal Council on February 17 2022 has activated Art. 9 of the electricity supply act, which allows the Federal Council to take enhanced measures to secure the Swiss electricity supply (increases in energy efficiency, procurement of electricity, further investment in generation capacities and grids).[29] The Federal Council implemented a strategic hydro power reserve for the coming winter and, based on a concept created by ElCom, has advocated the construction of two to three gas power plants (1000 MW in total) to mitigate possible shortages in winter until 2025.[30][31] From the Federal Council's perspective, this seems to be the most feasible approach to tackle the winter issue. It is however highly controversial, since gas power plants are considered by many to be an unsustainable, unreliable option because of the current crisis situation (and possible future crises).

Flexibility from industry consumers as a lever to mitigate structural production deficits in winter has, as of yet, played a small role in policy discussions. If they did, the focus is mostly on short flexibility durations (integration into ancillary services).[4] Recently, there has been a more vivid discussion in policy making surrounding the role of industry for addressing possible winter shortages. In parliament, a motion calls for the implementation of an auction mechanism to utilize industry loads in shortage situations.[33] The idea is that the state demands a certain amount of shiftable or reducible demand for extraordinary situations. Companies can then voluntarily offer up their

[4] According to media coverage, intermediary companies have started to pool industry loads (mostly positive control energy) and sell them to Swissgrid around 2015.[32]

flexibility and receive a compensation. The motion also claims that this option would be cheaper than building gas power plants. Moreover, the Federal Council has proposed new drafts for the energy act and the electricity supply act late in 2020. The revision for the electricity supply act includes a new article regarding strategic energy reserve for critical supply situations (Art. 8a E-StromVG). This mechanism is supposed to come into effect in situations, where the overall Swiss balance leaves demand not served after markets close. These are shortages that go beyond the short- and mid-term in volatility that is addressed with ancillary services. Thus, the measure is "in the middle" between a functioning market solution and a mandated rationing of electricity.[34] The draft explicitly states that industry loads are welcome to participate in the tenders for this strategic reserve. Therefore, this thesis will focus on such a scenario. The following graph contextualizes the different scopes of measures:

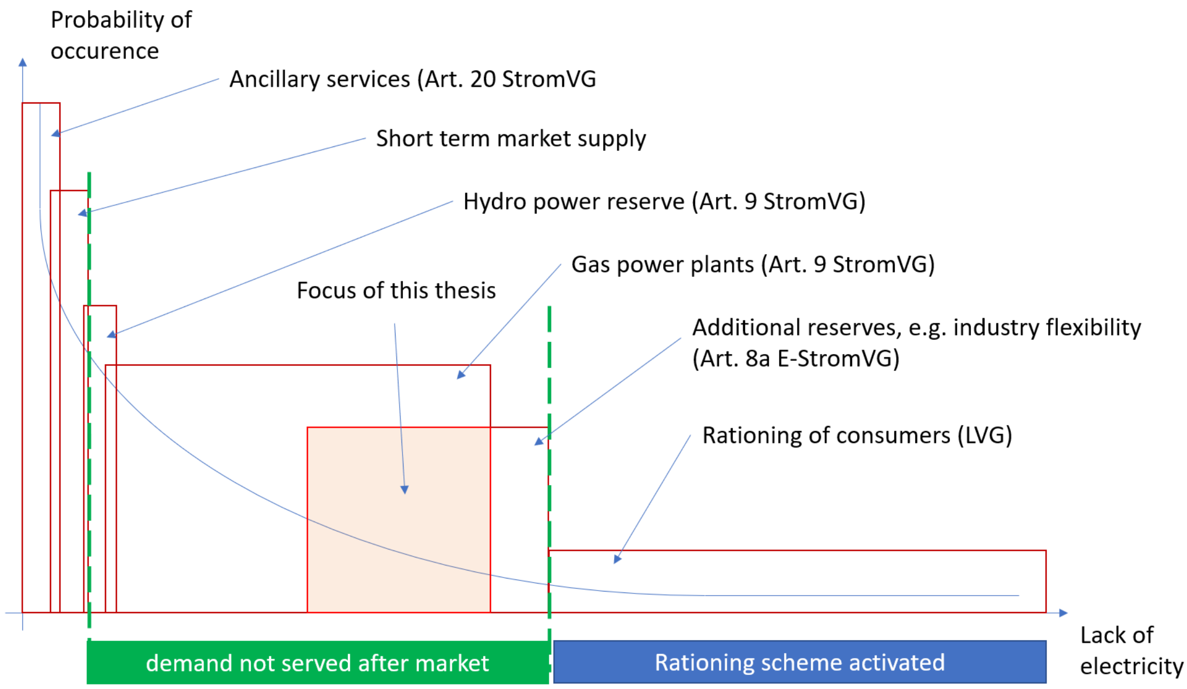


Figure 8: Instruments against electricity shortages, based on [35]. The focus of this thesis is marked red.

ElCom, in the above-mentioned concept for gas power plants, has considered load shedding and interruptible loads as alternatives for said power plants and concluded, that the potential for additional contractual load shedding in Switzerland is negligible.[35] The analysis was however superficial. It was not substantiated with data or a modeling analysis. Problem statement and research questions

The observations made so far show a growing interest in the topic of a flexible industry electricity demand. There is some research on this topic, but predominantly for shorter time horizons (i.e. not focused on seasonal security of supply issues) and mostly from abroad. For security of supply in Switzerland, there have not yet been any substantial inquiries into whether industry flexibility can substitute additional generation capacities for the winter season, such as gas power plants. Therefore, this thesis aims to give an overview of the current discussion and contribute to a better understanding of the nature and driving factors of electricity flexibility over longer periods of time in the Swiss industry. The overarching research question is: **If there is an electricity deficit in winter, how and to what extent can the flexibility of the Swiss industry contribute to security of electricity supply?** Flexibility meaning load shifting and shedding of industry electricity consumers over longer periods of time (at least days, up to months). By addressing this issue, the thesis should ideally motivate further research and hopefully contribute to ongoing policy discussions.

2. Methodology

This thesis uses mixed methods approach to produce a wide spectrum of results: Insights from the current literature on industry flexibility, anecdotal evidence from semi-structured interviews with different stakeholders and quantitative evidence from a system modelling analysis using the Interconnected Energy Systems Modelling Platform Nexus-e by ETH Zürich. The following section describes the methodology used in the latter two parts.

2.1 Interviews

Overall, I conducted 16 semi-structured interviews with industry associations, individual companies as well as regulators and grid operators. In the category of industry associations this included statements from the utility sector, the mechanical, electrical and metal industry and from a cross-sectoral association representing energy-intensive companies. In the category of regulators and grid operators, all relevant perspectives were covered (transmission grid, distribution grid, market supervision, regulatory authority). The companies interviewed cover 8 out of the 12 industry subsectors mentioned in section 1.3 (see figure 9). The interviews were intended as a reality check and as a tool to identify sub-topics that merit further investigation. The goal was to generate anecdotal evidence from the conversations to improve my understanding of the individualistic business perspective on flexibility and the connections to the systemic perspective. In such an explorative approach, the interviews do not follow a strict set of questions but instead a set of pre-defined topics that allow for an open conversation. A list of these topics can be found in appendix 1.

Representatives from the following organizations were interviewed:		
Industry Associations	**Companies**	**Regulators & grid operators**
▪ Verband der Schweizerischen Elektrizitätswirtschaft VSE ▪ Verband der Schweizerischen Maschinen-, Elektro- und Metallindustrie Swissmem ▪ Gruppe Grosser Stromkunden GGS	▪ Migros Genossenschaftsbund (Food products) ▪ Lonza AG (Chemicals / pharmaceuticals) ▪ E. Schellenberg Textildruck AG (Textiles) ▪ Holcim AG (Cement) ▪ Steeltec Group AG (Basic metals) ▪ MAN Energy Solutions AG (Machines & equipment) ▪ ABB AG (Other Industries) ▪ Perlen Papier AG (Paper products)	▪ Swiss Federal Office for Energy SFOE ▪ Swiss Electricity Commission ElCom ▪ Swissgrid AG ▪ BKW AG

Figure 9: List of interviewed organizations, own representation.

2.2 Energy System Optimization

To get a better understanding of the systemic relevance of industry flexibility, I develop and run scenarios for 2030 to identify conditions under which utilizing industry load shedding becomes more cost-effective to address a supply deficit than building new gas-fired power plants. To run the scenarios, I use Nexus-e, an integrated energy system modeling platform.

2.2.1 Overview Nexus-e

Nexus-e represents the entire Swiss energy-economic system via multiple, interconnected models and allows for a comprehensive analysis of Swiss energy policy and market developments. In this thesis, I use two models of this platform – CentIv [60] a model for the centralized part of the power system, and DistAB [61], a model for the decentralized part - and simulate the expansion path under lowest cost. The CentIv model co-optimizes generation investment and operational decisions on the transmission system level. The module contains a grid-constrained generation expansion planning and includes system flexibility requirements. DistAB is an agent-based model and simulates the diffusion of solar photovoltaic and battery storage systems. It represents the decision making of individual, heterogeneous households to invest in these technologies.

The platform has an hourly resolution and the load flows resulting from electricity production and demand are calculated on transmission grid level (298 power lines, 165 transformers). Neighboring countries are considered in an aggregated fashion (electricity demand and production at one transformer, one power line to Switzerland and between each neighboring country). Electricity trade with neighboring countries is constrained by "Net Transfer Capacities" [MW]. The input parameters for the model include techno-economic factors, such as demand, generation, cost, etc., as well as special scenario parameters. The main output parameters include installed capacity, installed gas units and used industry load shedding.[62] Figure 10 gives an overview of the model and the main input and output parameters.

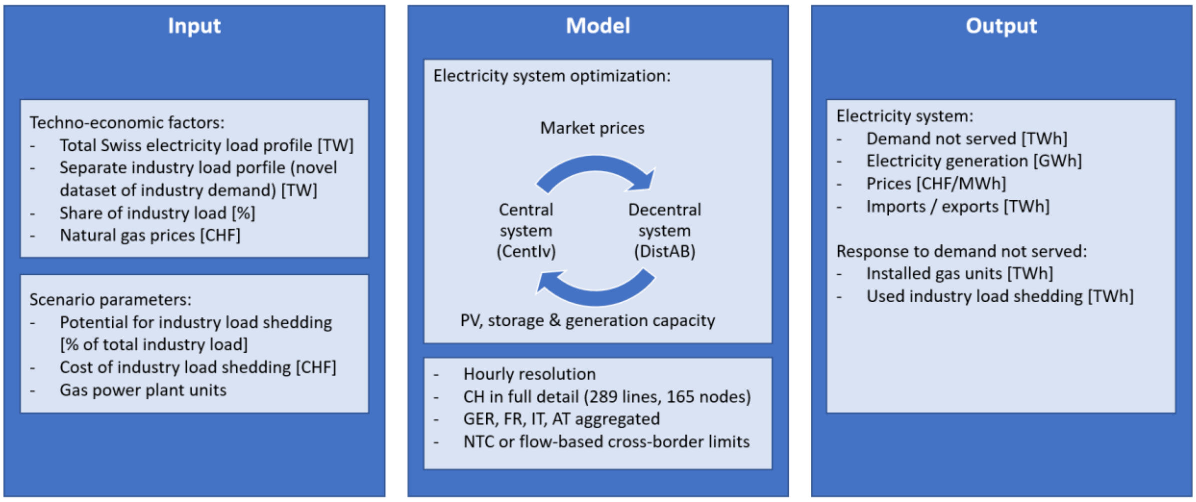


Figure 10: Overview of the model used in this thesis

The two models go through the following steps for the scenario years 2020 (reference year) and 2030: First, CentIv calculates the optimal addition of centralized power generation and storage (nuclear, wind, hydro, gas, battery storage) to meet electricity demand, taking into account existing infrastructure and developments in power generation and demand in neighboring countries that are important for electricity trading. Subsequently, the resulting electricity market price is passed on to DistAB. DistAB the simulates the decision making of households whether to invest into solar PV and battery storage investments. In their decision making, each household considers the profitability of the investment (which is affected by electricity market prices) and social factors such as neighborhood effects. The annual deployment of solar PV and battery storage subsequently flows back into CentIv, which adjusts the optimization of the entire power system accordingly.

2.3 Data on industry load profiles

To assess industry flexibility with Nexus-e, I created a novel data set for industry demand in Switzerland with a nodal and hourly resolution. In a first step, I collected load profiles for all twelve subsectors used in the analysis by SFOE [22] (see section 1.3). Seven of the load profiles were provided by the interviewed stakeholders and represent the actual load data of the interviewed companies. For three sectors, anonymized but real company profiles were used.[5] For the two industry subsectors I was not able to collect real-life load data, I used the standardized proxies by the German “Bundesverband der Energie- und Wasserwirtschaft”[39]. Subsequently, I normalized the

[5] These were not provided by interviewees, but by “Energieagentur der Wirtschaft” EnAW.

load profiles and thus received a comparable view on the demand structure in each industry subsector.

In a second step, I used an existing data set of about 3000 anonymized Swiss companies including their electricity demand in 2021, the address of each company, and their General Classification of Economic Activities (NOGA) [41][42]. The data was provided by "Energieagentur der Wirtschaft" (EnAW)[40]. The sample includes a considerable share Swiss companies with an electricity consumption of more than 100 MWh.[6] Each listed company, I assigned to one of the twelve industry subsectors using the provided NOGA code and to one of the transmission grid nodes using the companies' addresses. This provided us with an accurate picture of the electricity demand per industry subsector and per node in Switzerland. Figure 11 compares the electricity generation per industry subsector from the EnAW dataset with the SFOE data.[22][7] While the EnAW dataset is a fairly accurate representation of the SFOE data, it deviates from the latter by 3.8 TWh (29.3% of total industry load). This is electricity demand from companies that are not EnAW customers. To account for this missing industry load, I distributed the total equally per industry subsector across all transmission grid nodes.

In a third step, I combined the datasets on hourly load profiles (first step) and on industry load and location (second step) to obtain hourly demand profiles per transmission grid node for the industry sector.

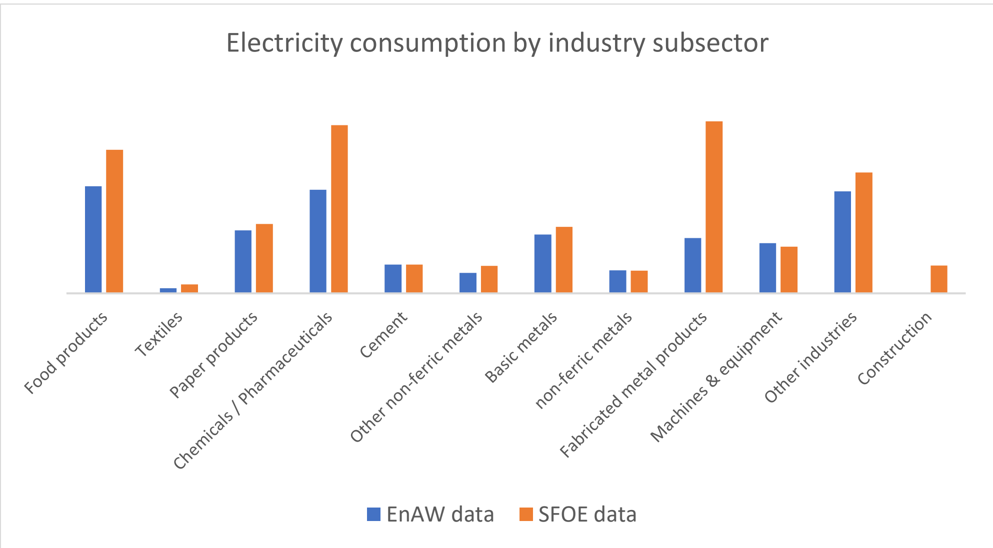


Figure 11: Electricity consumption by industry subsector, comparison of the two datasets used, based on [22] and [40].

---

[6] EnAW works with companies that participate in emission reduction and energy efficiency schemes under the Swiss CO_2 act, the Swiss energy act and the energy legislation of the cantons that targets large energy consumers.[40]

[7] Figure 11 is stylized to ensure confidentiality of the EnAW data.

2.4 Scenarios

In this thesis, I develop scenarios to identify conditions under which utilizing industry load shedding becomes more cost-effective than building new gas-fired power plants to address a supply deficit. To do so, I first develop a Baseline scenario that outlines an "optimized" expansion path for the Swiss electricity system by 2030 leading to the lowest total cost of power supply. This scenario builds upon input on the current (or announced) regulatory framework and on expected development of technology costs. Based on the Baseline scenario, I identify a number of deficit scenarios by adjusting the available Net Transfer Capacities[8] (NTC) but "freezing" the technology mix from the Baseline scenario. A scenario has a "deficit" when part of the electricity demand cannot be served with domestic generation and imports in any month of any year. For each of the identified deficit scenarios, I then allow the model to address the deficit by investing in new gas-fired power plants and utilize industry electricity demand for load shedding. In these "trade-off" scenarios, I then vary the available potential for industrial load shedding and its costs.

Scenario (#)	**Technology mix**	**NTC**	**Cost of industry load shedding [CHF/MWh]**	**Share of industry load shedding [%]**	**Number Gas candidate units [#]**	**Capacity gas candidate units [GW]**
Baseline Scenario (1)	Technology mix is optimized to serve domestic demand with lowest costs, no gas units considered	Current NTCs; assumed to be constant until 2030	-	0	0	0
Deficit Scenarios (2)	Similar to Baseline scenario	30-0% of NTCs in baseline scenario, in steps of 5%	-	0	0	0
Trade-off scenarios (24)	Similar to Baseline scenario	For each identified deficit scenario	steps: 500, 1000, 1500, 2000, 2500, 5000, 7500, 10000	0-25% of total industry load, in steps of 5%	11	5.5GW

Figure 12: Scenario overview.

2.4.1 Baseline scenarios

The Baseline scenario outlines an expansion path for the Swiss electricity system by 2030 that leads to the lowest total cost of power supply. The system costs comprise investment, maintenance, CO_2-emissions, and fuel costs. The optimization considers learning effects (decreasing prices of the

[8] Low NTC or unavailable imports from neighbouring countries can cause insufficient electricity supply in the scenarios and also under real circumstances.

technologies over time) and current subsidies (for example, return tariffs and one-time payments for photovoltaic systems). The included technical potential of photovoltaics for rooftop installations is 53 GW by 2050 (not all potential is installed in the cost-optimal expansion path). The expansion of wind power is limited to 2 GW due to permits and financing, and biomass to 0.4 GW. Electricity generation from run-of-river power and pumped storage power plants remain at today's levels. The scenario assumes a general phase-out of nuclear power after 50 years, except for already confirmed lifetime extensions. Beznau 1 and Gösgen are therefore phase-out before 2030, while Beznau 2 and Leibstad are included in the 2030 technology mix. The scenario excludes geothermal power for electricity generation and ground-mounted photovoltaic plants e.g. in the alpine region. Electricity demand assumptions follow the "Zero Basis" scenario of Energy Perspectives 2050+, which considers increasing electricity demand mainly due to the electrification of the transportation and heating sectors with electric vehicles and heat pumps. The development of the electricity generation capacities in the neighboring countries is based on the ENTSO-E TYNDP "Global Ambition" scenario.[63] The Net Transfer Capacities (NTC) for 2030 are based on the latest ENTSO-E ERAA (i.e., FR: 3700MW, DE: 3800 MW, IT: 1910 MW, AT: 1200 MW) and are assumed to identical for both directions (e.g., CH-FR, FR-CH).[64]

2.4.2 Deficit Scenarios

Deficits are created by reducing the Net Transfer Capacities[9] (NTC) but keeping installed electricity generation and storage units similar to the Baseline scenario. This is to ensure that the model does not re-optimize the system to build more generation capacities to avoid a deficit situation. Reducing NTCs can cause deficits as it limits the potential to import electricity from the neighboring countries. Already today, Switzerland has insufficient domestic generation to cover inland demand in winter and depends on imports.

2.4.3 Trade-off scenarios

For each of the identified deficit scenarios, I then develop trade-off scenarios in which the model can decide to invest in additional gas-fired power plants and/or utilize industry load shedding to address the unserved electricity demand in the respective deficit scenario. This analysis thus only focuses on the negative potential of industrial demand side management (i.e. load shifting or shedding, but no load increases) and provides the lowest cost option to address electricity shortages in winter.

To assess the conditions under which the model prefers industrial load shedding over building new gas-fired power plants, I vary the cost of industry load shedding between 0 CHF/MWh and 10'000 CHF/MWh in steps of 2'500 CHF/MWh and the available potential for industrial load shedding between 0% and 25% of the total industry load, in steps of 5%. The available potential for industrial

[9] Unavailable NTC or unavailable nuclear power plants in Switzerland seem to be to the most likely cause for insufficient electricity supply in winter also under real circumstances.

load shedding is defined for every hour and is independent of previous or future load shedding. Meaning that the decision to load shed in hour t has no impact on the available potential and decision to load shed in hour t+1.

Instead of load shedding the model can also build new gas-fired power plants based on the included candidate units. We include gas-fired power plants at 7 locations of the transmission grid (based on the “Konzept Spitzenlast-Gaskraftwerke” by ElCom [35], with a total capacity of 5.5 GW. The gas-fired power plants can either be build running on natural gas and CCS (Investment cost: 135000 EUR/MW/a, total variable cost 159.5 EUR/MWh) or running with carbon-neutral synthetic methane without CCS (Investment cost: 765000 EUR/MW/a, total variable cost 308.8 EUR/MWh).[65]

3. Results

3.1 Insights from the literature

Existing literature covers the topic of industry electricity flexibility in a variety of publications. In many cases, flexibility is addressed as a subtopic of demand side integration., as was described in the introduction. Generally, literature covers two core topics, the first being the *definition* (e.g. categories, direction, etc.) of industry flexibility potential and the second being the *size* (power and amount of electricity) of industry flexibility potential. The following section will explain these considerations and assess a few different standpoints. It will then argue for a definition and potential range that best fits the scenario of industry demand shifting or shedding over longer periods of time as a contribution for security of supply in winter. This should give an intuition of what role industry flexibility can actually play for possible Swiss winter issues.

3.1.1 Flexibility potential definition

Different studies show that there is no universal definition of flexibility potential. For example, Ausfelder et al. (2018) [46] have conducted a comprehensive meta-study on industry flexibility potential in Germany. In the 28 studies they analyzed, they identified no less than 15 different concepts. Based on this, the definition was identified as one of eight critical factors that account for differences in potential assessments (see Appendix 3). Similarly, Steurer (2017) [6], in his detailed work on demand side integration, remarks that most studies use similar terminology such as “technical” or “economic” potential, but the underlying definitions build on very different technical, organizational, or economic aspects.[7] In particular, there are considerable differences between an electricity system perspective and the individual companies’ perspective. As the modeling part of this thesis takes the former, the literature review and interviews take the latter in order to cover both perspectives.

Because there are different perspectives, I decided to bring together two different approaches for the definition of flexibility potential: On the one hand this is the approach used by Vossebein et al. (2019) [7]. It is the most comprehensive and most relevant study on demand side integration and industry flexibility in Switzerland so far. It mainly follows the systemic logic. It does however not consider longer lasting demand shifting or shedding (only up to hours), which would be the most relevant aspect for security of supply in winter. On the other hand, the normative definition in VDI (2020) [13] gives an interesting complementary perspective for individual companies, that also considers longer periods of demand shifting or shedding (up to weeks). The following table displays the combined potential definition and key flexibility drivers.

Potential definition	**Combined definition after [7] and [13]**	**Key flexibility drivers from a company-perspective**
Theoretical potential	Connected electrical load that can be shifted, increased or decreased.	Electricity consumption of the company
Technical potential	Possibility of varying power requirements with the technological boundary conditions and according to seasonal availability (summer vs. winter) and daily availability (day vs. night)	Production technology, machinery and equipment (e.g. production process and sequence, production cycle over short and long timespans)
Practical or socio-technical potential	Subset of technical potential that can be used within social, regulatory or administrative limitations	Regulatory framework for production (e.g. labor laws, environmental laws, energy efficiency requirements, building codes, etc.)
Economic potential	Subset of the technical potential that can be used economically (benefits > costs)	Opportunity cost of using flexibility options (e.g. foregone market opportunities)
Realizable potential	Intersection of practical /socio-technical and economic potential	

Figure 13: Flexibility potential definition, based on [7] and [13].

Flexibility potential is not just a matter of definition, it also is highly circumstantial for individual companies and their business context. This is probably best described by the following quote of Köberlein et al. (2022) [48]: “Ultimately, the transformation of an arbitrary factory system to an energy-flexible factory system is neither clear-cut nor universal. Hence, the planning and techno-economic evaluation of energy flexibility measures for various implementation levels and time horizons are of great importance.” It can therefore be assumed, that there is much more variation and granularity in the company perspective on flexibility potential than in the systemic perspective.

One more central learning for industry flexibility over longer durations (i.e. in winter scenarios) from VDI (2020) [13], is that longer durations of load shifting or shedding affect companies more deeply.

While flexibility options for minutes or hours usually require technical adjustments of existing processes on a manufacturing level, shifting or shedding over days or weeks can change fundamental aspects of a business, such as process flows, job sequences or energy procurement. Flexibility options for weeks or even moths and thus profoundly influence production and capacity planning, shift allocation and production set ups. This makes the assumption plausible that it is very difficult for companies to leverage economic and realizable flexibility potential for longer durations, because their opportunity cost is very high.

The modeling approach used in this thesis focuses on the technical potential from a systemic perspective, since the CentIv module of Nexus-e will take an investment decision and therefore decide whether it is economically feasible to use flexibility in the given circumstances. The output is consequently the economic potential. The interviews on the other hand are meant to give insights into socio-technical and economic potentials for longer flexibility durations. From there, it could be debated in further research which regulatory framework would help to maximize potentials from both the systemic and the company perspective.

3.1.2 Flexibility potential quantification

The quantitative literature on industry flexibility is rather thin for Switzerland and it is particularly thin for longer flexibility durations. Nevertheless there are some learnings to be drawn from studies that focus on short-term flexibility. For example, Imboden et al. (2016) [49] analyze the potential for industry to provide ancillary services. They conclude that certain processes are more suitable for flexibility, e.g. in the cement industry, where it is comparatively easy to store semi-finished products and optimize the production sequence for flexibility. This methodology translates quite well for longer flexibility durations. Understanding the intricacies of specific production processes and technologies helps to derive the theoretical, technical and socio-technical flexibility potential and assess for how long it would be available, as Vossebein et al. (2019) [7], Ausfelder et al. (2018) [46], Bons et al. (2020) [47] and many others[10] show. Ausfelder et al.(2018) [46] analyze eight processes from five industries. They conclude that cement milling and Chloride-alkali electrolysis in basic chemistry have the highest potential for flexibility durations of up to five days.[11] Similarly, Bons et al. (2020) [47] argue that the overall industry flexibility potential in Germany beyond durations of a few days is very limited, due to ensuing production cuts that cannot be compensated. Same as Ausfelder et al. (2018) [46], they see the highest potential for longer flexibility durations in the basic chemistry and cement subsectors.

[10] See for example Marchiori et al. (2017) [52] for steel production, Uhlig et al. (2022) [53] for heat treatment process chains of foundries or Golmohamadi (2022) [54] for aluminium smelting, cement production.

[11] However, in the case of cement mills, reference is made to the anyway seasonal production patterns of the cement industry, and in the case of chlor-alkali electrolysis, to unavoidable value-added losses in case of load reductions.

The overall flexibility potential seems to be closely linked to the economic structure of a country. Further evidence from abroad illustrates this: Söder et al. (2018) [50] have looked at more than 50 studies for the Nordics and identified industry load to be quite flexible due to the high share of forestry and metal processing, but the range is very large depending on the specific country (between 0.2 and 8.5% of peak load). Countries with higher shares of heavy industry such as metal processing do generally have a higher theoretical and technical flexibility potential. Kirkerud et al. (2021) [51] expanded the work of Söder et al., showing that the total economic flexibility potential of industry consumers in the Nordics is still considerably lower than the technical potential.

As mentioned in the introduction, the Swiss economy is considerably less energy intensive than the OECD-average. Subsectors like basic chemistry, basic metal production or cement are still important, but contribute less to the overall economic output than in Germany or the Nordics. Flexibility potential estimates from abroad have therefore only limited applicability. At the same time, heavy industries do have very similar properties across Europe, so insights for specific production processes do transfer well to the Swiss context. In addition to this, Switzerland does have other very competitive flexibility options available in the form of hydro power plants, that other countries don't necessarily have. Such alternatives opportunities are however not taken into account in the studies reviewed, nor are they the topic of this thesis beyond the standard assumptions of Nexus-e in the system modelling part.

For Switzerland, there is only one comprehensive quantitative analysis of industry flexibility potential so far (Vossebein et al. (2019)[7]) The following graphs show the technical and the socio-technical potential for different scenarios, the first focusing on the technical potential e and the second focusing on the socio-technical potential. The authors have not quantified the economic potential because of high uncertainties regarding opportunity cost for companies or how market mechanisms would assess the value of industry flexibility. The numbers do also consider shorter and longer flexibility durations (up to days), but the numbers were evened out and the study does not contain detailed results on this aspect. Because of this, it has to be stressed that the mentioned technical potential is to be viewed as a very optimistic upper bound estimate. It is very plausible that the actual potential for longer flexibility durations is still significantly smaller. The large gap between technical and socio-technical potential solidifies that impression.

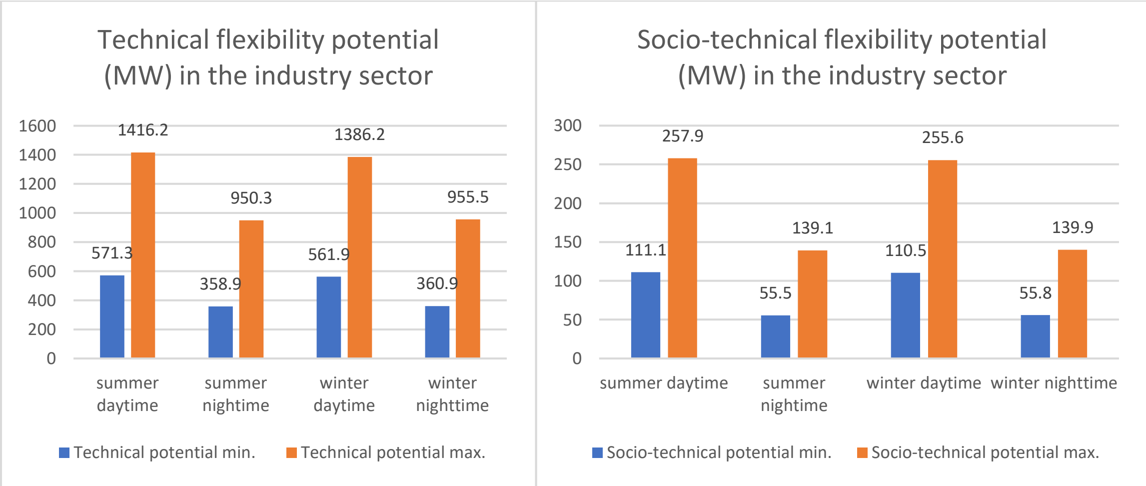


Figure 14: Technical and socio-technical flexibility potential in the industry sector, based on [7].

3.2 Interviews

The following section will reproduce, summarize and interpret the most important take-aways from the conversations with grid operators, regulators and industry stakeholders.

Generally, the purpose and the value of electricity flexibility were assessed differently depending on the perspective of the interviewed stakeholders. Roughly, the two viewpoints described in this thesis so far were also expressed in the interviews: a systemic perspective and an individualistic perspective. The three groups of stakeholders mostly took the following positions:

- Regulators: Primary interest in flexibility because of fast, efficient, and secure supply integration of renewable, decentralized energy generation, for which a flexible demand is a prerequisite (corresponds to the systemic perspective).
- Grid operators: Primary interest in flexibility as a tool to increase resilience, where flexible demand serves as an additional resource for system stability (corresponds to the systemic perspective).
- Companies and industry associations: Primary interest in flexibility to adapt to volatile energy markets and ensure cost-effective and secure electricity supply. Flexible demand serves cost optimization and security of supply (corresponds to the individualistic perspective).

Based on these different interests and viewpoints, there were also differences in the interpretation of the nature and size of technical, socio-technical and economic flexibility potential in the industry sector. Overall, the opinions expressed by the company representatives were considerably more skeptical than those of regulators or grid operators. Implementation issues such as lacking technology, know-how, or investment capacities were frequently named as main drivers. Moreover, the potential for a flexible industry demand to contribute not just to the short-term grid and system stability, but also to substitute significant amounts of energy generation over longer periods of time was almost unanimously dismissed. The conversations thus indicated that the flexibility potential quickly reaches practical limitations in many industrial processes.

The narrow boundaries for flexibility potential seem to be determined by the following factors, as they were mentioned consistently throughout the different interviews: flexibility limitations in the production process, limitations in the preparation-time for using flexibility, trade-offs and opportunity cost of flexibility, contractual security and robust market mechanisms as flexibility enablers. These factors are described in the following sections.

3.2.1 Flexibility limitations in the production process

- **The technical characteristics of many industrial processes.** Although they vary considerably depending on the subsector and business model, most production processes were described as being inherently unfit for production with reduced electricity input. An example of this is chemical production, where starting up and shutting down processes is very energy-intensive and inefficient at the same time. It was mentioned that a short-term reduction of about 15% of energy consumption would result in production cutbacks of up to 50% over a longer period. In such a case, there is also little incentive to restart production to full capacity if further shortages are to be expected in the near future. Another example that was mentioned by several industries is the implications of varying levels of electricity supply on product quality. These can be severe, even for small reductions in electricity supply. Industries such as cement, steel or paper therefore depend on a guaranteed baseload, so that they can achieve the required product quality. In the pharmaceutical industry, where production is done in badges with biochemical processes and relatively long lead times, even a small reduction in electricity supply can cause fundamental issues.
- **The production planning** Is another limiting factor, as it defines when and how much is produced in a given period of time. One key determinant in this regard seems to be the number of work shifts a company implements. The interviewees have stated that production sites with two shifts have a higher flexibility for load shifting or shedding during the day and during the week than sites with three or four shifts. This is intuitive since more shifts generally means less downtime. It is also something that is clearly visible in the exemplary load profiles analyzed for this thesis: companies with three or four shifts have a constant baseload, whereas companies with fewer shifts have more demand fluctuations during days and weeks. This correlation (worktime and load) is also mentioned in the documentation for standardized load profiles used in the system modelling part.[12]

[12] The work shift allocation is a variable in the standardized load profiles used for the modelling approach.[39]

- **The inflexibility of value chains** plays a crucial role, as all of the interviewed companies stated that their production does follow the customer needs of their respective market first and foremost. Of the companies interviewed, almost none reported following seasonal patterns in production. Unsurprisingly, customer relationships were therefore named as the biggest "flexibility killer". This a bit of a double-edged sword, since electricity shortages would disturb production more than flexibility measures. However, especially companies with low cost shares of electricity mentioned implementing special contingencies for this (still unlikely) case rather than optimizing their whole production process for more flexibility. Also, electricity procurement for the winter months was identified as an important lever. Especially within bigger companies it is optimized as much as possible (multi-supplier strategies, price- and security-optimized procurement, multi-year procurement contracts). This is done to hedge the market driven production cycle against possible shortages. In some cases, the value chain needs may even coincide with the seasonal availability of electricity. In the cement industry for example, production is slowed down in winter as construction activity is usually very low. For the cement industry, this synergizes with avoiding the higher electricity prices in winter. However, it is an isolated example and rather a “lucky coincidence” than a general proof that seasonal flexibility is relevant for companies.

3.2.2 Limitations in the preparation time for using flexibility

With almost all interviewed stakeholders, the preparation time for reducing or shifting industry loads seems to be a second important determinant of the flexibility potential. Generally speaking, longer preparation times imply a higher flexibility potential because production planning can be adjusted to some degree. However, in some cases even long preparation times are not enough to incentivize flexibility. Large or long-lasting load shifts or reductions of electricity consumption interfere fundamentally with most business models - No company interviewed said that under normal circumstances they could reduce loads for weeks or even months without it fundamentally affecting their business continuity.

An interesting correlation that was hinted towards by several interviewees was that further economic potential for short-term load shifting or shedding is much easier to come by than additional potential for long-term shifting or shedding. The reasoning is that the more fundamentally flexibility affects a company’s business model, the higher the marginal cost are for leveraging that flexibility. An example which was mentioned repeatedly was labor laws and productions planning. While it might be technically feasible to adjust production patterns for a company with, say, fewer work shifts, it is very costly to implement from a social perspective. Most flexibility measures may have unfavorable consequences for the workforce, such as unregular worktime, working at night or on weekends and so on. Thus, the marginal cost is quite high. On the other hand, technical measures, such as short-term digital optimization of a production system, ideally have marginal cost of zero. They can be deployed instantly without affecting labor too much. To summarize, longer preparation times seem to increase the flexibility potential, but almost exclusively via technical improvements that yield small demand shifts or sheds and do not fundamentally affect the production and work patterns.

Lastly, some companies indicated that they are considering their own investments in electricity production due to increasing uncertainties in the energy markets. Some companies came upon this strategy “accidentally” when investing in their energy efficiency and re-using e.g. waste heat in their production. One company mentioned expanding an on-site biomass power plant for gas and electricity production, which was initially built for waste management purposes. Obstacles for such investments however appear to be large. The investment cycles are long and a lot of capital is required. Moreover, on-site power plants are seldom able to fully meet the need for readily available power for the entire production. One interesting alternative, that was mentioned, was Power Purchase Agreements with utilities. In this setup, a utility and an industry company will agree to long term procurement contracts at fixed rates, which give the utilities an incentive to invest in generation capacities and provide the industry consumer with a secured supply.

3.2.3 Tradeoffs and opportunity costs of flexibility

One of the main viewpoints on flexibility from the individualistic perspective revolved around trade-offs and opportunity cost. This is not just about the inflexibility of value chains, but in a broader sense about the strategic decisions, that a company takes. In other words, the value of flexibility appears to depend on what a company could miss out on, if it were not flexible. All interviewees from the industry stated that meeting customer demands is still their primary concern, even with energy supply becoming more expensive and more uncertain. None of them feel like they miss out on an opportunity, when they concentrate their efforts on business continuity rather than a flexible electricity demand.

For the larger companies interviewed, the current energy markets still offer the best chance to hedge their financial and availability risks, whereas smaller companies with limited market access have more difficulties, because they cannot procure electricity freely in the market. The current production process, which is customer- and quality-driven, is always the focal point. Material flows are planned to meet customer needs, energy flows and information flows are then optimized to match these material flows. This seems to be especially true for sites or subsidiaries within larger companies, that can hedge their electricity demand on the market or within their conglomerate. None of the companies are interested in running their processes on a reduced energy supply (e.g.

pharmaceutical industry, which requires a constant energy supply for many processes to remain intact or the steel industry, which prefers to shut down completely instead of producing with reduced power because the latter reduces the lifespan of production facilities and impedes product quality). On the other hand, some companies with high shares of electricity cost and large demand are looking into new opportunities. One such company mentioned that it was evaluating a change to an integrated energy management system, meaning that material and energy flows are considered together in business decisions and mutual dependencies are taken into account in production planning. While the company would still optimize for low energy cost and high security of supply, such a measure would also enable a more flexible demand. This changes the view on trade-offs and opportunity cost for a company, if an electricity shortage is on the horizon. In this particular case, digitalization was mentioned as the main challenge. Bringing the material flow and the energy flow closer together requires a reliable data flow. Measuring, interpreting, and leveraging data for an integrated energy management does not seem to be trivial. It requires substantial capacities for investment, process integration, organizational changes, and also support from grid operators and energy providers. Some companies have dismissed it completely, arguing that their cost-share of energy would never be high enough to justify such an investment.

While the cost of energy flexibility currently seem to outweigh the benefits for almost all interviewed companies, there are also interesting solutions on the horizon that may shift the perspective in the future and increase the relative value of flexibility for industry users. One solution that was repeatedly mentioned was demand pooling. Solutions like virtual power plants can potentially offer large and small industry users the right incentives to increase their flexibility and bring it to the market. Virtual power plants can act as an intermediary that manages ancillary services, energy trading or peak-load. In some countries, there are already a few such solutions in place, some of them start to include industry demand.[13] Once again, digitalization and a reliable data flow were mentioned as an issue that keeps the entry-barriers high at the moment. Another limitation for pooling industry loads are the specific power requirements of certain industries. For example, a steel production plant needs high power availability and thus would only really benefit from pooling with similar loads or large generation capacities. From such assessments, it can be reasonably assumed that pooling is more interesting for less energy-intensive production setups.

One last topic which was addressed repeatedly was the complex relationship between energy efficiency and energy flexibility. Some companies expressed concerns that increasing the flexibility of their energy demand would counteract the gains in energy efficiency they have achieved over the past years. Generally, higher efficiency reduces the reserves and redundancies in a production

[13] See for example Next Kraftwerke GmbH in Germany.[55]

system (achieving the same production output with less energy input). Higher flexibility, on the other hand, relies on such reserves to even out fluctuations in energy supply and keep the production process going. A simple example would be stockpiling semi-finished products between production steps. This increases the capability to shift or shed loads in every production step, but it usually consumes additional energy (e.g. in food production where the cooling of semi-finished products is required). Moreover, flexibility needs can damage production equipment or reduce its lifespan as starting or stopping processes can cause considerable wear and tear (e.g. in the steel industry). The systemic need for flexibility and the simultaneous need for efficiency were viewed as contradictory by some interviewees. Nevertheless, both goals should be compatible in principle. One regulator estimated, that most companies can still increase their overall energy efficiency by 20 to 30% without impeding their flexibility potential.

3.2.4 Contractual security and robust market mechanisms as flexibility enablers

Electricity markets reflect the value of flexibility as prices are defined by matching supply and demand. Limited electricity supply results in higher prices which in turn makes flexibility options such as load reduction more attractive for the companies. All companies interviewed are large enough (consumption of more than 100’000 MWh per year) to choose their own electricity supplier. Most of them also participate in the electricity market, while only some rely exclusively on individual procurement contracts with local or national suppliers. Companies that participate in the market stated that hedging their electricity cost and supply with long-term contracts is crucial for their business continuity. This seems to be easier for larger companies with multiple sites since they can diversify more than smaller, single site companies. In addition, day-ahead and intra-day markets reflect the short-term value of flexibility. Generally, the industry representatives have stated that the reliability of these price signals and market mechanisms is crucial for their planning. On the other hand, situations where electricity demand is not served in a structural way and markets break down, are very hard for them to assess and prepare for upfront since the usual signals and mechanisms will not work anymore. This statement refers to the situations “in between” a market not closing and a mandated rationing regime (see section 1.5), that can occur in a winter shortage scenario.

A different approach for using energy flexibility in the industry, which is however not sufficient as a contribution to security of supply in winter, is the integration of industry loads into ancillary services. Some interviewed companies participate in tertiary balancing power and thus contribute to grid and system stability. However, grid operators have stated, that the potential for using industry demand in ancillary services is not very high. Once again, pricing and the value of flexibility seem to be critical aspects that make it harder to leverage additional potential.

There are also important considerations from the systemic perspective on flexibility. The difficulties in assessing the value of flexibility when the market breaks down originates partially from the design of the Swiss and European markets as Energy-only-markets. With the current market design, energy receives a price but the available capacity (either generation or load shedding) does not. This issue was recognized in almost all interviews, yet especially regulators were skeptical whether addressing it with capacity markets is a good idea. Some grid operators have publicly stated that they support the concept of a capacity market.[56]Other experts advocated a strategic reserve for extraordinary situations as it currently discussed in Swiss policy making. Some companies have emphasized the importance of a technology-neutral reserve on both sides of the market, even if the potential for industry participation is assumed to not be very large in the first place. If industry demand wanted to contribute to strategic reserves, it should be allowed to do so, according to these statements. It is about providing the right framework and incentives.

Regarding market integration of flexibility, grid operators and regulators also addressed the situation in other countries. Italy for example has apparently had contractual industry load shedding in operation for some time. Industry consumers can negotiate contracts for emergency load shedding with the transmission grid operator. When a system inadequacy occurs, the transmission grid operator can apply load shedding for a fixed price of 3000 Euro/MWh. It is however limited to ancillary services, hence no longer timespans are considered.[59] This "market of last resort" contributes to system stability. Italy is a net-importer of electricity, therefore, the demand side has a larger role to play in grid and system stability than in Switzerland. Similarly, France has apparently implemented comparable load shedding mechanisms for industry consumers as a contingency against issues with nuclear power plants. These concepts do however not consider seasonal shortages.

Overall, market integration and contractual security for industry load shedding or shifting is seen as an important topic. However, the maturity of market integration of industry loads is assessed as low by all interviewed stakeholders. Certain learnings can be drawn from other countries with higher maturity. However, most mechanisms to leverage industry flexibility in these countries are optimized to their circumstances. They depend on the energy mix, the demand structure, and the economic structure of these countries. They also focus on dealing with short term requirements such as peak load, not with structural production deficits over longer periods.

3.3 Nexus-e

I complement the induvial perspective from the interviews and the literature with scenario results from the system modelling platform Nexus-e.. In the following section, I first present the baseline scenario for the year 2030, which is used as a jumping-off point. Then, I developed deficit scenarios by adjusting the NTCs to create deficit situations, meaning that not all inland electricity demand could be served Finally, I look at specific trade-off scenarios in which the deficit can be addressed by either investing in gas power plants or shedding industry load (i.e. leveraging industry flexibility).

3.3.1 Baseline scenario

The baseline scenario represents a possible state of the Swiss energy system in the year 2030 based on many assumptions (see section 2.4). Most notably, the energy mix is fundamentally different in this scenario compared to the reference year 2020: PV generation increases from 2.65 TWh in 2020 to 16.99 TWh in 2030, overcompensating the decline of nuclear power from 24.19 TWh to 12.23 TWh. The total load increases from 59.69 TWh to 64.14 TWh and the yearly net exports grow from 5.5 TWh to 9 TWh. Moreover, the annual average electricity price increases from 53.3 CHF/MWh to 175.4 CHF/MWh. Looking at the monthly generation in the baseline scenario further indicates that the discrepancies between summer and winter seasons accentuate. Most notably, PV generation drops from 2.37 TWh in July to 0.35 TWh in December. The seasonal discrepancy is reduced by generation from pumped hydro that shifts to the winter months. Also biomass and wind contribute to generation in winter. However, the import deficit in winter still increases from 2020 to 2030.

Another important development is that the seasonal electricity market price fluctuations intensify. In 2020, the price peaks at 56.9 CHF/MWh in February and reaches its minimum at 51.1 CHF/MWh in June. In 2030, the prices fluctuates between 196.6 CHF/MWh in February and 152.4 CHF/MWh in May. The price surge and the changes in the energy mix are the results of endogenuous calculations of CentIv. One important exogenuous factor applied was the natural gas price which was assumed to increase from around 30 to 100 CHF/MWh from 2020 to 2030.

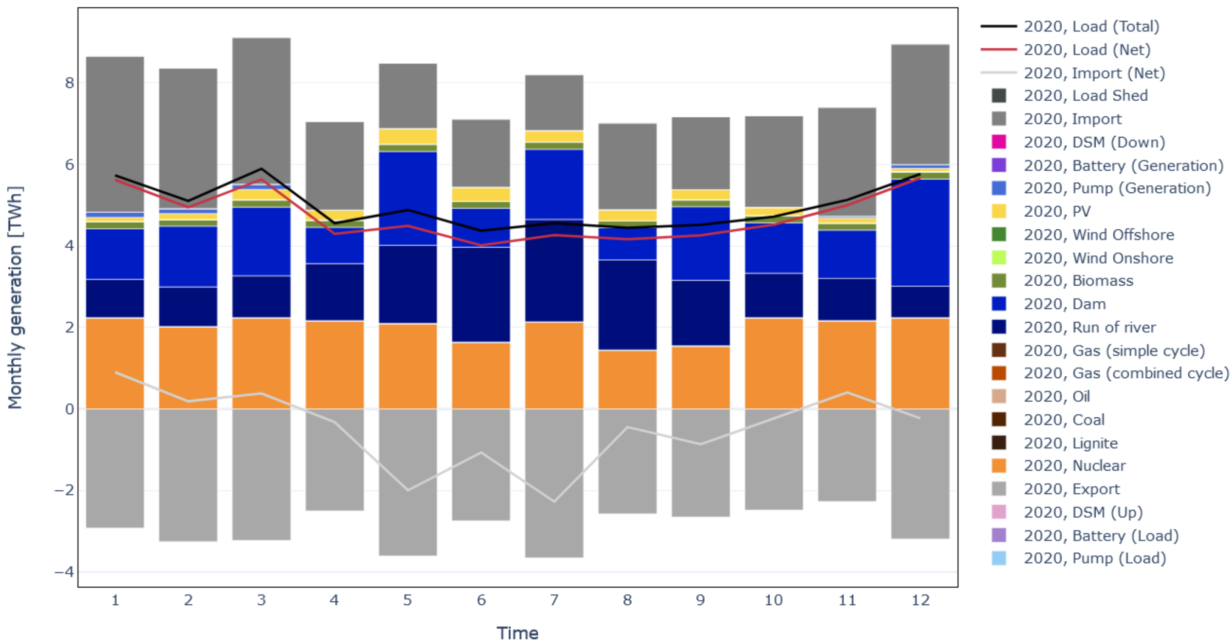


Figure 15: Monthly electricity generation and consumption 2020, baseline scenario.

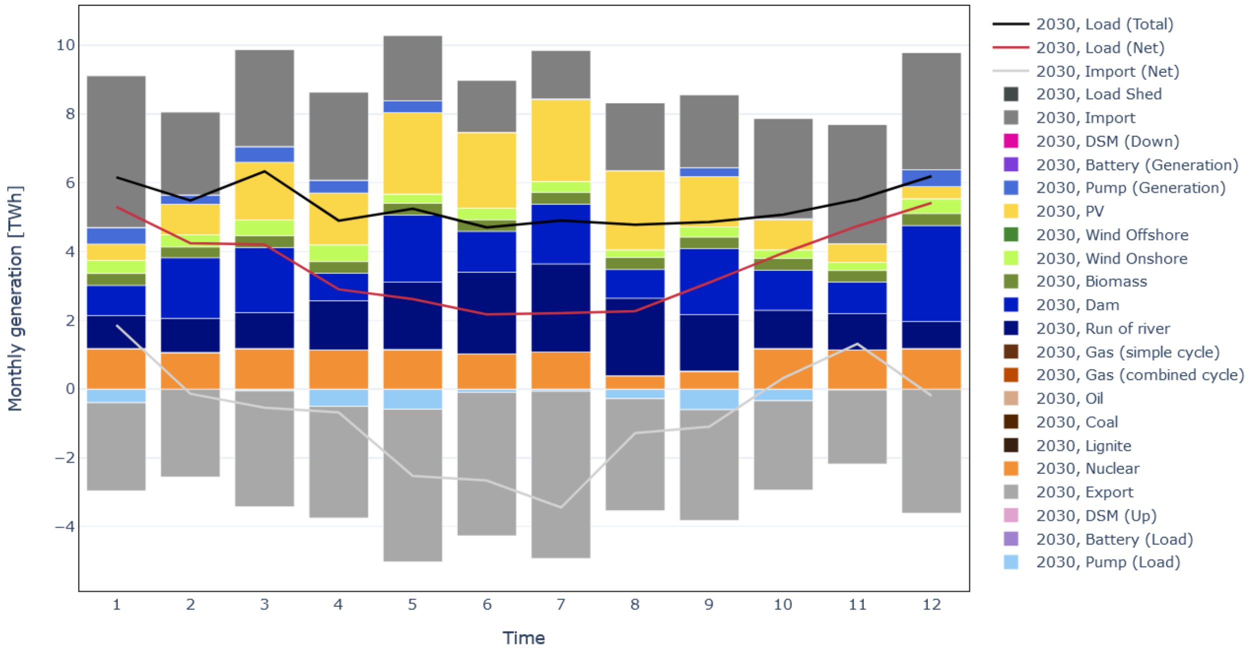


Figure 16: Monthly electricity generation and consumption 2030, baseline scenario.

3.3.2 Deficit scenarios

Based on the baseline scenario, I developed seven deficit scenarios by varying the NTCs from 30% to 0% of the baseline NTC values, in steps of 5%. The aim is to create a deficit, meaning a situation in which part of the inland demand could not be served. Such a deficit situation is a requirement for assessing the value of gas power plants and industry load shedding in the trade-off scenarios (see section 3.3.3).

Overall, the deficit scenarios suggested a high resilience of the energy system in 2030. When reducing NTCs and thus options for electricity trading, the model reacts by shifting hydro power as much as possible to the winter months (given storage volume and hydro inflow) while maximizing storage buildup in summer. As also exports are limited, the most expensive form of electricity generation is getting curtailed in summer months during which inland generation is higher than inland demand. In this scenario nuclear power is the most expensive form of electricity generation.

Only two scenarios (5% and 0% NTC remaining) caused a situation in which not all electricity demand could be served. In the NTC 0 scenario, the annual deficit amounts to 1.69 TWh, peaking in January with 0.35 TWh. In the NTC 5 scenario, the annual deficit amounts to 0.65 TWh, peaking also in January with 0.15 TWh. Figure 17 shows the deficit by the “Load shed” section of the bars. In this context, load shed means that there is residual demand that is not served after markets close. It does not represent actual reduced or shifted demand by companies or household as a contribution to the energy system (this is represented as “DSM” section of the bars).

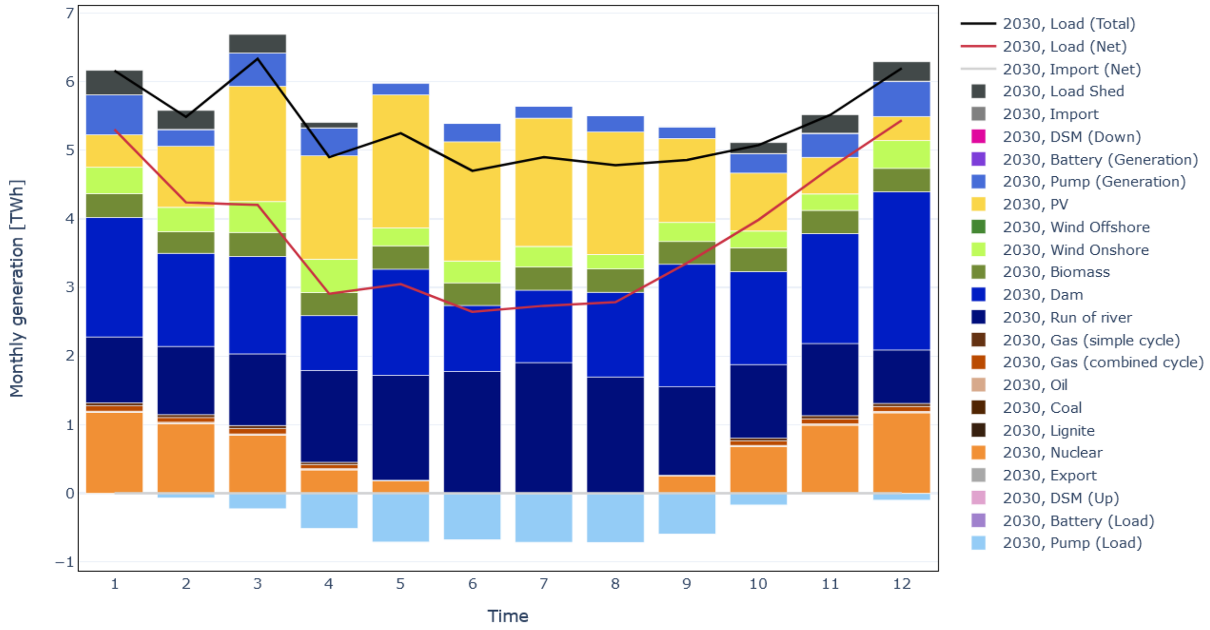


Figure 17: Deficit scenario with 0% NTC.

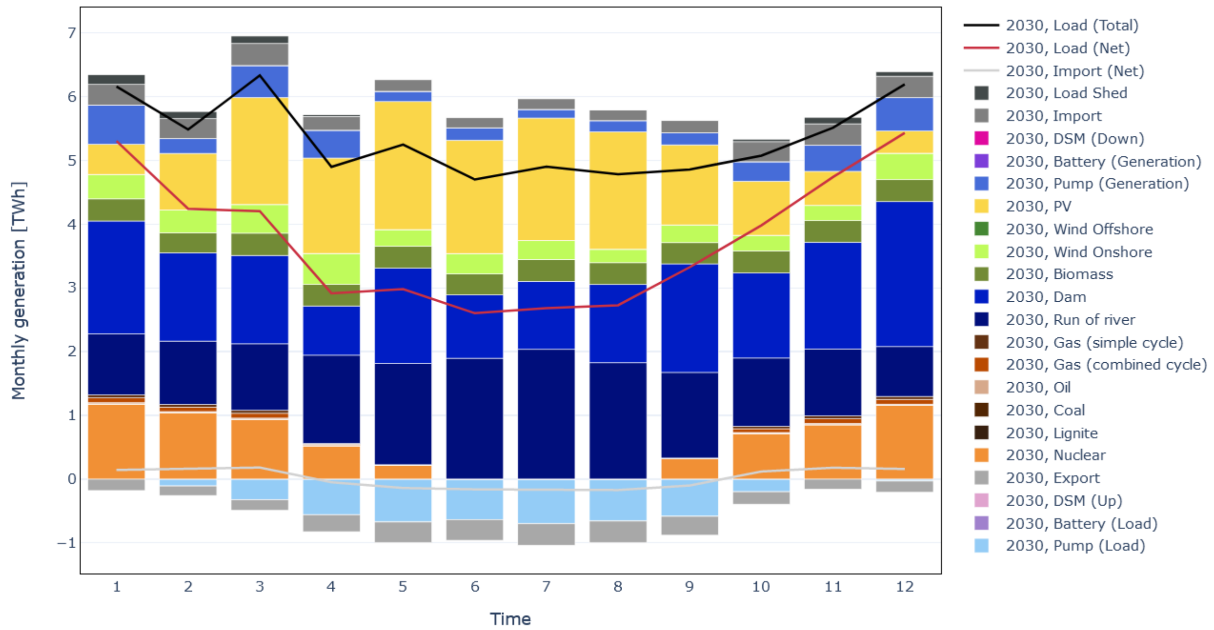


Figure 18: Deficit scenario with 5% NTC.

3.3.3 Trade-off-scenarios

Based on the deficit scenarios NTC 0 and NTC 5, which showed some level of demand not served, I developed 24 trade-off scenarios: For each of the two deficit scenarios, I developed five scenarios by varying the costs of load shedding from CHF 0,- to CHF 10’000,-/MWh in steps of CHF 2’500, and five scenarios by varying the potential of load shedding (percentage of total industry load that can be shed) from 0% to 25% in steps of 5%. Total industry load in all scenarios is 13.5 TWh. For the NTC 5 case only, I developed four additional scenarios to assess more granular price differences from CHF 500,- to CHF 2’500.-/MWh, in steps of CHF 500.-/MWh.

Table 19 shows an exemplary trade-off scenario for NTC 0. The cost of industry load shedding is CHF 500.-/MWh and the load shedding potential is 25% of the total industry load. In this scenario, the model uses 1.039 TWh of industry load shedding in the year 2030. This would theoretically cover more than half of the 1.69 TWh deficit in NTC 0. In the NTC 5 case the industry load shedding would even cover 0.57 TWh of the 0.65 TWh deficit under optimal conditions.

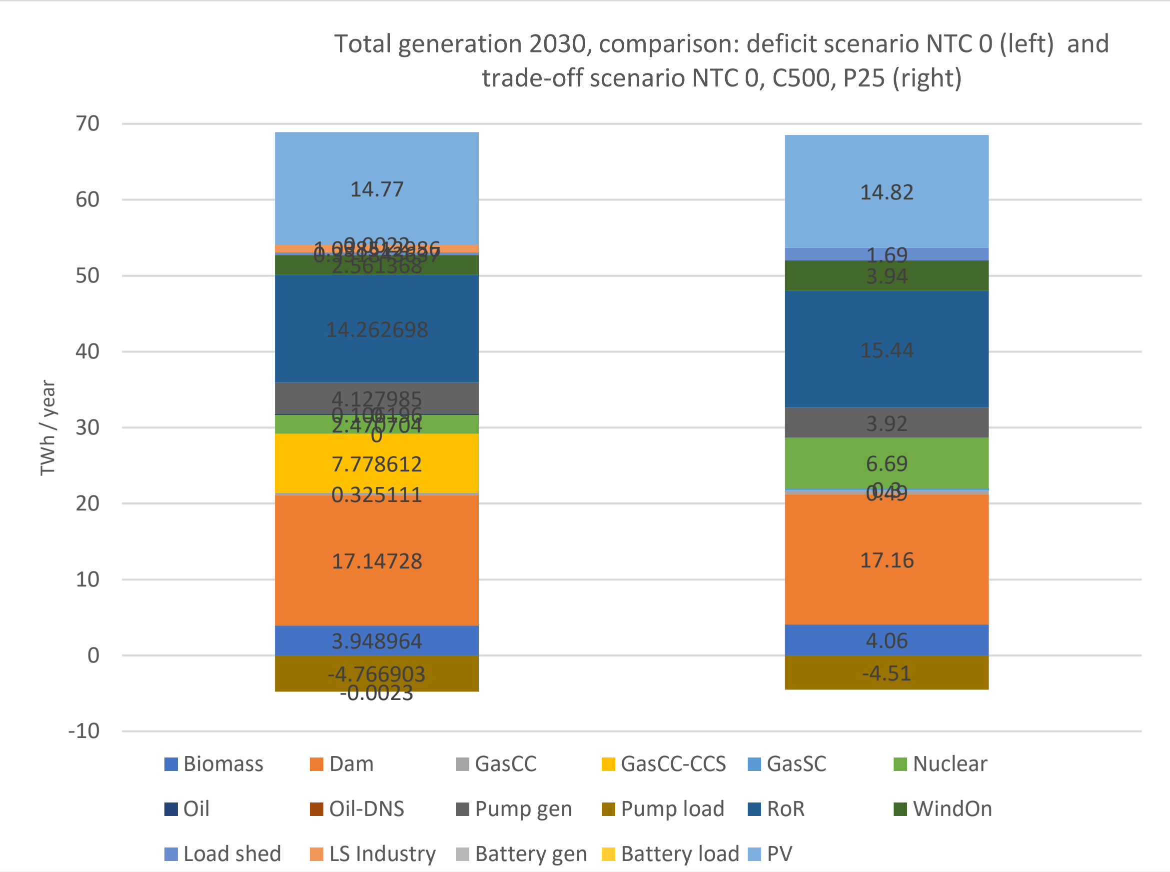


Figure 19: Comparison: deficit scenario NTC 0 (left) and trade-off scenario NTC 0, C500, P25 (right).

Figure 20 shows the results for the NTC 0 and NTC 5 trade-off scenarios at five different levels of industry load shedding potential. The model uses more industry load shedding, the higher the potential gets. Also, the amount used under NTC 0 is higher than under NTC 5. Moreover, the share of used industry load shedding at NTC0 and NTC5 is almost constant when varying available load shedding potential. This indicates that some part of industry load (e.g. load profile, location of site) is more valuable to the system than others.

Table 21 shows the results for the NTC 0 trade-off scenarios at five different cost levels for industry load shedding and for the NTC 5 scenarios at eight different cost levels. In the NTC 0 scenario (with a higher deficit than NTC 5), industry load shedding is leveraged at higher cost than at NTC 5. In the NTC 5 case, the contribution of industry load shedding starts at a cost level of 2’500 CHF/MWh and equals zero at higher cost levels. In the NTC 0 case, industry load shedding is already leveraged at 10’000 CHF/MWh. This implies that industry flexibility could be leveraged more easily, the worse the situation. Furthermore, load shedding seems to occur at prices which are higher than the market prices for electricity (in both NTC 0 and NTC 5 the prices are around CHF 500.-/MWh). This seems counter-intuitive since the cost for load shedding can be seen as opportunity cost of a company. From this perspective, one would assume that there is a strong correlation to electricity prices.

Available industry load shedding potential [%]	**Available industry load shedding potential [TWh]**	**NTC 5: Used industry load shedding trade-off scenarios [TWh]]**	**NTC 5: Share of industry load shedding potential used [%]**	**NTC 0: Used industry load shedding trade-off scenarios [TWh]**	**NTC 0: Share of industry load shedding potential used [%]**
5%	0.675	0.14	20%	0.22	33%
10%	1.35	0.27	20%	0.43	32%
15%	2.025	0.29	14%	0.63	31%
20%	2.7	0.46	17%	0.83	31%
25%	3.375	0.57	17%	1.04	31%

Figure 20: load shedding at cost of CHF 500.- / MWh for different flexibility potentials (maximum 25% of total industry load).

Industry load shedding cost [CHF/MWh]	**Available industry load shedding potential [TWh]**	**NTC 5: Used industry load shedding trade-off scenarios [TWh]**	**NTC 5: Share of industry load shedding potential used [%]**	**NTC 0: Used industry load shedding trade-off scenarios [TWh]**	**NTC 0: Share of industry load shedding potential used [%]**
500	3.38	0.57	17%	1.04	31%
1000	3.38	0.28	8.3%	-	-
1500	3.38	0.19	5.6%	-	-
2000	3.38	0.11	3.2%	-	-
2500	3.38	0.07	2.1%	0.39	12%
5000	3.38	0	0%	0.23	7%
7500	3.38	0	0%	0.15	4.4%
10000	3.38	0	0%	0.06	1.8%

Figure 21: Load shedding at 25% flexibility potential of total industry load for different cost levels.

The key observation is that the model does generally leverage quite a lot of industry load shedding under some assumptions. In both NTC 0 and NTC 5 scenarios, the maximum amount of load shedding covers a good portion of the demand not served in the two deficit scenarios.

Therefore it is interesting that the model still focuses the bulk of investments on extra generation capacities. For example, the highest shares of industry load shedding are achieved in the trade-off-scenarios with the highest flexibility potentials and the lowest load shedding cost. The overall maximum load shedding is reached at NTC 0, cost of CHF 500.- and a flexibility potential of 25%. In this case, the model uses 1.039 TWh of industry load shedding. However, even then, the contribution to total generation remains marginal as the model also uses 8.1 TWh of generation from gas power plants to meet demand. If we look at the scenarios with cost of CHF 500.-/MWh more closely, we also see that the load shed grows in a linear fashion as the flexibility potential increases. Similarly, the share of power generation from gas plants decreases linearly, but slightly less steeply. This is illustrated in the following figures 22 and 23. Figures 24 and 25 illustrate the scenarios with fixed flexibility potential and variable cost. The curves behave similar to the figures 22 and 23, even though the decrease in load shedding used (figure 24) is not quite linear but a bit steeper in the beginning (meaning for low load shedding cost).

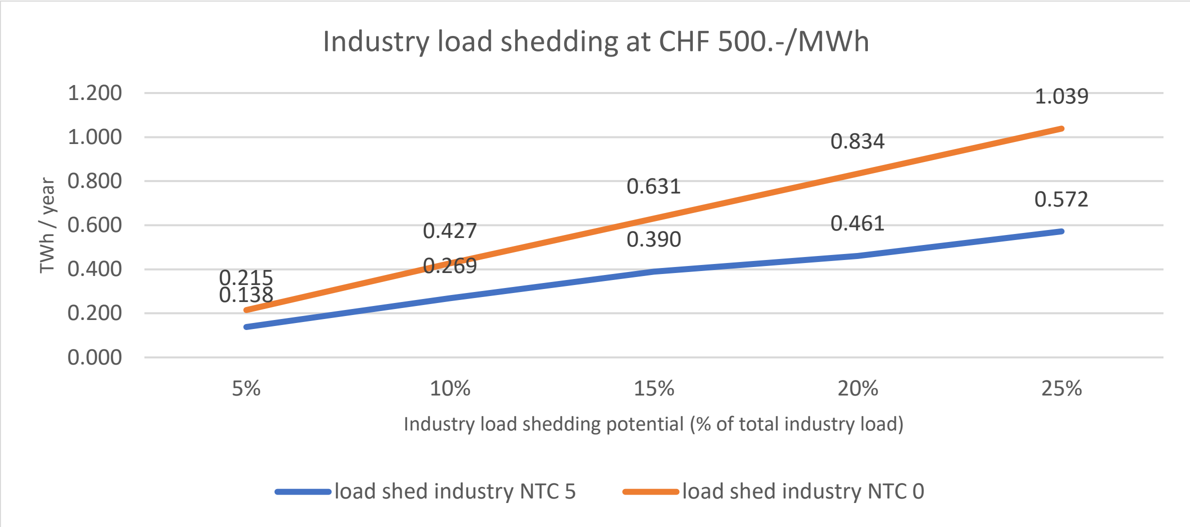


Figure 22: Amount of industry load shedding at cost of CHF 500.-/MWh.

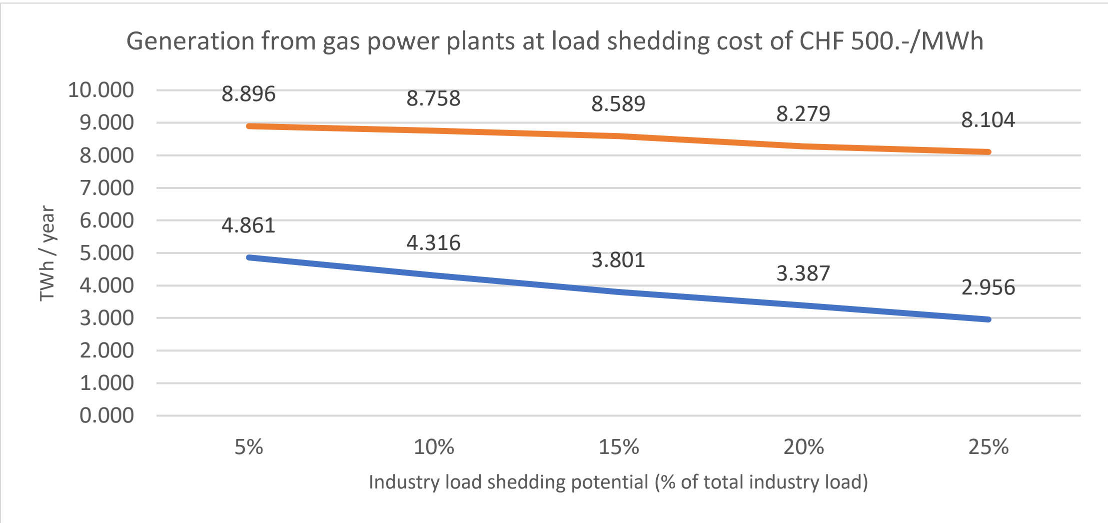


Figure 23: generation from gas power plants at industry load shedding cost of CHF 500.-/MWh.

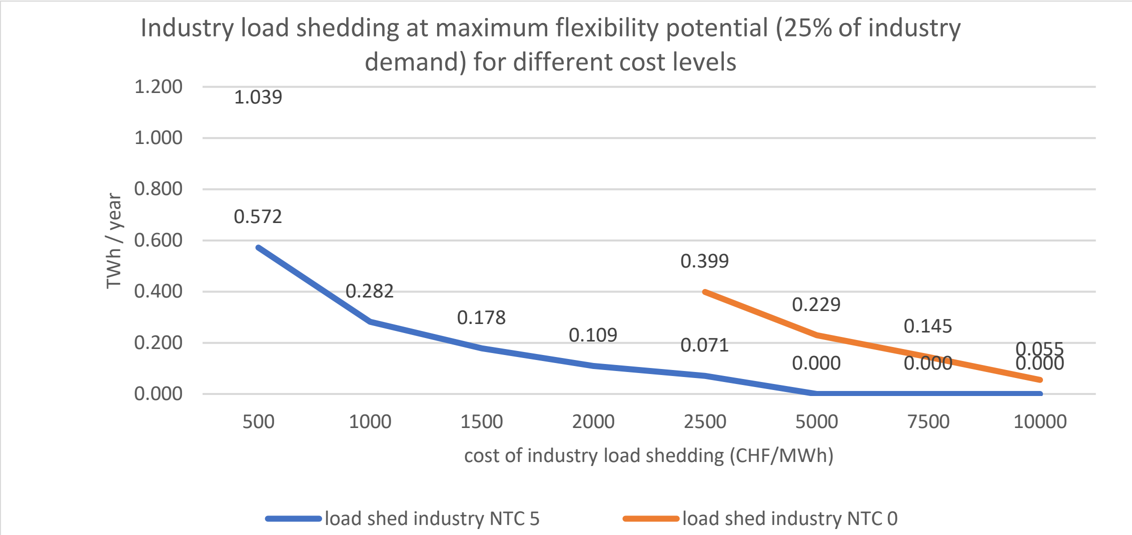


Figure 24: Industry load shedding at maximum flexibility potential (25% of industry demand) for different cost levels.

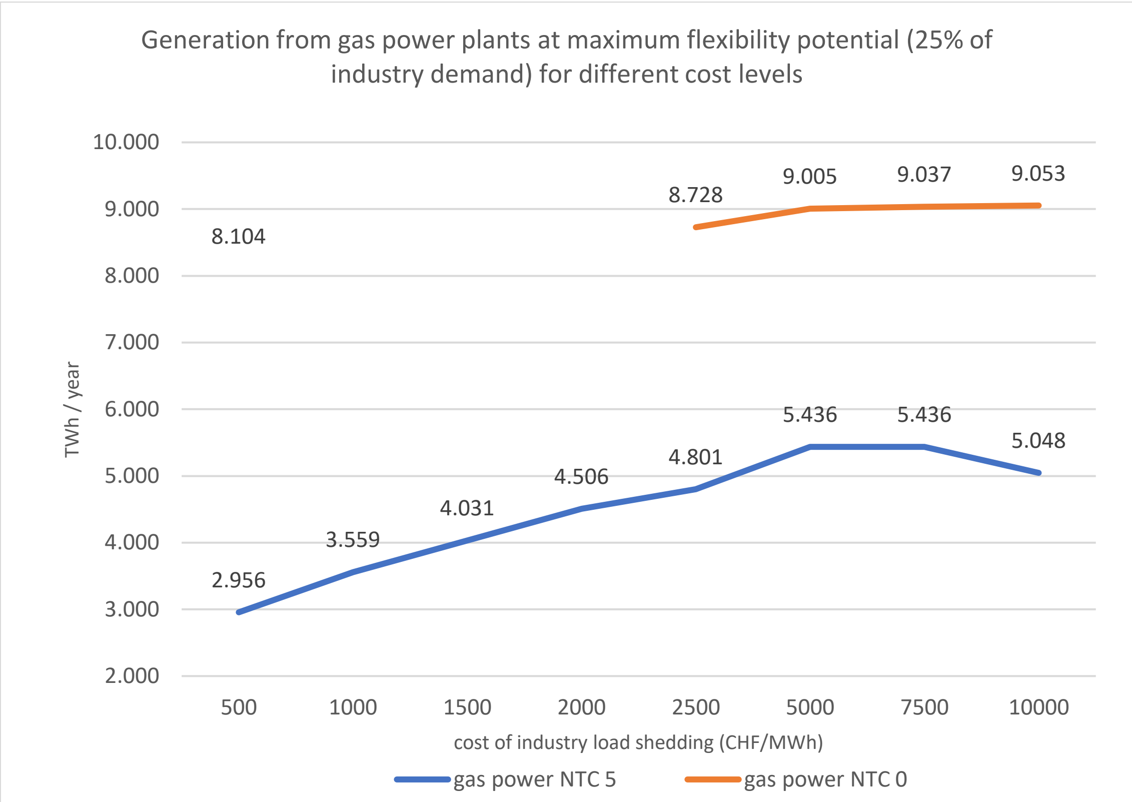


Figure 25: Generation from gas power plants at maximum flexibility potential (25% of industry demand) for different cost levels.

4. Discussion

When it comes to the question whether flexible industry loads can contribute to security of supply in winter, three aspects stand out consistently in the available literature, in the stakeholder interviews and in the system modelling results:

1. **The potential for load shedding or shifting over longer time periods in a winter scenario with electricity shortages appears to be very limited.** This is especially consistent in the literature review results and the interviews. The best available estimates for Switzerland suggest a very low flexibility potential compared to total load, current industry load, expected winter deficits for Switzerland. Although the evidence is rather thin for Switzerland, this is consistent with research from other countries. The reservations expressed and limitations identified in almost all interviews fully support this rather pessimistic viewpoint. The analysis in Nexus-e suggests that there may be a larger contribution under optimistic assumptions (e.g. a flexibility potential of 25% of total industry demand in the system modelling, which exceeds the more optimistic estimates from the literature). Still, it is plausible to conclude that flexible industry loads will not be able to fully substitute for additional generation capacities in a scenario of winter shortages in 2030, as substantial investments in gas power plants can be observed in all scenarios.
2. **Trade-offs and opportunity cost for companies to leverage flexibility are significant influences.** For individual companies, there is no universal pathway to leverage flexibility, but it's always a very contextual decision depending on what their business model is and what their costumers' needs are. Unfortunately, there is little to no data on these decision processes. The literature and the interviews however support this viewpoint. The Nexus-e analysis gives further indications in this direction, since industry load shedding is leveraged the most at the lowest flexibility cost (i.e. the lowest opportunity cost or the highest value of flexibility) and the highest flexibility potential.
3. **There are profound discrepancies between the systemic perspective and the individualistic perspective on industry flexibility.** Particularly the Nexus-e analysis and in part also the literature review gave some indications on what kind of flexibility the future energy system requires. This systemic perspective seems to be very dominant in most research so far. In contrast, some studies and especially the interviews gave a very different picture of the kind of flexibility that the industry sector is willing and able to provide. To achieve more meaningful results in future research or also in policy making, the two perspectives need to be reconciled.

No matter the potential and the cost of industry flexibility, market opportunities and incentives are always required to activate individual companies. It can be argued that, with the right market design, an optimum of industry flexibility could be achieved, if companies received strong and positive incentives to invest in flexibility. It is however difficult to find the right market design. From the anecdotal evidence of the interviews, it became clear that it is challenging to match the company-specific interest in secure and cheap supply match with the socio-economic interests and system stability. The best strategy is therefore to avoid winter shortages at all. While the market integration of Renewables and the necessary demand side changes make the considerations on industry flexibility worthwhile, it is less complex and uncertain to invest in sufficient electricity generation, storage and transmission capacities to avoid issues with security of supply in the first place.

Blind spots of this thesis need to be addressed as well at this point. For a more in-depth literature review, there is not yet enough research on the given topic for Switzerland. A few more studies on the industry flexibility potential in Switzerland and on their role for longer shortages in winter scenarios would go a long way to put any further analysis on a more solid foundation. Research that focuses on a better understanding of the technical, socio-technical and economic flexibility potential and particularly on flexibility potential for longer durations would be very beneficial. Moreover, empiric research into the considerations and decision processes of individual companies could lead to a better understanding of their perspective on flexibility: The interviews could be improved with a more structured approach that covers more stakeholders and focuses on creating data points. This would be a great opportunity to get more systematic insights into the preferences and choices of individual companies when it comes to flexibility. The accuracy and the scope of the system modelling could also still be improved. This thesis only used two of the five modules of Nexus-e and only one of three loops. Especially an analysis using the Macro Economics Module would help to better model and understand the decision processes (for example by considering the elasticity of electricity demand of industry companies or by including more seasonal effects). Equally, more real-life load profiles would further enrich the input data. The static nature of the modules used in this thesis imply that investment decisions are only taken at a certain point in time and not continually as with a dynamic model. Also, CentIv does not consider uncertainties, meaning that investment decisions are made with "perfect knowledge of future demand, inflows, weather conditions, etc."[14] These factors limit the practical relevance of the model to a certain extent. Under real conditions, the trade-off between investments in industry demand flexibility and additional gas power plants is taken continually and with considerable uncertainty. Overall, the mixed method approach yielded some interesting results used could still be refined. Last but not least, practical research on how to increase flexibility by improving certain production processes could be a fruitful collaboration effort between the industry sector and academic research. In Germany, such an approach has produced very promising results.[15] It has also helped to align business interests with systemic interests and

[14] [37] S. 9

[15] A prime example is the "Kopernikus-Projekt SynErgie", a collaborative work between the German government, Science and industry. It defines and assesses flexibility potential and also fosters technology pilots to leverage flexibility.[58]

direct policy making towards effectively improving regulatory conditions for flexible industry loads. In Switzerland, the market design is being reshaped right now, which would be an ideal opportunity to have a more prominent discussion about the role of demand side integration and industry flexibility for mitigating the Swiss electricity deficit in winter. The draft for the new Swiss electricity supply act would enable industry loads to participate in a strategic energy reserve. This is a step in the right direction. Further steps, such as a full market liberalization are unfortunately not likely to be adopted any time soon. The contributions of such reforms to demand side integration, industry flexibility and ultimately system resilience is still overlooked.

5. Conclusion

This thesis investigates how and to what extent the flexibility of the Swiss industry can contribute to security of electricity supply in a winter shortage scenario in 2030. First, two distinct perspectives on industry flexibility are identified: a systemic perspective and a individualistic perspective. The topic is then introduced to create an understanding of the demand structure in the Swiss industry sector and the significance of flexibility for the electricity system and individual companies. A mixed methods approach is used afterwards to bring these viewpoints together and to give a broad overview of the topic. Evidence from a literature review gives an indication of flexibility definitions and flexibility potential assessments. Anecdotal evidence from semi-structured interviews illustrates how flexibility options are assessed under real conditions. Also, the Nexus-e platform is used to gain quantitative evidence from a system modelling analysis. This produces a wide spectrum of insights: Defining industry flexibility is complex and the realizable potential may be small. Industry companies and other stakeholders name many limitations to leveraging more flexibility potential, either technical or socio-economic. Lastly, the Nexus-e analysis indicates that industry flexibility may contribute to security of supply winter shortage situations via load shedding, but never to the extent that additional generation capacities (gas power plants) can be fully replaced. According to these findings, this thesis concludes that electricity flexibility from industry consumers is unfortunately no panacea for a winter scenario with a structural electricity deficit over longer periods of time. Flexibility can only be part of a mix of measures that increases seasonal resilience of the Swiss electricity system. To foster industry flexibility measures and to find its optimal role in the electricity system of the future, further research and policy action is advisable. From a scientific perspective it is also necessary to better understand the individualistic viewpoint on flexibility and bring it together with the more established systemic viewpoint. For example, a company's decision processes for investing in flexibility are still poorly understood and do not tie into system-driven research. Without a holistic view and a strong baseline of scientific evidence, this discussion will prove difficult. Therefore, this thesis hopes to motivate further research, e.g. with more structured interviews or a more refined system modelling analysis.

Acknowledgements

I would like to acknowledge and thank my advisor for this thesis, Dr. Marius Schwarz, as well as all people who supported me with the development of the scenarios: Arijit Upadhyay, Jared Garrison, and Elena Raycheva. I would also like to thank all the interviewees, colleagues and friends who helped me to realize this project.

Appendix

1) List of interview topics

- General viewpoints on the topic of energy flexibility
- For industry associations:
  - Position on the general development of the energy system
  - Position on demand side integration and incentives for industry flexibility
- For companies:
  - Description of the general production set up
  - Sequence of the production process
  - Electricity use during production and overall energy management
  - Assessment of flexibility potential in their given context
  - Provision of an electricity load profile as input data for the quantitative analysis conducted for this thesis.
- For grid operators:
  - Functionality and current state of ancillary services
  - Possible benefits of industry flexibility for grid stability
  - Limitations and challenges due to the complexity of the Swiss and the European power grid.
- For regulators:
  - Regulation or market design which prohibits more energy flexibility in the industry sector, examples of successful market integration
  - Systemic benefits and limitations of industry flexibility
  - Blind spots from a conceptual or empiric point of view

2) Definition of the twelve subsectors analyzed (based on NOGA 2008)

Subsector	**NOGA Codes included**
Food products	10, 11, 12
Textiles	13, 14, 15
Paper products	17, 18
Chemicals / pharmaceuticals	20, 21
Cement	23.32, 23.51, 23.52
Other non-ferric minerals	23.11-14, 23.19, 23.20, 23.31, 23.41-44, 23.49, 23.61-65, 23.69, 23.70, 23.91, 23.99
Basic metals	24.10, 24.20, 24.31-34, 24.51, 24.52
Non-ferric metals	24.41-46, 24.53, 24.54
Fabricated metal products	25.11, 25.12, 25.21, 25.29, 25.30, 25.50, 25.61, 25.62, 25.71-73, 25.91-94, 25.99, 26, 27.11, 27.12, 27.20, 27.31, 27.32, 27.33, 27.40, 27.90, 28.23, 29.31
Machines & equipment	25.40, 27.51, 27.52, 28.11-15, 28.22, 28.24, 28.25, 28.29, 28.30, 28.41, 28.49, 28.91-96, 28.99, 30.40

Other industries	07, 08, 09, 16, 22, 29.10, 29.20, 29.32, 30.11, 30.12, 30.20, 30.30, 30.91, 30.92, 30.99, 31, 32
Construction	41, 42, 43

3) Eight critical factors that account for differences in potential assessments

Issue	Critical questions
Concept of flexibility potential	▪ Are there differences in semantics for descriptions of the same thing? ▪ Is the granularity of analysis similar (same amount of flexibility categories)? ▪ Are identical categories calculated with different data? ▪ Is the concept used comprehensive or does it have gaps? ▪ How are the interdependencies of categories assessed?
Parameters for data used in assessment	▪ Which parameters are used to identify the potentials (e.g. company load profiles, energy cost or technical key figures)?
Direction and timeframe of flexibility	▪ Is there a differentiation between positive and negative flexibility? ▪ Are both positive and negative flexibility included? ▪ Are load shifts and sheds equally considered? ▪ For how long is flexibility used?
Static and dynamic effects	▪ Is the potential constant or does it change over time (e.g. with technological progress)?
Boundaries for data collection	▪ Are the potentials assessed for single processes, companies or entire industries?
Boundaries for description of potentials	
Methodology for assessment of potential	▪ Is data projected or extrapolated and if yes, how?
Differentiation	▪ Are economic, temporal and local differences considered in the analysis?

References

[1] Paquier, Serge: «Elektrizitätswirtschaft», in: *Historisches Lexikon der Schweiz (HLS)*, Version vom 26.01.2016, übersetzt aus dem Französischen. Online: https://hls-dhs-dss.ch/de/articles/042014/2016-01-26/, last visited: 25.07.2022

[2] Bellwald, Werner: «Lonza», in: *Historisches Lexikon der Schweiz (HLS)*, Version vom 28.07.2009. Online: https://hls-dhs-dss.ch/de/articles/041941/2009-07-28/, last visited: 25.07.2022.

[3] Marti, Kurt: «Die Lonza und der Ausverkauf der Wasserkraft», in: Infosperber, Version vom 02.11.2012. Online: https://www.infosperber.ch/politik/schweiz/die-lonza-und-der-ausverkauf-der-wasserkraft/, last visited: 25.07.2022.

[4] EnAlpin AG: «Historie», Online: https://www.enalpin.com/enalpin/ueber-uns/historie/, last visited: 26.07.2022.

[5] «1891: Das Jahr des grossen Coups der Regionalwerke Baden», in: Badener Tagblatt, Version vom 19.05.2016. Online: https://www.badenertagblatt.ch/aargau/baden/1891-das-jahr-des-grossen-coups-der-regionalwerke-baden-ld.1556634, last visited: 25.07.2022.

[6] Steurer, Martin: «Analyse von Demand Side Integration im Hinblick auf eine effiziente und umweltfreundliche Energieversorgung», Stuttgart, 2017. Online: https://elib.uni-stuttgart.de/handle/11682/9198, last visited: 25.07.2022.

[7] Vossebein, André; Muster, Stefan; Betschart, Ueli; Kölliker, Beat: «Potential Demand Side Management in der Schweiz», Bern, 2019. Online: https://pubdb.bfe.admin.ch/de/publication/download/9887, last visited: 25.07.2022.

[8] Moura, Pedro S.; de Almeida Anibal T.: «The rôle of demand-side management in the grid integration of wind power», Applied Energy 87 (2010) 2581–2588.

[9] International Renewable Energy Agency IRENA: «Power System Flexibility», Online: https://www.irena.org/energytransition/Power-Sector-Transformation/Power-System-Flexibility, last visited: 25.07.2022.

[10] International Energy Agency IEA: «Demand Response», Paris, 2022. Online: https://www.iea.org/reports/demand-response, last visited: 25.07.2022.

[11] O'Shaughnessy, Eric; Shah, Monisha; Parra, David; Ardani, Kristen: «The demand-side resource opportunity for deep grid decarbonization», 2022.

[12] SmartEn: «European Market Monitor for Demand Side Integration 2021», Online: https://smarten.eu/wp-content/uploads/2022/02/EU_Market_Monitor_2021_PUBLIC_ONLINE.pdf, last visited: 26.07.2022.

[13] Verein Deutscher Ingenieure (VDI): «Energieflexible Fabrik – Grundlagen», 2020. Online (Paywall): https://www.vdi.de/richtlinien/details/vdi-5207-blatt-1-energieflexible-fabrik-grundlagen, last visited: 25.07.2022.

[14] Swissgrid: «Grid stability», Online: https://www.swissgrid.ch/en/home/operation/regulation/grid-stability.html, last visited: 26.07.2022.

[15] Union for the co-ordination of transmission of electricity UCTE: «System Adequacy Methodology», Online: https://www.ucte.org/_library/systemadequacy/saf/UCTE_System_Adequacy_Methodology.pdf, last visited: 26.07.2022.

[16] Swissgrid: «Grundlagen Systemdienstleistungen», Online: https://www.swissgrid.ch/dam/swissgrid/customers/topics/ancillary-services/as-documents/AS-concept-V1-1-de.pdf, last visited: 25.07.2022.

[17] Swiss Federal Office for Energy SFOE: «Energieperspektiven 2050+ - Zusammenfassung der Ergebnisse», 2020, Online: https://pubdb.bfe.admin.ch/de/publication/download/10320, last visited: 26.07.2022.

[18] Swiss Federal Office for Energy SFOE: Schweizerische Elektrizitätsstatistik 2021, 2022, Online: https://pubdb.bfe.admin.ch/de/publication/download/10942, last visited: 26.07.2022.

[19] Swiss Electricity Commission ElCom: System Adequacy 2030: Schlussbericht, 2020, Online: https://www.elcom.admin.ch/dam/elcom/de/dokumente/2020/schlussberichtelcomsystemadequacy2030.pdf.download.pdf/Schlussbericht%20ElCom%20System%20Adequacy%202030.pdf, last visited: 26.07.2022.

[20] Swiss Federal Office for Energy SFOE: Energieperspektiven 2050+ - Exkurs Winterstrom, 2021, Online: https://pubdb.bfe.admin.ch/de/publication/download/10641, last visited: 26.07.2022.

[21] Swiss Federal Office for Energy SFOE: Schweizerische Gesamtenergiestatistik 2021, 2022, Online: https://www.bfe.admin.ch/bfe/de/home/versorgung/statistik-und-geodaten/energiestatistiken/gesamtenergiestatistik.exturl.html/aHR0cHM6Ly9wdWJkYi5iZmUuYWRtaW4uY2gvZGUvcHVibGljYX/Rpb24vZG93bmxvYWQvMTA5ODE=.html, last visited: 26.07.2022.

[22] Del Taglia, Christian; Scherer, Roman; Chalimoudra, Athanassia; Stamm, Natalia: Energieverbrauch in der Industrie und im Dienstleistungssektor – Resultate 2020, Bern, 2021, Online: https://pubdb.bfe.admin.ch/de/publication/download/10553, last visited 26.07.2022.

[23] OECD: Switzerland – Economic snapshot (June 2022), Online: https://www.oecd.org/economy/switzerland-economic-snapshot, last visited: 26.07.2022.

[24] International Energy Agency IEA: Key Energy Statistics 2021: Final consumption, Online: https://www.iea.org/reports/key-world-energy-statistics-2021/final-consumption, last visited: 26.07.2022.

[25] Swiss Federal Office for Energy SFOE: Energiestrategie 2050 – Erstes Massnahmenpaket, 2020, Online: https://www.bfe.admin.ch/bfe/de/home/politik/energiestrategie-2050/erstes-massnahmenpaket.html, last visited: 26.07.2022.

[26] Swiss Federal Office for Energy SFOE: «Stromversorgungssicherheit Schweiz 2025 – Zusammenfassung der Studie «Analyse Stromzusammenarbeit Schweiz-EU»», 2021, Online: https://pubdb.bfe.admin.ch/de/publication/download/10716, last visited: 26.07.2022.

[27] Swiss Electricity Commission ElCom: «Höhere Tarife, unsichere Versorgungssituation, Version vom 02.06.2022, Online: https://www.elcom.admin.ch/elcom/de/home/dokumentation/medienmitteilungen.msg-id-89087.html, last visited 26.07.2022.

[28] Federal Office for Civil Protection FOCP: Strommangellage – Gefährdungsdossier, 2020, Online: https://www.babs.admin.ch/content/babs-internet/de/aufgabenbabs/gefaehrdrisiken/natgefaehrdanalyse/gefaehrddossier/_jcr_content/contentPar/accordion/accordionItems/technikbedingte_gef_/accordionPar/downloadlist/downloadItems/153_1604483426621.download/26-Strommangellage-GD-de.pdf, last visited: 26.07.2022

[29] Bundesgesetz über die Stromversorgung (Stromversorgungsgesetz, StromVG), Version vom 01.06.2021, Online: https://www.fedlex.admin.ch/eli/cc/2007/418/de, last visited: 26.07.2022.

[30] Swiss Federal Council: «Bundesrat treibt Vorsorgeplanung für Stromversorgungssicherheit voran», Version vom 13.10.2021, Online: https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-85447.html, last visited: 26.07.2022.

[31] Swiss Federal Council: «Versorgungssicherheit: Bundesrat richtet ab dem nächsten Winter eine Wasserkraftreserve ein und plant Reserve-Kraftwerke», Version vom 17.02.2022, Online: https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-87202.html, last visited: 26.07.2022.

[32] Vogel, Benedikt: «Industrieanlagen stabilisieren Stromnetz», Version vom 30.08.2017, Online: https://www.bulletin.ch/de/news-detail/industrieanlagen-stabilisieren-stromnetz.html, last visited: 26.07.2022.

[33] Schaffner, Barbara: «Ostral 2. Eine Strommangellage mit marktwirtschaftlichen Mechanismen effizient bekämpfen», Version vom 17.03.2022, Online: https://www.parlament.ch/de/ratsbetrieb/suche-curia-vista/geschaeft?AffairId=20223260, last visited: 26.07.2022.

[34] Swiss Federatl Council: «Botschaft zum Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien», Version vom 18.06.2021, Online: https://www.newsd.admin.ch/newsd/message/attachments/67174.pdf, last visited: 26.07.2022.

[35] Swiss Electriticty Commission ElCom: «Konzept Spitzenlast-Gaskraftwerk zur Sicherstellung der Netzsicherheit in ausserordentlichen Notsituationen – Bericht zuhanden Bundesrat», Bern, 2021. Online: https://www.elcom.admin.ch/dam/elcom/de/dokumente/2022/konzeptspitzenlastgaskraftwerk.pdf.download.pdf/Konzept%20Spitzenlast-Gaskraftwerk.pdf, last visited: 25.07.2022.

[36] Nexus-e: Model Framework, Online: https://nexus-e.org/model-framework/, last visited: 26.07.2022.

[37] Raycheva, Elena; Schaffner, Christian; Hug, Gabriela: Nexus-e: Integrated Energy Systems Modeling Platform – CentIv Module Documentation, Version vom 27.06.2020, Bern, Online: https://nexus-e.org/wp-content/uploads/2021/01/ModuleReport_CentIv.pdf, last visited: 26.07.2022.

[38] Garrison, Jared; Gjorgiev, Blazhe; Han, Xuejiao; van Nieuwkoop, Renger; Raycheva, Elena; Schwarz, Marius; Yan, Xuqian; Demiray, Turhan; Hug, Gabriela; Sansavini, Giovanni; Schaffner, Christian: Nexus-e: Integrated Energy Systems Modeling Platform – Input Data and System Setup, Version vom 27.11.2020, Bern, Online: https://nexus-e.org/wp-content/uploads/2021/01/Nexus-e_InputData_Report.pdf, last visited: 26.07.2022.

[39] Bundesverband der Energie- und Wasserwirtschaft BDEW: Standardlastprofile Strom, Version vom 01.01.2017, Online: https://www.bdew.de/energie/standardlastprofile-strom/, last visited: 26.07.2022.

[40] Energieagentur der Wirtschaft EnAW, Online: www.enaw.ch, last visited: 26.07.2022.

[41] Stamm, Natalia; Kost, Michael: Energieverbrauch in der Schweiz 2011-2016 nach NOGA Stufe 2 (Abteilungen), Bern, 2019. Online: https://pubdb.bfe.admin.ch/de/publication/download/9627, last visited: 25.07.2022.

[42] Swiss Federal Statistical Office: NOGA 2008 – General Classification of Economic Activities: Explanatory Notes, Version vom 15.12.2008, Bern, Online: https://www.bfs.admin.ch/bfs/en/home/statistics/industry-services/nomenclatures/noga.assetdetail.344620.html, last visited: 26.07.2022.

[43] Gruppe grosser Stromkunden GGS: «Verlauf des Strompreises an der Börse», Online: https://stromkunden.ch/?p=1144, last visited: 27.07.2022.

[44] Swiss Electricity Commission ElCom: «Terminmarktbericht, Version vom 31.05.2022, Online: https://www.elcom.admin.ch/dam/elcom/de/dokumente/terminmarktberichte_MU/terminmarktbericht31-05-2022.pdf.download.pdf/Terminmarktbericht%20vom%2031-05-2022.pdf, last visited: 27.07.2022.

[45] European Electricity Exchange EEX: Market Data – Power – Futures, Online: https://www.eex.com/en/market-data/power/futures#%7B%22snippetpicker%22%3A%22EEX%20Swiss%20Power%20Futures%22%7D, last visited: 27.07.2022.

[46] Ausfelder, Florian; Seitz, Antje; von Roon, Serafin (Hrsg.): «Flexibilitätsoptionen in der Grundstoffindustrie – Methodik, Potenziale, Hemmnisse», 2018. Online: https://dechema.de/dechema_media/Bilder/Publikationen/Buch_FLEXIBILITAETSOPTIONEN.pdf, last visited: 25.07.2022.

[47] Bons, Marian; Creutzburg, Philipp; Schlemme, Jannik: «Energiewende in der Industrie – Potenziale und Wechselwirkung mit dem Energiesektor», 2020. Online:

https://www.bmwk.de/Redaktion/DE/Downloads/E/energiewende-in-der-industrie-ap2b-executive-summary.pdf?__blob=publicationFile&v=4, last visited: 25.07.2022.

[48] Köberlein, Jana; Bank, Lukas; Roth, Stefan; Köse, Ekrem; Kuhlmann, Timm; Prell, Bastian; Stange, Maximilian; Münnich, Marc; Flum, Dominik; Moog, Daniel; Ihlenfeldt, Steffen; Sauer, Alexander; Weigold, Matthias; Schilp, Johannes: «Simulation Modeling for energy-fexible manufacturing: pitfalls and how to avoid them», Energies 15 (2022), 3593.

[49] Imboden, Christoph; Schneider, Daniel; Abt, Reto; Hiltbrunner, Remo: «Teilnahme industrieller Regelleistungs-Anbieter am Schweizer SDL-Markt – Technische und wirtschaftliche Opportunitäten, Bewertungsmethodik», Bern, Version vom 21.11.2016, Online: https://www.aramis.admin.ch/Default?DocumentID=61115&Load=true, last visited: 27.07.2022.

[50] Söder, Lennart; Lund, Peter D.; Koduvere, Hardi; Bolkesjö T.F.; Rossebö, G.H.; Rosenlund-Soysal, Emile; Skytte, Klaus; Katz, Jonas; Blumberga, Dagnija: «A review of demand side flexibility potential in Norther Europe», Renewable and Sustainable Energy Reviews 91 (2018), 654 – 664.

[51] Kirkerud, N.; Nagel, N.O.; Bolkesjö, T.F.: «The role of demand response in the future renewable northern European energy system», Energy 235 (2021) 121336.

[52] Marchiori, F.; Belloni, A.; Benini, M.; Cateni, S.; Colla, V.; Ebel, A.; Lupinelli, M., Nastasi, G.; Neuer, M.; Pietrosanti, C.; Vignali, A.: «Integrated dynamic energy management for steel production», Energy Procedia 105 (2017) 2772 – 2777.

[53] Uhlig, Benjamin; Kloock, Markus; Mennenga Mark; Herrmann, Christoph: «Simulation-based energy flexibility analysis of manufacturing process chains: heat treatment in a foundry», Procedia CIRP 107 (2022), 1379–1384.

[54] Golmohamadi, Hessam: «Demand-side management in industrial sector: A review of heavy industries», Aalborg, Renewable and Sustainable Energy Reviews 156 (2022), 111963.

[55] Next Kraftwerke GmbH, Online: https://www.next-kraftwerke.com/, last visited: 27.05.2022.

[56] Swissgrid: Flexibilitätsmarkt: «Effizientes und nachhaltiges Strommarktdesign», 2022. Online: https://www.swissgrid.ch/dam/swissgrid/operation/regulation/market/flexibility-market-de.pdf, last visited: 25.07.2022.

[57] Fattahi Meyabadi, A.; Deihimi, M.H.: «A review of demand-side management: Reconsidering theoretical framework», Renewable and Sustainable Energy Reviews 80 (2017) 367–379.

[58] Kopernikus-Projekt SynErgie: «Wie das Kopernikus-Projekt SynErgie der Industrie dabei hilft, ihre Stromnachfrage an das Stromangebot anzupassen», Online: https://www.kopernikus-projekte.de/projekte/synergie, last visited: 27.05.2022.

[59] EU Commission: [Italian] Implementation Plan [of the Internal Electricity Market IEM], Brussels, 2020, Online: https://ec.europa.eu/energy/sites/default/files/italy_market_reform_plan.pdf, last visited 27.05.2022.

[60] Raycheva, Elena; Schaffner, Christian; Hug, Gabriela: «Nexus-e: CentIv Module Documentation», Zürich, 2020, Online: https://www.research-collection.ethz.ch/handle/20.500.11850/471885, last visited: 15.08.2022.

[61] Pranjal, Jain: "Diffusion of Solar PV and Battery Storage in Switzerland under Different Energy System Scenarios Master thesis report. Master thesis report, Zürich, 2021, Online: https://nexus-e.org/wp-content/uploads/2022/07/Master_Thesis_ABM_Final.pdf; last visited: 22.08.22.

[62] Garrison, Jared; Gjorgiev, Blazhe; Han, Xuejiao: «Nexus-e: Input Data and System Setup.», Zürich, 2020, Online: https://www.research-collection.ethz.ch/handle/20.500.11850/474810, last visited: 15.08.2022.

[63] European Network of Transmission System Operators for Electricity (ENTSO-E): "Ten-year network development plan 2018", Online: https://tyndp.entsoe.eu/tyndp2018/, last visited: 22.08.22.

[64] European Network of Transmission System Operators for Electricity (ENTSO-E): “European Resource Adequacy Assessment 2021 Edition”, Online: https://www.entsoe.eu/outlooks/eraa/eraa-downloads/, last visited: 22.08.22.

[65] Christian Bauer, Stefan Hirschberg, Y. Bauerle, S. Biollaz, A. Calbry-Muzyka, B. Cox, T. Heck, M. Lehnert, A. Meier, H.-M. Prasser, W. Schenler, K. Treyer, F. Vogel, H.C. Wieckert, X. Zhang,M. Zimmerman, V. Burg, G. Bowman, M. Erni, M. Saar, and M.Q. Tran: “Potentials, costs and environmental assessment of electricity generation technologies”, Villigen, 2017.

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

Security of electricity supply in Switzerland - What can demand-side flexibility in the industry sector contribute?

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	**First name(s):**
Federer	Lukas

With my signature I confirm that
- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date	**Signature(s)**
Basel, 24.08.22	

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.