Power generation and stability of the Swedish electricity system 2045

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I would like to thank everyone that helped me during my work with this thesis, but most of all my supervisor Öivind Andersson for his support and encouragement during the project.

> The one thing we can be certain of is that the future will not be as we predict it.
>
> *Anonymous*

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List of Symbols

List of symbols that will be used in the report.

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CHP	Combined Heat and Power
CHPP	Combined Heat and Power Plant
EC	European Commission
EEA	European Environment Agency
EI	The Swedish Energy Market Inspectorate (Energimarknadsinspektionen)
EU	European Union
HEPP	Hydroelectric Power Plant
IEA	International Energy Agency
IRE	Intermittent Renewable Energy
NPP	Nuclear Power Plant
P2G	Power to Gas
PSH	Pumped Storage Hydroelectricity
PV	Photovoltaic
SCB	Statistiska Centralbyrån
SMR	Small Modular Reactor
SP	Solar Power
SPP	Solar Power Plant
SVK	Svenska kraftnät
TPP	Thermal Power Plant
TSO	Transmission System Operator
UN	United Nations
USA	United States of America
V2G	Vehicle to Grid
VRE	Variable Renewable Energy
WPP	Wind Power Plant

Sammanfattning

På grund av energiomställningen, Sveriges mål om att ha en fossilfri elproduktion 2040 samt målet om nettonollutsläpp av växthusgaser 2045 förväntas en omfattande utbyggnad av förnybara energikällor ske. I denna rapport har därför elbehovet, potentialen för elproduktion, möjliga framtida systemproblem samt lösningar undersökts.

Efter en omfattande litteraturstudie har det framkommit att elbehovet kommer att öka till det dubbla i Sverige och den största delen av detta ökade behov förväntas komma från vätgasproduktion för tillverkning av fossilfritt stål. Då antal parter som styr investerinsbesluten för de mest energikrävande projekten är få, råder stor osäkerhet kring hur stor denna ökning faktiskt kommer att bli. I det högsta fallet kan elbehovet uppgå till 370 TWh. Med antagandet att elektrifieringstakten i samhället är hög tillsammands med insikten att Sverige har ambitiösa energi- och klimatmål är det sannolikt att det inhemska elbehovet kommer ligga i närheten av 286 TWh. Utöver det förväntas effektbehovet och därmed effektbehovet under topplasttimmen öka markant. Det kommer med stor sannolikhet ligga i intervallet 42 - 49 GW.

När det gäller utbyggnad av vattenkraft verkar det osannolikt med nybyggnation. Kärnkraftens potential och produktion i framtiden kommer bero på ett antal lagar om konstruktion av nya reaktorer, huruvida befintlig kärnkrafts livstid förlängs bortom 60 år samt möjligheten att hantera avfallet. Vindkraften spås bli det dominerande kraftslaget med en årsproduktion på upp till 157 TWh men där det finns ett antal flaskhalsar i form av ansökningsprocessen samt intressekonflikter med andra intressenter som påverkar utbyggnadstakten. Solkraftens potential bedöms vara god trots att Sverige har låg solpotential jämfört med många andra länder, detta då solkraften har få intressekonflikter med andra intressenter. Kraftvärmen kan öka sin elproduktion i det fall då antalet produktionstimmar ökar och värmekraften tar tillvara på spillvärmen. Denna potential är dock beroende av behovet av fjärrvärme, något som kan äventyras av ökande medeltemperaturer och energieffektivare byggnader.

Om kärnkraften fasas ut eller då drifttiden inte förlängs kommer systemets svängmassa och tröghet att minska, vilket kan leda till snabbare frekvensavvikelser och potentiella systemfel. I fallet då kärnkraft inte fasas ut kommer en ökad andel av solproduktion leda till stabilitetsproblem under sommaren. Detta särskilt då det är låg elförbrukning under dagen samtidigt som solkraften producerar som mest och kärnkraften är tagen ur drift för revision under en period på sommaren.

Som en lösning har syntetisk svängmassa föreslagits. I korta drag innebär vindkraften, som vanligtvis inte bidrar med svängmassa, kan göra det under en kort stund genom att använda den upplagrade energin. Detta skulle tillåta vindkraft att temporärt öka sin produktion vid produktionsbortfall, vilket bidrar till systemets stabilitet. Det framgår av rapporten att detta kan täcka Sveriges behov av snabb frekvensreglering (FFR) under en kort tid och med förutsättningen att det blåser.

Det framkommer också att flexibilitet kommer vara avgörande för att inte effektunderskottet ska bli för stort. Detta blir också viktigt för att efterfölja den norm enligt vilken Sverige ska täcka sitt behov med produktion och import under 99.989% av tiden, dvs 0.99 timmar per år. Vid användning av efterfrågeflexibilitet, produktionsflexibilitet och energilager kommer antalet timmar med underskott att vara godtagbart. Med antagandet att alla flexibilitetsresurser används täcks effektbehovet endast inte under 0.5 timmar per år.

Slutligen har energilagring också undersökts. Det har framkommit att pumpkraftverkspotentialen är begränsad av geografin och den höga kostnaden. Batterier lämpar sig bäst för korta variationer medan vätgaslagring bör användas för säsongslagring av elektricitet. Dessutom bör den totala effektiviteten för omvandling av vätgas (under 50%) beaktas, särskilt givet det faktum att effektiviteten för omvandlingen minskar ytterligare då elektrolysen kräver konstant spänning - vilket, till en del, går emot premissen att generera vätgas från den överskottsel som tillkommer till följd av utbyggnad av variabla energikällor.

Abstract

In light of Sweden's goals for fossil-free electricity by 2040 and net-zero greenhouse emissions by 2045, an expansion of renewable energy is expected. This report explored electricity demand, production potential and possible future system issues with solutions.

Following a literature study, it's found that Sweden's electricity demand will double, primarily due to hydrogen production for fossil-free steel manufacturing. Given the limited parties governing investment decisions for energy-intensive projects, there's uncertainty regarding the extent of this increase, with a potential demand of up to 370 TWh. Assuming a high electrification rate and Sweden's ambitious energy goals, domestic demand is likely to be around 286 TWh, with significant increase in power demand, especially during peak load hours, ranging between 42 - 49 GW.

The expansion of hydropower through new constructions seems unlikely. Future nuclear power potential and production depend on laws regarding new reactors, lifespan extension beyond 60 years and waste management. Wind power is predicted to dominate, with a potential annual production of 157 TWh, albeit with bottlenecks like application processes and stakeholder conflicts affecting expansion rate. Solar power has good potential despite Sweden's low solar capacity compared to other countries. Co-generation could increase electricity production by utilizing waste heat, contingent on the need for district heating, which may be threatened by rising temperatures and energy-efficient buildings.

Phasing out nuclear power or not extending its operating time will reduce system's rotational mass and inertia, leading to faster frequency deviations and potential system failures. An increased solar production could cause stability issues during summer, especially when electricity consumption is low, solar production is high and nuclear power is out for review.

Synthetic inertia, allowing wind power to temporarily increase production during disruptions, has been proposed as a solution, covering Sweden's Fast Frequency Response (FFR) needs momentarily, given wind availability.

Flexibility will be crucial to minimize power deficit, adhering to the norm where Sweden covers its needs 99.989% of the time, or 0.99 hours per year. Utilizing demand and production flexibility along with energy storage, the power demand is not covered only during 0.5 hours per year, assuming all flexibility resources are used.

Lastly, the study explored energy storage. The potential for pumped storage power plants is geographically and financially limited. Batteries suit short variations, while hydrogen storage is for seasonal electricity storage. The efficiency of hydrogen conversion, under 50%, should be considered, particularly as electrolysis efficiency decreases with the requirement of constant voltage, contradicting the premise of generating hydrogen from surplus electricity due to the expansion of variable energy sources.

Keywords

Duck curve, capacity factor, availability factor, stability, flexibility, synthetic inertia, ancillary services, hydrogen, electrolysis, fuel cells, V2G, PtG, P2G, P2G2P, IRE, FRR, IRE, VRE, NPP, CHP, WPP, SP, HEPP, SMR

1 Introduction

In 2015, a landmark deal was signed at COP21 (Conference of the Parties) in Paris and later ratified by 195 parties (194 states and European Union) to UNFCCC (United Nations Framework Convention on Climate Change) (UN, 2023). This, legally binding agreement, known as The Paris Agreement, mandates that each signatory commits to limiting global warming to well below 2 °C. The ambition is to further restrict the temperature rise to 1.5 °C compared to pre-industrial levels (UN, 2015). This was to be accomplished by providing financing, technology, promotion of sustainable energy and boosting of renewable energy development (UN, 2015). The commitment to limiting and reducing the amount of greenhouse-gases in the atmosphere by moving away from fossil fuels and reviewing energy policies was reaffirmed in later COPs.

The Paris Agreement operates on a 5-year cycle, with progressively stricter targets set every five years. Each party to the agreement has to provide NDC (Nationally Determined Contribution) each five years stating the climate action plans (UN, 2016). As a member of the European Union - Sweden, together with other countries, submitted their NDC in 2020 (EC, 2020). In that document, the EU has, among other things, pledged to become climate neutral by 2050. Additionally, the EU aims to decrease its domestic greenhouse gas (GHG) emissions by 55% by the year 2030, using 1990 levels as a baseline (EC, 2020). Sweden has, in turn, passed a law in effect from 2018 setting a framework with a goal of reaching net-zero emissions by 2045 (Naturvårdsverket, n.d.) and introduced a political goal of having a 100% fossil-free electricity generation by 2040 (Regeringen, 2023). This goal was previously 100% renewable electricity generation by 2040 (Regeringen, n.d.) but was revised in 2023 (Regeringen, 2023). Concurrently, there's an objective related to energy efficiency. The target is to achieve a 50% improvement in energy efficiency by 2030 compared to 2005 levels. This efficiency is evaluated based on energy consumption per GDP (Gross domestic product) unit and the calculations consider the annual temperature fluctuations (Energimyndigheten, 2022a).

1.1 Political framework

Following Sweden's recent election in 2022, the majority block in the Swedish parliament drafted a political document called "Tidöavtalet". Although not implemented by law, this document serves as a comprehensive political agreement among the parties involved, providing an overarching framework for the government's future decision-making process (Energimyndigheten, 2023f).

Of particular interest to this report is the commitment to change Sweden's long-term energy goal from "100% renewable" to "100% fossil-free". The same document also indicates that Vattenfall, a government-owned enterprise, was tasked with planning the construction of new nuclear power plants near Ringhals or another suitable location (Energimyndigheten, 2023f). This implies a shift in stance regarding nuclear power, as a decision has been made to enhance the viability of nuclear power in a political context.

1.2 Problem identification

Energimyndigheten (Swedish Energy Agency) projects a significant rise in both energy consumption and the electrification of Swedish society in the upcoming decades. This, combined with Sweden's goal of achieving renewable electricity generation by 2040 with a higher proportion of intermittent sources, presents new challenges for the grid. As a result, when power generation from inherently less predictable sources (e.g., wind) becomes more dominant in the grid, there is an increased need for greater foresight in planning for grid stability and power availability.

1.3 Project scope

Over recent years, Swedish institutions have published several reports exploring potential scenarios for electricity in 2040 and beyond. The intersection between these different visions for the future and the experience from other parts of the world with high penetration of variable renewable energy will be discussed in this report. The main interest of this report lies in answering the following three questions:

- How much electricity will Sweden need in 2045?

- What is the share of each major electricity generation source in Sweden in 2045?
- What methods, technologies and strategies can be applied to increase stability and electricity availability in the Swedish system year 2045?

1.4 Method

This study was performed as a literature study using official reports and data from various governmental and non governmental-institutions such as Energimyndigheten, SCB, Statista, SVK (Svenska kraftnät), European Network of Transmission System Operators (ENTSO-E), other grid operators around the world (CAISO and others), OECD (Organisation for Economic Co-operation and Development), IEA (International Energy Agency) and other similar organizations. As the scope of this work is in the future there is a need to create a few scenarios that could represent the potential development; one with fossil-free electricity mix and one where the majority of electricity demand is met by building a high share of renewables.

This project can be divided into several smaller parts. At first, the objective was to find out where we are today, that is to analyze energy use, electricity consumption and share of each power source in today's system together with the political goals and frameworks that might affect future decisions (like Paris Agreement, Tidöavtalet and similar).

In the second part, projected results from different reports were compiled for the electricity use, electrification, share and potential of renewable power generation by source and volatility mitigation strategies (energy storage, ancillary services and similar).

In the last part, mitigation strategies and potentials are discussed from the perspective of Sweden along with the results from previous parts of this project (where we are, where are we heading and what awaits us). This is finished with a discussion reviewing possible shortfalls and error points that might affect the true future scenarios.

1.4.1 Main data sources

There are several main governmental agencies related to the electricity system that are of interest in this report.

- Energimyndigheten (Statens energimyndighet or Swedish Energy Agency) are responsible for the statistics related to the energy system in Sweden and provide financing for research projects (Energimyndigheten, 2023c).
- SVK (Svenska kraftnät or Affärsverket svenska kraftnät) is the TSO (Transmission System Operator) that operates the electricity system (SVK, 2021).
- Energimarknadsinspektionen (Ei or Energy Markets Inspectorate) which oversees the energy market (Ei, 2023).
- SCB (Statistikmyndigheten) which aggregates the statistics in Sweden and analyzes it (SCB, 2023).

On a wider frame Svenska kraftnät, as Sweden's TSO is a part of Nordic TSOs (Nordic Transmission System Operators), which is a constellation of Energinet.dk (Denmark), Statnett (Norway), Svenska kraftnät (Sweden) and Fingrid (Finland) (ENTSO-E, 2018b). On an even wider frame it is a part of the European association for the cooperation of transmission system operators (TSOs) for electricity - ENTSO-E (ENTSO-E, 2018b).

A large number of reports from Energimyndigheten were studied and information was compiled into the result section with recency of publication being the main point of interest. Svenska kraftnät (SVK) was the main source of many of the generation statistics which were retrieved through their data system "Mimer".

1.4.2 Multivariate linear regression (MLR)

Having reviewed a number of studies that examined long term projecting of power consumption in the future for different countries in the world, several models of interest were identified together with input variables used to create these projections. Most commonly used independent input variables for electricity demand projection were identified as GDP, population and temperature. Several other important indicators were also identified with the most notable being day length and electricity prices. The electricity price data for Sweden was not included as different entities have different taxes and contracts depending on the region and the type of consumption which leads to different prices. As the main goal of this study was not to create a model, a simple multivariate linear regression (MLR) model was used on historic data of electricity use together with data for GDP, population and temperature retrieved from Energimyndigheten, World Bank, SCB and SMHI was used to project a future power electricity demand assuming linear trend development for each variable. The value was later given the title "MLR" and presented with the other literature-derived values in the results section.

1.4.3 System outlook simulation

A simulation of a future system model was performed using historical data retrieved from SVK and compiled into a simple system. The simulation was conducted in three parts. First, the production was simulated by retrieving the 2021 data from SVK and dividing it into columns by power generation type (e.g., wind, solar, nuclear). The data then represented the magnitude and time of generation during 2021. Next, each column was scaled by a separate constant for each generation type. These constants were determined from a literature study of the historic values and power generation potential for each type in 2045. Finally, the total production was summed and presented in a graph with consumption.

A consumption model was subsequently developed using a slightly different approach. The 2021 consumption was scaled by the ratio of the peak load value for the chosen scenario in 2045 to the peak load hour value in 2021. The total consumption was then summed and checked to be in the vicinity of the predicted electricity consumption from the literature study.

Finally, an accompanying graph for each case represents an energy storage system designed to charge when production is higher than consumption and discharge when consumption is higher than production. The system was coded using AppScript to follow a simple flowchart described in Section flowchart.

1.5 Delimitations

This project was limited to the most common and commercially viable storage technologies (e.g. pumped storage hydro) with vast adaptation potential and will hence not focus on futuristic and conceptual strategies that are yet to be researched extensively (e.g. gravitational energy storage using concrete blocks in a tower).

This project is also limited to electricity generation in Sweden, other countries' experiences are taken into consideration but with the fact in mind that every country has a different energy profile and development potential.

In terms of electricity generation, only the biggest generators of electricity were studied, excluding technologies such as geothermal and tidal energy as their contribution to Swedish electricity generation is minuscule.

It should be clarified that "electricity demand" refers to the energy need (TWh) in terms of electricity that is used during a year in Sweden including transmission and distribution losses. This also means that maximal power need (GW) was not studied to the same extent as the electricity demand.

1.6 Scientific contributions

The purpose of this study is to expand on existing knowledge, foresee possible opportunities and obstacles and provide valuable insights for future scholars and decision-makers. The goal is to outline solutions that could counteract potential difficulties down the line with the overarching aim to present today's solutions for tomorrow's possible problems.

1.7 Resources

The resources that are needed to accomplish these goals are found freely on the World Wide Web. In cases where data or reports are not accessible for free an attempt was made to retrieve them using LUBsearch, Scopus, ScienceDirect, Springer and databases that are accessible to students of Lund University.

The historical data can be found at SVK, Energimyndigheten and SCB. The majority of the computations using the raw data was performed using Excel/Sheets and scripting using AppScript.

2 Background

2.1 Energy

Energy, is a physical concept which describes a system's potential to perform work. Power, measured in Watts, W, is the rate at which energy is used or produced. Watt-hour, Wh is a measure of energy, representing one Watt of power flowing for one hour. For instance, a 1 kW device consumes 1 kWh of energy each hour.

Energy comes in different forms (e.g. kinetic, potential, thermal) and the most important law governing it is the First Law of Thermodynamics (law of conservation of energy). It states that energy in a closed physical system is constant and cannot be created or destroyed, although could be converted into different forms.

The majority of the harvestable energy originates from the nuclear reaction inside the Sun that emits energy to its surroundings in the form of sunlight. This energy is later transformed into other primary energy forms like biomass, oil, gas and wind through different physical and chemical processes (such as photosynthesis) and finds itself at our disposal.

When plants and animals perish, over the span of millions of years, some of their remains become fossilized and can later be extracted in the form of coal, natural gas or oil. These are also known as the **fossil fuels** and are not infinite by their nature as they are used at a greater rate than they are replenished.

Renewable energy (solar, wind, hydropower, geothermal and biomass) on the other hand, is produced from primary energy sources that are replenished naturally within a short period of time and do not emit a considerable amount of greenhouse gasses to the atmosphere over their lifetime.

Uranium, on the other hand, which is the most commonly used fuel inside nuclear power plants (IAEA, n.d.) does not fall into either of these categories. Reason being that uranium used today was formed during the fusion process (nucleosynthesis) during a supernova explosion more than 6 billion years ago and was likely present during the formation of Earth (McWilliam and Rauch, 2022), why it is neither considered as fossil nor renewable.

2.2 Energy use

Energy is used through many different primary energy forms, among them are primary energy carriers like oil, gas, coal and uranium. But, as the processes of energy extraction and final uses differ, so does the conversion efficiency. This leads to an energy loss between the amount of energy available in the primary energy carriers and its final use scenario. To differentiate that, several terms are used (these are defined in great detail by documents related to the EU's Energy Efficiency Directive). Among these are *primary energy consumption* and *final energy consumption*.

2.2.1 Primary, secondary and final energy

Primary energy consumption (PEC) includes consumption together with conversion and distribution losses which would equate to the energy use at the power-plant. This means the total amount of energy used from sources like oil, gas, solar, wind, hydro before conversion (e.g. into electricity) and later distribution or transformation. When the primary energy source is used to create energy, that energy becomes ***secondary energy*** (such as **electricity**, gasoline, diesel and heat). The relation between different energy forms is described by figure 1 where we can see that primary energy is the sum of secondary energy and conversion losses.

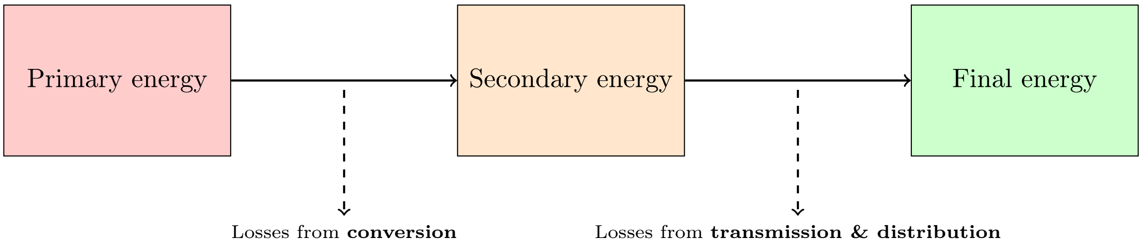

Figure 1: Relation between different energy types (primary, secondary and final) along with losses (conversion, transmission and distribution).

The **final energy consumption** (FEC) is the energy consumed at the end-users without including the transmission and distribution losses. This is the energy consumed after being converted from primary energy carriers into secondary forms of energy like electricity, heat or fuels and then delivered to the final consumers to be used in their specific use scenario (for instance, electricity in an outlet to charge a phone). In essence, this means that numbers present in various reports considering electricity consumption might differ, yet describe the same process, either including or excluding different losses. The primary focus of this report is on the secondary energy demand, specifically the domestic electricity demand prior to accounting for transmission and distribution losses. The relation between different energy forms described above is illustrated in equation 1.

$$\text{primary energy} = \underbrace{\text{final energy} + \text{transmission \& distribution losses}}_{\text{secondary energy}} + \text{conversion losses} \tag{1}$$

2.2.2 Energy use in Sweden

According to REN21 the total final energy consumption in the world 2019 was split into three main categories; heating and cooling 51%, transport 32% and electricity 17% (REN21, 2022). According to data from Energimyndigheten, a third of final energy use is consumed in the form of electricity as an energy carrier in Sweden (Energimyndigheten, 2022b). In figure 2, we see the primary and final energy consumption in Sweden together with losses and self use inside the power generating infrastructure. We can see that the final energy use in Sweden has largely been constant, in the vicinity of 400 TWh, while the amount of primary energy use in Sweden has been varying between 550 and 600 TWh since the middle of the 1980's (Energimyndigheten, 2023b). The increase of *Losses in NPP* indicates the energy losses inside nuclear power plants due to low conversion efficiency from nuclear fuel to electricity and build-out of nuclear power plants in Sweden during the same period. This increase is also due to the increase in electricity demand, which is explained later in figure 3.

In 2020 the primary energy consumption was 499 TWh while the total final energy use was 355 TWh. Out of that, the largest energy carrier was electricity, accounting for 120 TWh of final electricity consumption (134 TWh if accounting for transmission losses) (Energimyndigheten, 2023b).

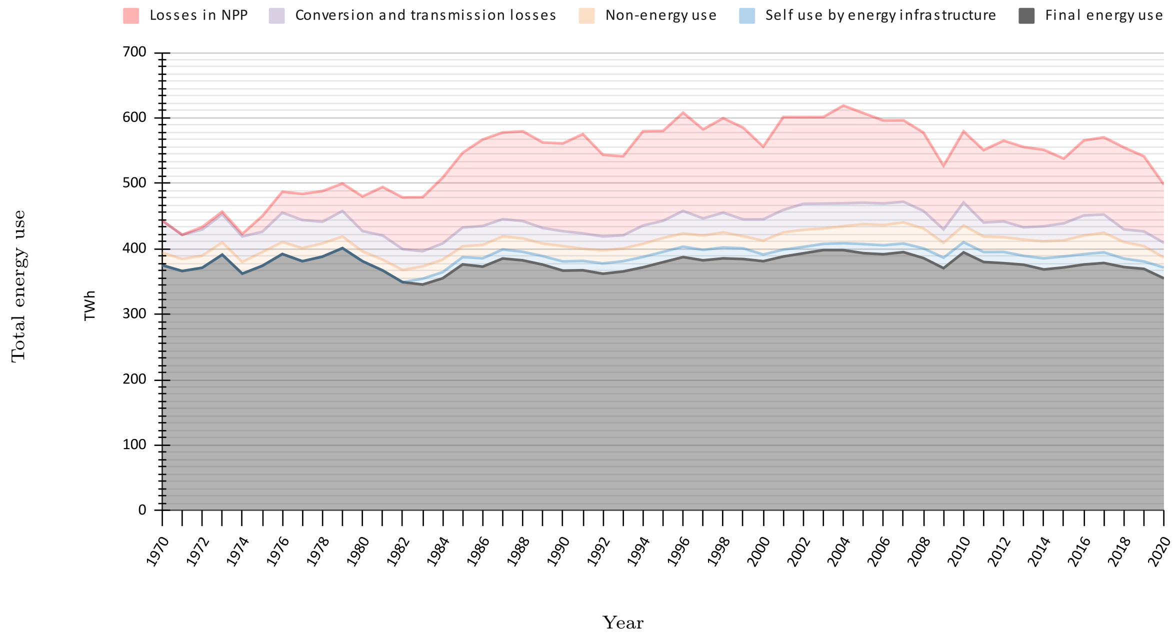

Figure 2: Total energy use by final use, losses and self use in Sweden between 1970 and 2020 (Energimyndigheten, 2023b). Non-energy use describes primary energy sources that are used in manufacturing processes (like additives in chemical industry).

Electricity consumption in Sweden

The electricity consumption in Sweden has increased from 1970 to the middle of the 1980's and has, since then, been relatively constant, laying in the vicinity of 140 TWh, which can be seen in figure 3 (Energimyndigheten, 2018). The figure describes the electricity consumption in Sweden that is split into several sectors with the largest being *Housing and services* together with *Industry*. We can also see that the electricity consumption increase is largely non-present since the middle of 1980's. From 1970 to the end of 1980s the housing sector increased its electricity consumption drastically due to the transition away from heating oil to direct electric heating systems together with the increase of electric devices (Energimyndigheten, 2018). From there on, many households transitioned to heating pumps and as the electricity use increased so did the efficiency of devices - resulting in flat electricity trend during the last 30 years, despite increasing population and GDP (Energimyndigheten, 2018).

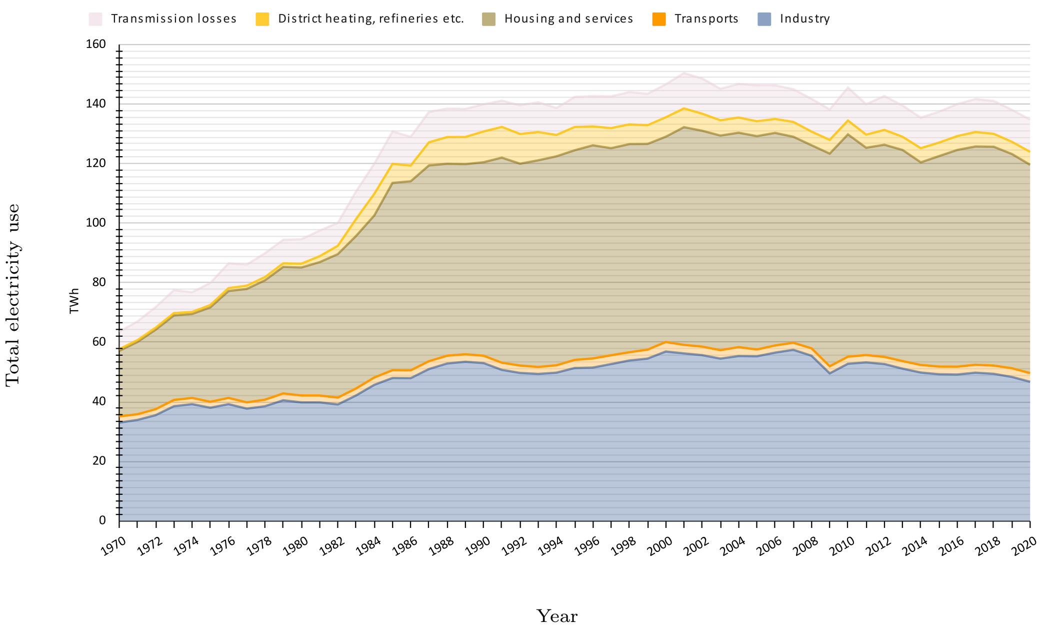

Figure 3: Total electricity use by sector in Sweden between 1970 and 2020 (Energimyndigheten, 2023b). Self use of electricity by power generating sector is not presented in this figure.

The electricity use in the industry sector has been increasing at a rate of 2% a year between 1970 and 2007 (Energimyndigheten, 2018). After that, the trend is slightly decreasing. The industry's electricity use is more dependent on the economy than the seasonal variation, contrary to the *Housing and services* sector (Energimyndigheten, 2018). The electricity use for the Transportation sector is currently 3 TWh compared to 70 TWh in *Housing and services* and 47 TWh in *Industry* (Energimyndigheten, 2023b).

Electricity intensity (input electricity by economic output) follows similar patterns as the energy intensity. The electricity intensity for Swedish biggest consumer of electricity; industry - is highest in *Forestry* (3.41 kWh/EUR) followed by *Iron & Steel* (2.37 kWh/EUR) followed by *Manufacturing and food industry* at 0.67 kWh/EUR (Energimyndigheten, 2022a).

2.2.3 Consumption profiles

The consumption of electricity in Swedish society follows a similar trend across several time-scales. The scales of interest are year-month, week-day and also that of momentary consumption. The momentary energy consumption refers to the power needed during a specific moment of time. The power consumption profile across two years can be seen in figure 4. It can be noted that the electricity consumption is lower during summer and higher during the winter.

The **peak load hour** refers to the specific hour in a year when electricity demand is at its highest. This hour is the time when Sweden uses the most energy during that year and is usually sometime during winter (SVK, 2023c). Since the amount of energy MWh is measured during one hour, h, means we get the mean power needed during that hour in MWh/h = MW, although that is not the maximum power needed since the need for power can be higher than the mean. The times of peak power consumption between 2003 and 2023 are seen in figure 5. It can be seen that the peak load hour is quite constant in the region between 23 - 28 GW. An important point is that the Y-axis starts at 20 GW which makes the trend look slightly decreasing while, in reality, the distribution is more even.

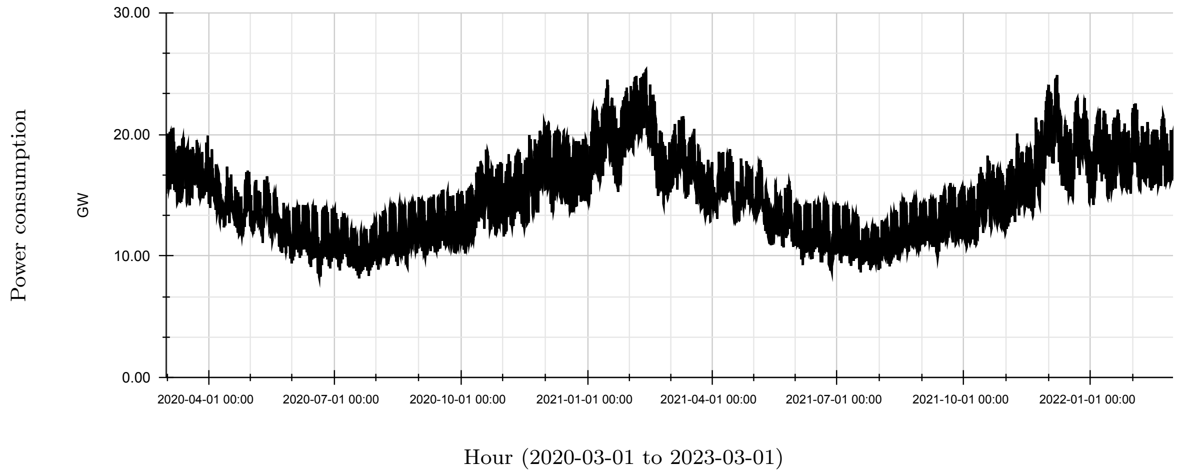

Figure 4: Total hourly power consumption (GW) in Sweden between 2020-03-01 and 2023-03-01 (SVK, n.d.).

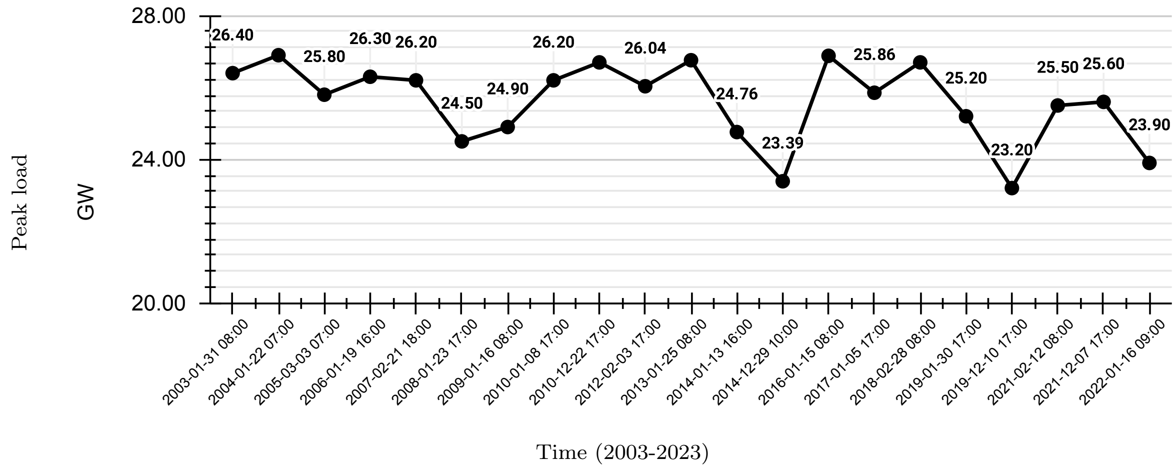

Figure 5: Peak load (GW) in Sweden between 2003 and 2023, where Y-axis starts at 20 GW (SVK, 2023c).

According to SVK's yearly reports, currently, it is calculated that Sweden has an approximate deficit of 1.4 GW of power during peak load in a normal winter and 2.7 GW during a case of a ten-year-winter (winter during which the temperatures are lower than usual, which usually occurs once every ten years) (SVK, 2022b). On the other hand, this does not necessarily mean that there is no installed capacity available in Sweden. It might mean that the price is simply too high compared with importing electricity from other countries.

On shorter time scales, such as two days and three weeks, the consumption patterns can be observed in the figures 6 and figure 7. During two days, we can note that the power consumption is smaller during early morning and late night. Over several weeks, we notice that the power consumption is smaller during the holidays (note that the graph starts on a Sunday).

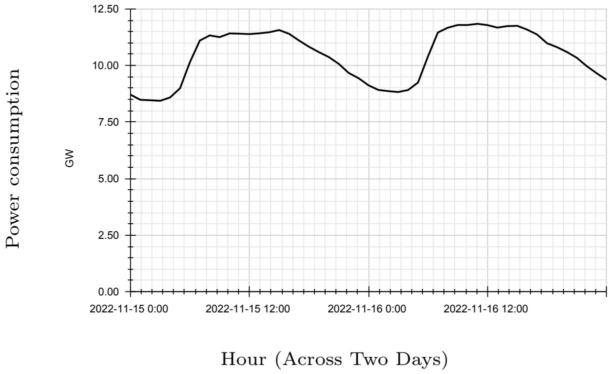

Figure 6: Total power consumption (GW) by hour in Sweden across two days; 2022-11-15 and 2022-11-16 (SVK, n.d.). This data does not account for power losses.

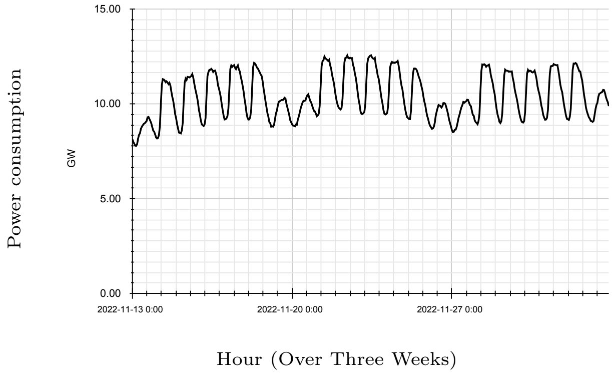

Figure 7: Hourly net power need (GW) seen over three consecutive weeks in Sweden starting with Sunday 2022-11-13 (SVK, n.d.). This data does not account for power losses.

2.3 Power generation

Sweden got its first electricity generation plant in the middle of the 1880's (Energimyndigheten, 2018). After that, hydropower was developed, followed by nuclear power and combined heat power. In the recent period, the majority of the new installed capacity in Sweden comes from wind power and solar power.

In general, power generation in a system comes from different types of sources. These, apart from the type of primary energy source used, have four generation profiles which depend on their type, seen from a system perspective. These modes are baseload, load-following, intermittent and peaking.

- **Baseload** power plants describe power stations that run most of the time at a fixed output. Sources that fit this description are Nuclear power plants, CHP, Geothermal.
- **Load-following** power plants adjust their output to the demand all the time. Hydroelectric power plants fit this category. Nuclear power plants also have the ability to perform load following operations.
- **Intermittent** power plants are power generators that generate power without a high degree of certainty (wind power, solar power). These are also sometimes called VRE (variable renewable energy) or IRE (intermittent renewable energy).
- **Peaking** power plants (peakers) are run when demand is high and additional power is needed (gas turbine power plants).

To better understand the intrinsic properties of each power source we first need to study their type and generation patterns.

2.3.1 Solar power

Electromagnetic radiation originating from the sun can be used to make useful energy in the form of electricity or heat using technologies like photovoltaic systems (PV) and thermal systems.

The amount of available solar radiation outside Earth's atmosphere is approximately 1361 W/m^2 (so called solar constant) which deviates slightly depending on events on the surface of the sun (Gueymard, 2018). Due to projection, a sunbeam of fixed area hits a greater area further away from the equator due to difference in incidence angle - spreading the electromagnetic radiation over a greater area (Widen and Munkhammar, 2019). Consequently, regions farther away from the equator receive less solar irradiation over the same area. This, together with the effect of Earth's tilt, the absorption and reflection of radiation in the atmosphere, yields different solar potentials at different locations on Earth (Widen and Munkhammar, 2019). Information about these potentials is compiled into maps to choose optimal locations for solar projects.

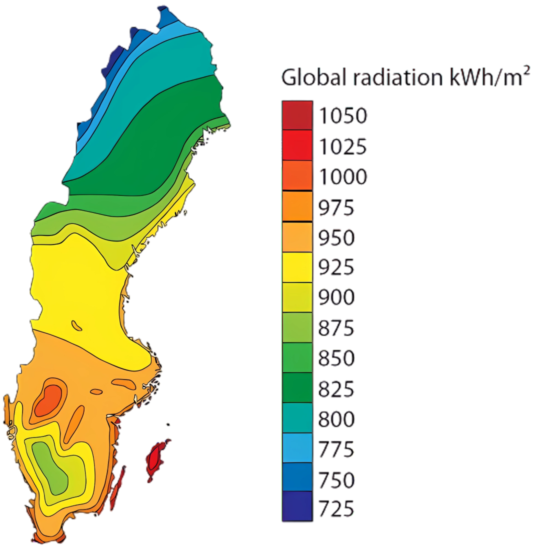

Figure 8: Global annual irradiation in Sweden in kW h/m^2 (Lindahl et al., 2022).

The total direct radiation incoming from the sun together with diffuse and reflected radiations results in global irradiation on the surface. The global solar radiation hence depends on variables such as season, position and weather. In Sweden, annual irradiation can be seen in figure 8 which yields about 950 kWh for each installed kWp (Lindahl et al., 2022), where Wp refers to the maximum power output of a solar panel under standard test conditions (STC). According to SVEA Solar, one installed kWp produces around 800 - 1100 kWh annually in Sweden depending on the location (Solar, 2019) which can be compared to Israel, where average yield is 1750 kWh per kWp (Masson and Kaizuka, 2022). This shows why, according to a report on PV potential in different countries, the practical PV power potential in Sweden (up to 60° N) is among the lowest in the world (ESMAP, 2020).

In total, solar power accounted for almost 1% of the annual electricity production in Sweden in the year 2021 (Lindahl et al., 2022). This was done while having an installed capacity of 1.6 GW compared to 43.7 GW total power generation capacity in the country (Lindahl et al., 2022).

2.3.1.1 Power generation pattern

Solar power presents a distinct power generation pattern with peaks in the middle of the day and during summer months, as seen in figures 9 and 10. Figure 9 shows that the production is highest during summer months of 2020 while being low during the winter months. Figure 10 shows that hourly power generation is highest close to 12:00 during 2020-07-21 while being minuscule during the darker hours.

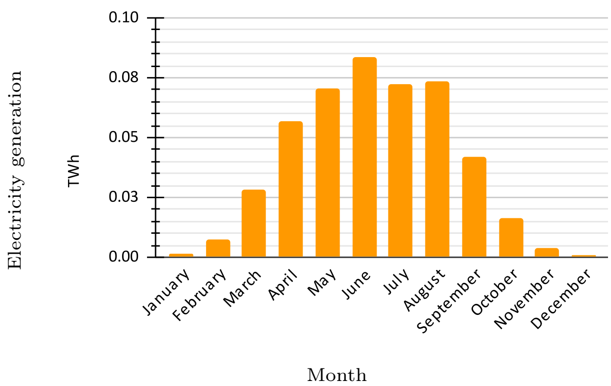

Figure 9: Monthly electricity production in Sweden during 2020 using solar power (SVK, n.d.).

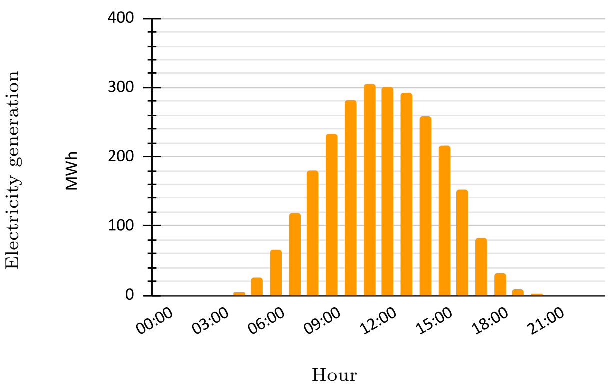

Figure 10: Hourly electrical power generation in Sweden using solar power on a summer day, 2020-07-21 (SVK, n.d.).

The optimal tilt angle is the angle at which the PV-panel generates the most electricity. But as the sun's path across the sky varies during the year, so does the optimal tilt angle (Dhimish and Silvestre, 2019). The optimal tilt angle to maximize annual electricity production is about 41 degrees in Stockholm, Sweden (Jacobson and Jadhav, 2018). Azimuth is the angle of the panel in relation to the north where an angle of 90^o is west and -90^o is east. The tilt is the angle between the normal of the plane and the normal of the panel, or in other words, in case of azimuth angle zero, the angle at which it is tilted towards the south (Dhimish and Silvestre, 2019). This angle can be changed to maximize the produced amount of energy during a specific hour according to the system requirements but the overall electricity production will be lower.

2.3.2 Wind power

Humans have always had an ambition to harness the energy of the wind through the use of sails to propel boats, windmills to process grain, saw wood and power water pumps to drain rivers (EIA, 2023).

By the nature of our planet, the sun heats the surface of the Earth along the globe, creating variations in temperature and atmospheric pressure, which results in a flow of air - wind (Manwell et al., 2009). These variations together with Earth's rotation and geographical features affect the wind speed and direction at any given location.

The kinetic energy in the wind can be utilized using wind turbines which convert the kinetic energy into AC-electricity that is transformed and fed into the grid. The most common type of turbine today is the three bladed Horizontal Axis Wind Turbine (HAWT) (Johnson and Smith, 2020).

The most important formula describing the amount of energy that is available in wind (Manwell et al., 2009) at any given location given height is given by:

$$P_{\text{ideal wind turbine}} = \frac{\rho A v^3}{2} \cdot C_p \tag{2}$$

From function 2, we see that power generated from an ideal wind turbine is the function of the rotor area of the turbine, height and efficiency of the system and the wind speed. A is the rotor area of the turbine (m^2), ρ is the air density (kg/m^3), v is the wind speed at hub height (m^2) (Manwell et al., 2009). C_p is the Betz limit which limits the maximal possible energy percentage that can be harnessed by a turbine from wind (Betz, 1926). The Betz limit is $\frac{16}{27} = 59.3\%$ while the practical efficiency of a three blade turbine is about 51% (Adeyeye et al., 2021).

This shows that the amount of energy that a turbine can generate relies on the properties of the turbine, wind energy at that location and wind speed at hub height. As the wind speed increases with height above the ground so does the energy in the wind (Manwell et al., 2009), which means that higher wind turbines can generate much more energy. For instance, doubling the turbine height can increase the available energy by 8 times due to properties seen in equation 2.

2.3.2.1 Wind power potential

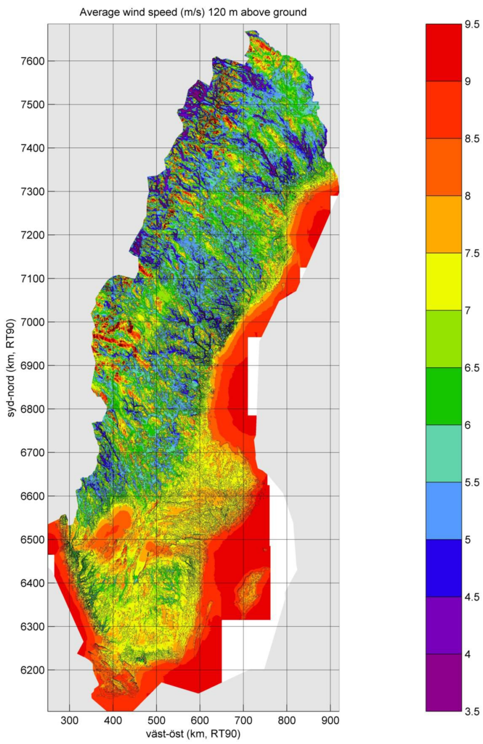

Figure 11: Wind speed model at height of 120m for Sweden with a 0.25 km^2 resolution (Bergström and Söderberg, 2022).

Earlier equation shows the importance of locations with high wind speeds, the height of wind turbines and sweep area of the turbine blades. The potential placement of wind turbines is hence critical with respect to these conditions.

The figure 11 illustrates the average wind speed at height of 120 meters which varies between 3.5 and 9.5 m/s. This height similar to that of modern turbines. Onshore turbines - which generate power on land, tend to be shorter than offshore turbines, which generate power being stationed in water offshore (Manwell et al., 2009). One of the biggest turbines today is the Haliade-X turbine with a hub height above 150 meters (GE Renewable Energy, n.d.).

As the potential in figure 11 is displayed for the whole of Sweden, the reality is that a lot less effective area is available for potential siting since majority of Sweden's area has competing interests in the form of natural-, cultural-, outdoor-spheres (62%) and defense (30%) (Energimyndigheten, 2019). This shows the complexity of choosing a site for locating a wind power plant.

Power generation pattern

The wind power generation varies with wind speed which varies greatly both in time and direction. This means that the production also appears in a randomized fashion. Although, on larger time scales the variations even out and the production pattern is more clear. We can see that from figure 12 the production is slightly higher during the winter months and lower during summer. On shorter time scales the intermittent nature of wind power is clearly seen. Looking at the wind production during a year in figure 13 we can see that hourly power generation varies greatly between different hours. Some consecutive hours have a difference of up to 7 - 8 GWh. The duration curve in the same figure shows the amount of hours a specific amount of energy is generated, starting from slightly higher than 8 GWh on the left (which happens during a few hours during a year) going to the right in the figure. For instance, according to data from figure 13 the energy 7.6 GWh was generated during a total of 13 hours out of 8784 hours that year (leap year). The downward slope of this curve represents a graphical representation of the variability and availability with respect to the total installed capacity.

A fascinating observation is that wind power follows electricity demand during the year on a month-to-month basis, as shown in figures 12 and 4. As we can see, the electricity demand is highest during the winter months as well as the average production for wind power. When the average wind power production decreases, so does the consumption of electricity during the summer months. This can also be seen from the availability factor (which will be introduced in greater detail later) presented by SVK in table 2 as they are the same during the summer and peak load (winter).

During the winter of 21/22, 90% of the time, the wind power produced 13% of the installed capacity (compared to 9% availability factor described in section section 2.4.2). With 12.1 GW total installed wind power capacity in Sweden, the power output on hourly scale ranged between 10.07 GW and 80 MW and provided 2.7 GW of power during the peak load hour which is twice as high as the predicted available power as per the usual availability factor (SVK, 2022b).

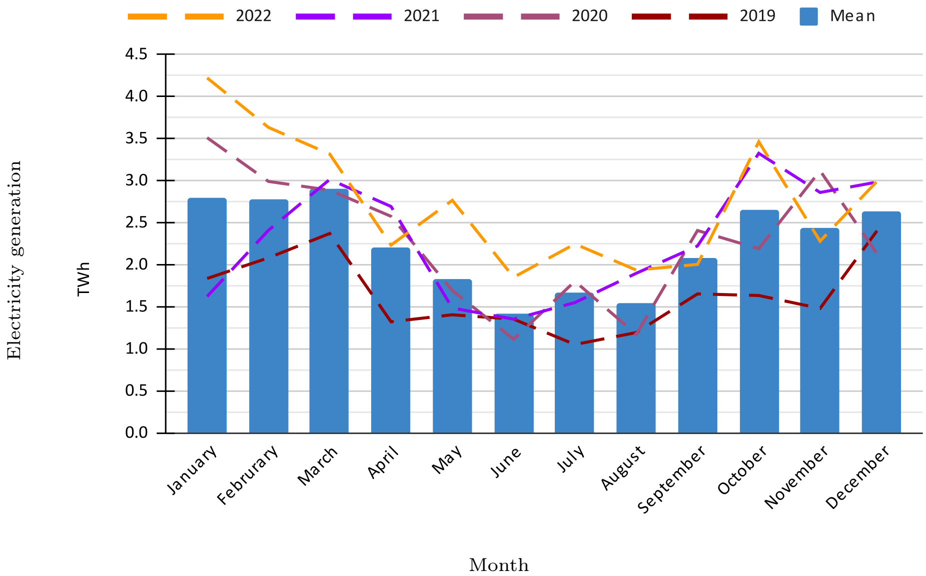

Figure 12: Monthly production of electricity using wind power for years between 2019 and 2022 in Sweden (SVK, n.d.). Values are not adjusted to relative terms with respect to increased installed capacity year-over-year.

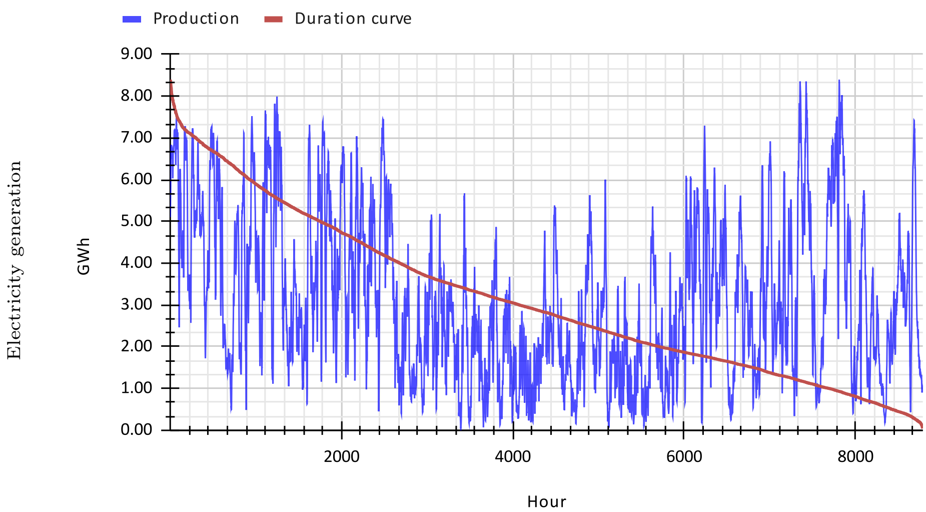

Figure 13: Hourly wind power production in Sweden year 2020. The X-axis represents the hour in that year and since the year of the data was recorded during a leap year, the total number of hours was 8784. The duration curve shows how many hours each year a specific amount of energy is generated, sorted from highest to lowest. (SVK, n.d.).

2.3.3 Hydropower

Hydropower refers to the energy that can be harnessed from the movement of water during its water cycle (Breeze, 2018). It is a renewable energy technology that converts the potential energy of falling water and the kinetic energy of flowing water into electricity using turbines and generators (Breeze, 2018).

Historically, hydropower served various purposes, from grinding grain to powering mines (Breeze, 2018). In recent times, hydropower has proven itself to be a cheap and reliable source of electricity for many countries around the world (REN21, 2022).

To harness the energy of water, different physical properties are utilized to convert that energy into electricity. The most widely used hydropower technology is the combination of an artificial dam and one or several turbines (hydroelectric power plant, HPP) (Breeze, 2018). Another widely used solution is where a turbine is used to utilize the flow of water directly, without any pondage restricting the flow of water (run-of-the-river power plant) (Breeze, 2018).

HPPs mostly utilize artificial dams which obstruct the natural flow of water in a river, leading to the creation of water reservoirs and a height differential between the two sides of the dam (Breeze, 2018). A controlled inlet leads water through a custom turbine that spins and generates AC-electricity using a connected generator as it is released from the power plant into a lower reservoir. This generated electricity is transformed to the desired voltage using a transformer in the power station and fed into the grid. The optimal turbine selection depends on properties such as the flow rate and height difference (head) (Sangal et al., 2012).

Sweden has about 2100 hydroelectric power plants (HPPs) with a total installed capacity of about 16.3 GW (Svenskt Näringsliv, 2020). A small portion of the hydropower reserve is included in the frequency disturbance reserve and is not considered available (SVK, 2022b). The practical maximal momentary capacity is considered to be between 13.4 GW (Svenskt Näringsliv, 2020) and 13.7 GW (Energimyndigheten, 2018).

About 208 of these HPPs provide 94% of the total production (Svenskt Näringsliv, 2020). These have an installed capacity of 10 MW or higher and are mostly located in the northern regions of Sweden (SE1 and SE2, see figure 3.3 where the division of the electricity system is shown). The total available energy in the yearly precipitation has varied between 49.2 TWh/year and 90.6 TWh/year since 1950, while the average annual precipitation is 67.6 TWh/year, which sets the approximate available electricity production for HPPs in a year (Svenskt Näringsliv, 2020). According to IVA (Kungl. Ingenjörsvetenskapsakademien), the difference between years with low and high precipitation, in energy terms, yields a ±20% difference (IVA, 2019).

Another statistic of interest is the available storage capacity for hydropower in Sweden, which amounts to 33.675 TWh (Nord Pool, 2023b), while the practically useful amount is about 50% of this number according to historical data from 1960 (IVA, 2019). The capacity of water reservoirs can be seen in figure 14. It is evident that the available amount of water and hence energy, varies throughout the year and is dependent on the precipitation throughout the year.

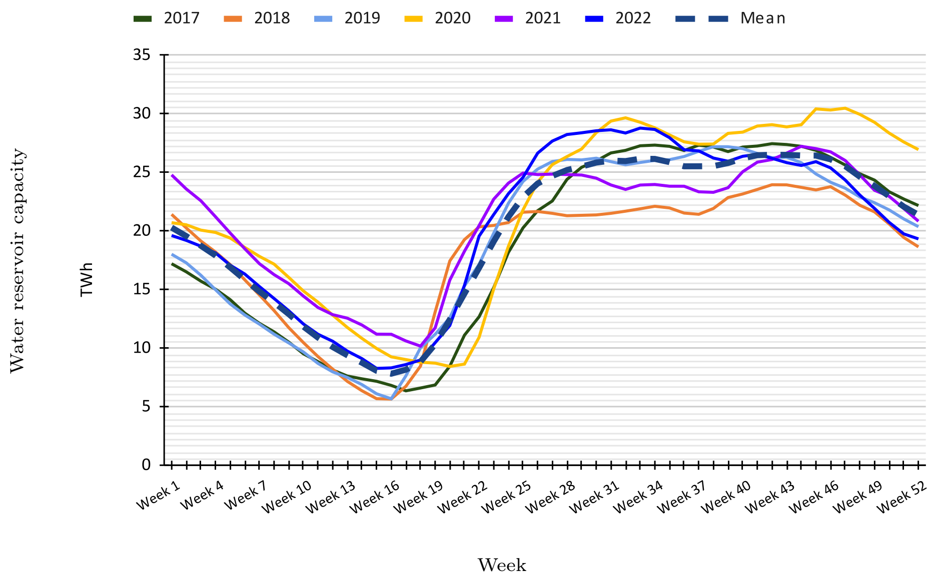

Figure 14: Water reservoir capacity during six years in Sweden together with their mean capacity during these years (ENTSO-E, 2023).

2.3.4 Nuclear power

Nuclear power is derived from harnessing the robust binding forces present within an atom's nucleus. This can be achieved either through the splitting of a heavy nucleus, a process known as fission, or by fusing lighter nuclei together, a process known as fusion (NEA, n.d.). Splitting an atom's nucleus results in a much greater energy amount than breaking a molecule bond (NEA, n.d.), which is what happens when burning ordinary fuels like methane. Humanity has mastered the process of fission (breaking nuclei) but has yet to create a commercially viable solution that could provide a net energy gain from fusion (fusing nuclei).

Currently, the most common reactor fuel is the mix of uranium isotopes U-238 and U-235, where the ratio depends on the enrichment grade (NEA, n.d.). During enrichment, the amount of U-235 is increased from the natural 0.7% to between 3 and 5% (SSM, 2023).

When a U-235 atom is hit with a neutron, it absorbs the neutron and becomes unstable. The instability causes the atom to split into two smaller atoms (fission products) and releases several neutrons. These neutrons can, in turn, hit other atoms, which leads to a chain reaction as this process continues. In a controlled chain reaction, this is kept under control and becomes self-sustaining by the use of moderators (Murray and Holbert, 2014). Moderators are materials that slow down neutrons to control the reactions. In Sweden, the most prevalent type of reactor is the Boiling Water Reactor (BWR), as shown in table 1 and this type of reactor uses water as a moderator (Murray and Holbert, 2014).

As the fission creates heat, water passes through the fuel elements and cools it down as it turns into steam (for BWR). This steam travels through a turbine that turns an electric generator, which produces AC electricity (Murray and Holbert, 2014). There are also Pressurized Water Reactors (PWRs) present in Sweden, as seen from table 1 for Ringhals 3 and 4. The main difference between PWR and BWR lies in the treatment of the water used as a coolant and neutron moderator. In PWRs, this water is kept under high pressure to prevent it from boiling in the reactor core and does not directly interact with the turbine system water. In BWRs, the water is allowed to boil and directly drive the turbine.

A small amount of electricity is used by the power plant and the rest is sent out to the grid. When the steam passes through the turbine, it goes through a condenser where it is cooled by sea water (Murray and Holbert, 2014) and the cycle is repeated.

The power rating of a nuclear power plant is determined by its thermal power rating, denoted by MWth, which represents the amount of heat the reactor can generate and transfer from the fuel to the coolant. Conversely, the net capacity, denoted MWe, refers to the net electrical output after accounting for the power plant's self-consumption. The number of interest is the net capacity as mainly all nuclear power plants produce only electricity.

A reactor's maximal operating thermal power is determined by its operating license. The majority of the reactors in Sweden have undergone power upgrades of up to 30%, increasing their net capacity beyond that of the initial design. Most of the reactors were constructed during the mid-1960s and 1970s, while the dates of commercial operation were several years later, culminating in a massive increase of installed nuclear capacity between the mid-1970s and 1980s. During the span of about 14 years, almost 11 GW (0.78 per year) of installed capacity was introduced. Assuming a capacity factor of 0.8 would correspond to an addition of 5.5 TWh per year during this period.

Small Modular Reactors

Small Modular Reactors (SMRs) are nuclear reactors characterized by their output, which is typically less than 300 MWe. This is in contrast to conventional reactors, which have an electrical power output several times greater (Energiforsk, 2019). A key advantage of SMRs lies in their compact size and the fact that they are often produced in a factory assembly line or shipyard, rather than being built on-site. This approach reduces costs and could also introduce a degree of mobility to the power plant (Energiforsk, 2019). SMRs come in a variety of types, each with differing levels of their technological maturity. Among these, the light water reactor is the most common and mature type. However, there are also other types such as molten salt, metal cooled, gas cooled, thorium and uranium reactors (Energiforsk, 2019).

Several projects are in their initiation phase in Sweden. A noteworthy project, called the Solstice, is initiating construction at the Oskarshamn nuclear power plant site. It has the goal of being operational by 2025, demonstrating some properties of the downsized version of the lead-cooled SEALER reactor. This project, a joint venture encompassing the Royal Institute of Technology (KTH) spin-off LeadCold (Blykalla AB) and Uniper Sweden. The anticipated thermal output is projected to be 2.5 MWth, while the commercial variant is expected to yield 140 MWth thermal and 55 MWe net capacity ratings (Wennberg, 2023).

Table 1: Operational and decommissioned reactors in Sweden along with their type, construction year and capacity (IAEA, 2022).

Reactor Unit	**Type**	**Net Capacity MWe**	**Status**	**Construction year**
Forsmark 1	BWR	990	Operational	1973
Forsmark 2	BWR	1121	Operational	1975
Forsmark 3	BWR	1172	Operational	1979
Oskarshamn 3	BWR	1400	Operational	1980
Ringhals 3	PWR	1072	Operational	1972
Ringhals 4	PWR	1130	Operational	1973
AGESTA	PHWR	10	Decomissioned	1957
Barsebäck 1	BWR	600	Decomissioned	1971
Barsebäck 2	BWR	600	Decomissioned	1973
Oskarshamn 1	BWR	473	Decomissioned	1966
Oskarshamn 2	BWR	638	Decomissioned	1969
Ringhals 1	BWR	881	Decomissioned	1969
Ringhals 2	PWR	852	Decomissioned	1970

One of the most important issues with nuclear power is waste management. A typical reactor contains about 100 tons of uranium and uses approximately 20 tonnes each year. A portion of this is renewed during a revision period, which can last from several weeks to months, typically during the summer when the reactor is switched off (SSM, 2017). According to Strålsäkerhetsmyndigheten (The Swedish Radiation Safety Authority), about 1050 tons of uranium, including new and used fuel, is present in Swedish reactors (SSM, 2023).

Spent fuel is initially stored at the nuclear power plant for about a year to allow the majority of the radioactivity to decay. It is then transported to Clab in Oskarshamn, where it is stored 30 meters underground for at least 30 years to allow further decay of radioactivity (99.99%) (SSM, 2023). The final step is to transport the waste fuel for final disposal. In Sweden, the chosen method is to encase the waste in copper capsules and place them in caverns 500 meters below ground near Forsmark (SSM, 2022). This method is designed to safely store the waste for 100,000 years and withstand a new ice age (SSM, 2022).

For each kWh of electricity produced using nuclear power, a certain price determined by the Swedish National Debt Office (Riksgälden) is paid by nuclear power plant owners to a fund responsible for spent nuclear fuel and plant decommissioning in the future. This cost has been less than 0.01 kr/kWh but has steadily increased and is expected to reach up to 0.09 kr/kWh for some nuclear power plants (Riksgälden, 2023).

2.3.5 Combined heat and power (CHP)

Conventional power plants in the old energy system produced electricity using fuel and boilers to generate heat and a separate power plant to generate electricity (IEA, 2008). Typically, the efficiency of electricity generation in such configurations is often below 50% (Office of Energy Efficiency & Renewable Energy, 2023), attributed to heat losses and inefficiencies in fuel conversion. One way to increase the overall efficiency of the energy conversion process is to utilize the surplus heat (i.e. in domestic heating applications). This is accomplished by generating electricity (using steam turbine generators, or similar) and using the waste heat for other means. Power plants that operate on this principle are called combined heat and power plants (IEA, 2008).

Co-generation, i.e., when we produce heat and electricity simultaneously, leads to efficiencies between 65-75% (Office of Energy Efficiency & Renewable Energy, 2023) or even close to 100% (Hammar, 2014). Combined heat and power plants (CHPP) can be powered using renewable and fossil fuels, although the renewable portion is of interest in this report.

One prime example in Sweden is Örtoftaverket, which generates 220 GWh of electricity and 550 GWh of heat annually from biomass and manages to achieve very high efficiencies (close to 100%) due to co-generation and the flue gas condensation process (Hammar, 2014).

2.4 Power generation in Sweden

Vattenfall, Fortum and Uniper are the largest electricity producers in Sweden. In 2021, they collectively accounted for approximately 66.7% of the total electricity production in Sweden (Energimyndigheten, 2022a). Since 2010, Sweden's electricity self-sufficiency has consistently been over 100%. This means that Sweden generates more electricity than it consumes, making it a net electricity exporter in TWh terms (Energimyndigheten, 2022a). Although the fuel for nuclear energy is imported, its production is considered to occur within Sweden. Despite being an electricity exporter, Sweden still experiences high demand for power, measured in GW, during peak consumption periods (Energimyndigheten, 2022a).

As previously defined, 74% of Sweden's power generation was from renewable sources in 2020 (Energimyndigheten, 2023b). Figure 15 depicts the power generation in Sweden by source, alongside the domestic electricity consumption. Since production exceeded domestic consumption, the surplus was exported to neighboring countries. It is notable that the majority of electricity is generated by hydropower, followed by nuclear and wind power.

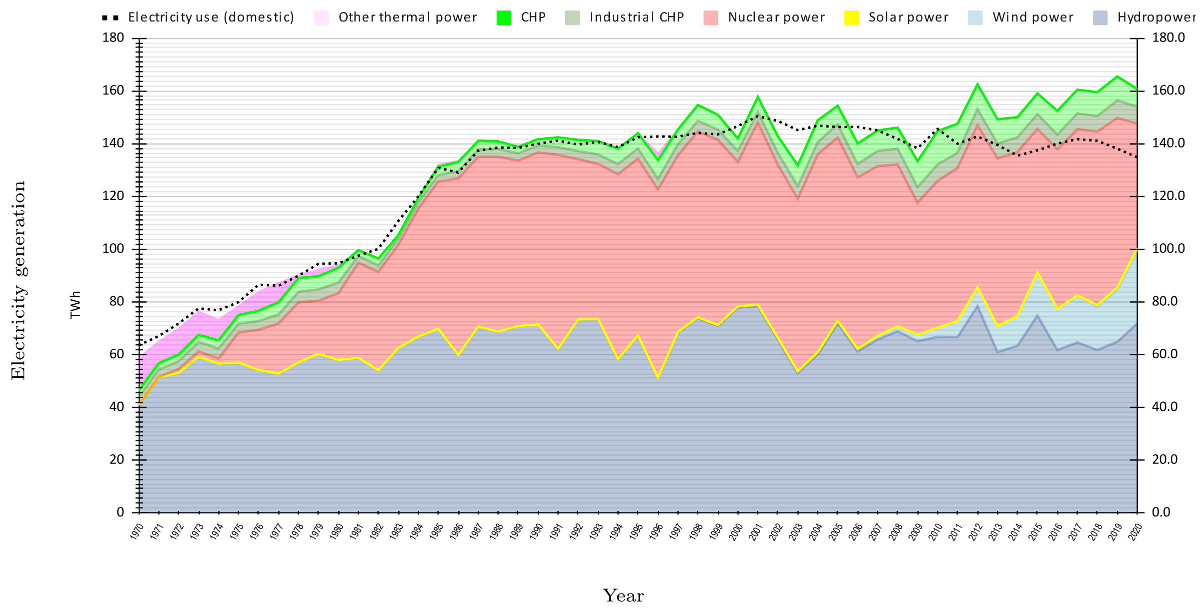

Figure 15: Total electricity generation by source in Sweden between 1970 and 2020 and domestic electricity use (Energimyndigheten, 2023b).

According to the SCB, production and consumption occur in different regions. The majority of electricity production occurs in the north of Sweden, while the south and areas near population centers account for most of the electricity consumption (SCB, 2016).

To comprehend the production capability of each generation, it is also necessary to examine the installed capacity of each power source in Sweden and compare it to the actual power generated.

2.4.1 Installed capacity

The installed capacity, often referred to as the nameplate capacity, represents the upper limit of power output that a generation facility can achieve under ideal conditions.

In 2021, the total installed power capacity in Sweden was 43.7 GW (Lindahl et al., 2022), the distribution among the power sources is seen in figure 16. Several observations can be made from this graph. Firstly, the installed capacity of wind power has surpassed that of nuclear power. Despite this, nuclear power generates approximately twice as much electricity. This discrepancy can be attributed to the high capacity factor of nuclear power, which will be discussed in more detail later. Another notable point is that, despite the permanent shutdown of nuclear plants since the mid-2010s, the amount of electricity generated by nuclear power has not significantly decreased. This can be partially explained by an increase in the power output of operational power plants that were left.

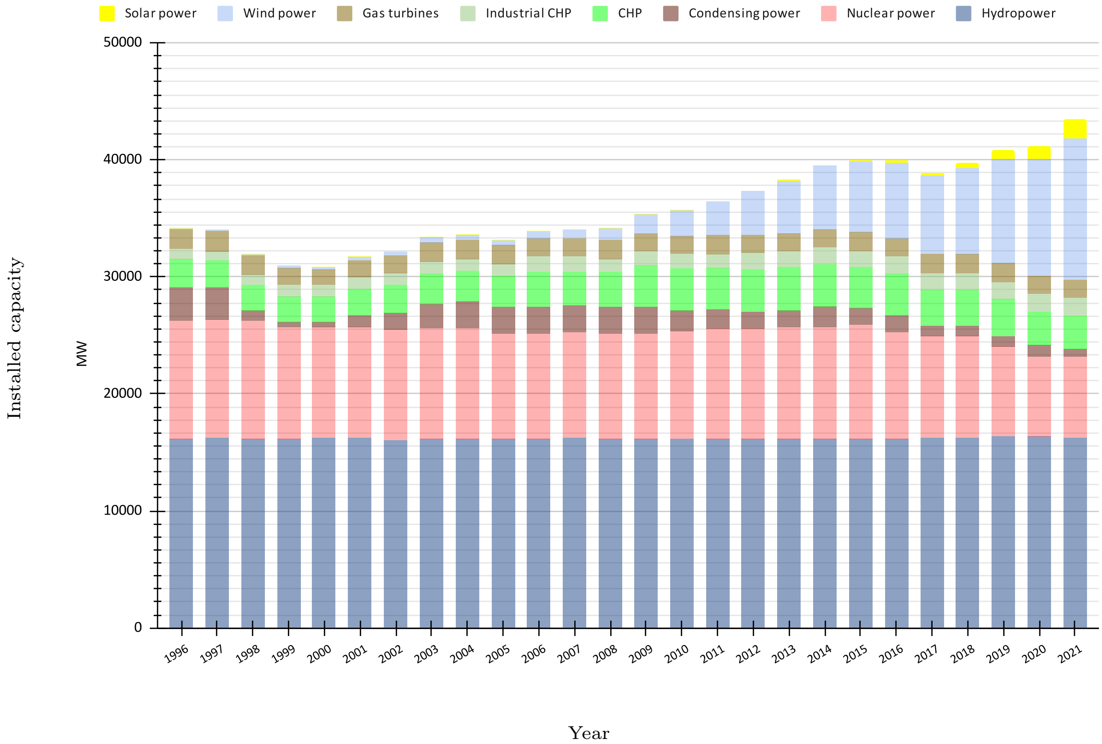

Figure 16: Installed capacity (MW) in Sweden between 1996 and 2021 in Sweden (Energimyndigheten, 2023b).

2.4.2 Power availability

The installed capacity by type in Sweden differs from the share of electricity generated by the given installed capacity. Since the actual power output differs from the theoretical power limit, there is a discrepancy between the maximum possible power generation under ideal conditions and the actual generation.

Availability can be defined in several ways. One way is technical availability, which is the ratio of the time a power plant is available for production to the total time. This equation is seen in equation 3. Technical availability is usually above 90% (Kaldellis and Zafirakis, 2013).

$$\text{technical availability} = \frac{\text{total time} - \text{downtime}}{\text{total time}} \tag{3}$$

Another metric for availability is the one used by SVK, which defines availability as the minimum power available during the time of highest peak load. For instance, SVK assigns a wind power availability factor of 9%, meaning that *there is a 90% probability that at least 9% of the total installed capacity will be available* during peak load times (SVK, 2022b). The availability figures for wind power have varied slightly over the years, but are of a similar magnitude. Availability factors used in SVK in their reports are seen in table 2. We can note that Hydropower, Nuclear power and CHP have the highest availability factors during the winter. We can also note that wind power has a low, yet constant availability factor compared to the other power sources. It can also be seen that solar power has an availability factor of 0 during peak load.

Table 2: Availability factors for each power source according to Svenska kraftnät. The availability for nuclear power during summer depends on the revision period (SVK, 2022b).

Power source	**Availability summer** (%)	**Availability peak load** (%)
Hydropower	75	82
Nuclear power	-	90
Wind power	9	9
Combined heat & power	10	77
Solar power	9	0
Condensing power	50	90

This metric is used to measure power availability during peak load hours, while the capacity factor is used as a measure of energy availability.

2.4.3 Capacity factor

The capacity factor is a measure of the energy generated by a power source in relation to its total installed capacity. It represents the degree to which the installed capacity is utilized over a specific time period. It is defined as the ratio of actual electricity production to the maximum possible output of a power plant operating at full capacity over a specified time period, typically a year. This metric is closely related to the concept of full-load hours, which is the number of hours a power source operates at full capacity over a year. The formula for capacity factor is seen in equation 4.

$$\text{capacity factor} = \frac{\text{generated electricity [Wh]}}{\text{installed power [W]} \cdot \text{period [h]}} \tag{4}$$

A power source with a high capacity factor generates electricity for a significant portion of the time it is operational. Some projects with their type, name and capacity factor are seen in table 3. It can be noted that nuclear power plant has the highest capacity factor with the lowest being a solar park, we can also note that wind power has higher capacity factor than solar power according to this table.

Table 3: Capacity factors for different renewable power plant types (Energimyndigheten, 2023a) along with nuclear (OKG, 2023) power plant.

Type	**Name**	**Installed capacity (MW)**	**Annual production**	**Capacity factor**
Offshore WPP	Lillgrund	110.4	336 GWh	0.35
Onshore WPP	Höge Väg	37.8	107 GWh	0.32
NPP	Oskarshamn 3	1450	10.4 TWh	0.82
Solar park	Nolato	7.2	8 GWh	0.13
Solar park	Eken	11.8	11.7 GWh	0.11
HPP	Yngeredsfors	21	93 GWh	0.5

2.5 Swedish energy system

The Swedish power system is a network of interconnected turbines and generators bound together by high-voltage AC-lines, HVDC-lines and transformers forming a synchronous grid in which all connected generators rotate at the same frequency - 50 Hz. To maintain uniform frequency, the generated electricity has to be produced at the same rate as it is being used or stored. When there is an imbalance between production and consumption, the frequency of the system changes - where uncontrolled frequency change can cause damage to the devices connected to it. According to SVK, 49 Hz is the critical frequency level with load shedding starting at 48.8 Hz (Eriksson, n.d.).

Equation 5 illustrates balance in the system, explaining the relation between mechanical power P_{mec} (W) and electrical power P_{el} (W) and how that difference changes the angular speed of the rotor ω (rad/s) with inertia J (kgm^2).

$$J\omega\frac{d\omega}{dt} = P_{mec} - P_{el} \tag{5}$$

If the load (electrical power consumption) increases while generation (mechanical power) is unchanged, the energy is converted from the kinetic energy of rotating synchronous machines into other forms of energy. Consequently the machines rotates at a slower pace, decreasing the angular speed and hence the frequency of the system. This can be seen from equation 5 since the left hand side becomes negative - indicating a decrease in frequency. The reverse happens when there is more production capacity than consumption.

2.5.1 Inertia

A system's inertia, or J, is its ability to resist changes in speed. This can be useful during unexpected events, such as when power plants or interconnections go offline suddenly. A decrease in inertia would cause faster fluctuations during a contingency (disturbance) (Denholm et al., 2020). Not only would the rate of change of frequency (RoCoF) increase, but so would the lowest frequency (nadir) and the amplitude of frequency variations during a disturbance (Saarinen et al., 2018). RoCoF and nadir are explained further in section 2.7.1.

The kinetic energy from a system perspective can be written in terms of other units than kWh, since inertia lasts for a short period of time there is an interest to describe the ability to provide power during several seconds. A generator that has 10 GWs inertia can deliver 10 GW during one second (Denholm et al., 2020). But as units Wh is power during an hour the corresponding energy would be $\frac{10\,\mathrm{GW\,s}}{3600\,\mathrm{s}} = 2.7\,\mathrm{MW\,h}$ of energy.

Furthermore, two equally rated (MW-terms) generators can have different inertia. This is due to the fact that the types may not be the same. This can be seen as the formula 6 is rewritten to describe the inertia constant H (MWs/MVA = s). This describes the time that a generator could provide its rated power only through the rotation of its mass. The typical range is from 2 to 9 seconds for synchronous generators.

$$H = \frac{Jw_s^2}{2S_n} = \frac{E_{rot}}{S_n} \tag{6}$$

The typical values for different power unit types are shown in table 4. As can be seen, nuclear power has almost twice as high value as the other power types. Wind power turbines do also have inertia but they are not directly connected to the grid like other generators (but rather through converters) and hence do not contribute with their inertia to the system (Jung, 2017). This inertia for wind turbines is calculated through the active power and is in the range of 2 to 6 s (Jung, 2017). Another report found it to be 3.57 s (Fernández-Guillamón et al., 2019).

Table 4: Typical inertia constant values for different production units (Eriksson, n.d.). Wind power does not contribute to the system inertia constant as wind power plants are not connected directly to the grid and are hence written in a cursive font (Jung, 2017).

Unit type	**H (s)**
Nuclear power	6 - 8
Hydro power	2 - 4
Thermal power	3 - 4
Wind power	*2 - 6*

For generated electricity to be useful, there must be an energy market and distribution system linking producers with consumers.

2.5.2 Electricity distribution

The Swedish national electricity grid is divided into transmission and distribution systems, which differ in the voltage used to transmit electricity. The distribution system, in turn, consists of a regional grid and a local grid, which differ in voltage and operator. The transmission grid consists of about 17,500 km of power lines and operates at voltages of 400 kV and 220 kV, while regional grids operate at voltages between 130 kV and 20 kV (SVK, 2022c). The main goal of the transmission system is to transport electricity long distances with low loss of energy, while the goal of the distribution system is to deliver that electricity from the transmission system to the end consumer (SVK, 2022c).

The Swedish electricity system was deregulated during the 1990s considering production and trading of electricity. During that time the state owned SVK (also known as Affärsverket svenska kraftnät, Svenska kraftnät) was formed and law 1997:857 (Ellagen) was introduced where SVK became the system responsible authority (chapter 8, paragraph 1). SVK was tasked to make sure there was a balance between production and consumption. From 2021 SVK is not only responsible for momentary power balance but also long term power balance of the system.

In Sweden, the transmission system operator (TSO) and responsible authority for transmission responsible on the Swedish national grid is SVK (SCB, 2023). The power lines operated by SVK need a permit to operate its power lines (concession). This permit (concession) is received from Swedish Energy Markets Inspectorate (Ei) for national lines and the government where a connection is made outside of the country. These permits usually apply until further notice with a possibility of review after 40 years. SVK has the indefinite right to construct the power lines without owning the property or land under it (right-of-way) providing the owner a lump sum of money for the land underneath it based on a specified valuation.

The transmission system is completely owned by SVK while the distribution system is largely owned by Vattenfall, Ellevio and E.ON while the local grids are mostly owned by municipal-owned companies.

2.6 Electricity market

Since 2011, Sweden has been divided into four different pricing/bidding regions, as seen from figure 3.3: Luleå SE1, Sundsvall SE2, Stockholm SE3 and Malmö SE4 (Ei, 2021). This results in different electricity prices across these regions (Ei, 2021). In Sweden, this electricity can be bought and sold in several markets, including the futures market (Stockholm Stock Exchange - Nasdaq OMX Commodities), Nord Pool or through a broker (Ei, 2021). The first market can be used to secure electricity supply several years ahead of delivery.

The price of electricity is determined at Nord Pool Spot, an exchange for trading electricity in the Nordic, Baltic and several other countries. Nord Pool is headquartered in Oslo and is owned by state-owned TSOs from the involved countries. The main entities operating on this market are producers and distributors. Nord Pool exchange consists of two main markets; day-ahead (Elspot) and Intraday (Elbas) (Ei, 2021). In the day-ahead exchange, producers and buyers bid for a price for each hour of the following day. The buyer estimates the demand during the specified time while producers bid a price and the amount of energy they can deliver during that time. When the market closes, the price is calculated according to the specified demand. This price becomes the overall system-price. This is the price that does not take into consideration where electricity is consumed or produced and whether there are transmission bottlenecks (Ei, 2021).

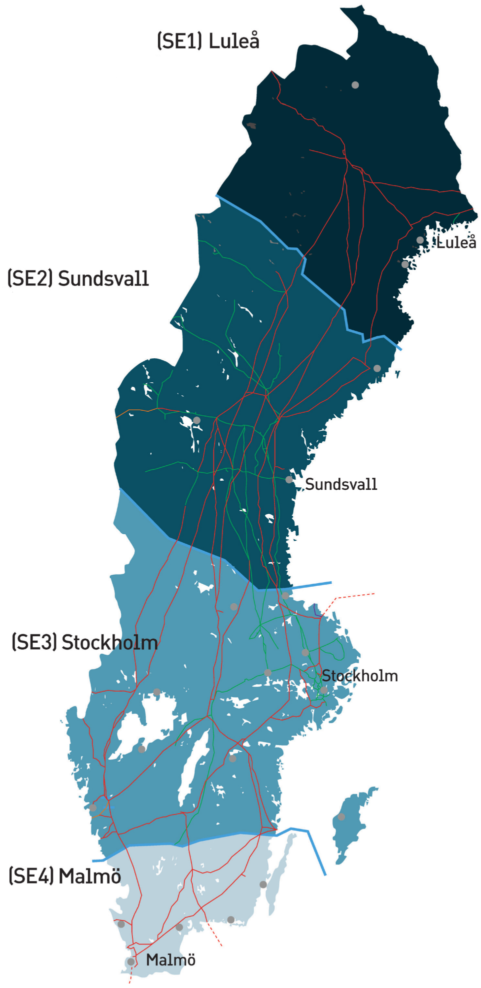

Figure 17: Map of Sweden showing the division of the electricity system into four regions SE1-SE4. Source: SVK.

In practice, the locations of electricity production and consumption often differ. This can lead to transmission constraints, which means that the flow of electricity is not always free between regions. The price of electricity is typically lower in SE1, the northern electricity price area in Sweden, where production is usually higher than consumption. By contrast, the price is typically higher in SE4, the southern electricity price area in Sweden, where consumption is usually higher than production. If a producer and consumer are located in different regions, the producer gets the spot price in the region where they are located and the consumer pays the spot price in the region where the electricity is being consumed.

Nord Pool is the largest exchange for electricity in Sweden and it accounts for the vast majority of produced electricity trade. In total, about 1077 TWh was traded on the exchange during 2022 with the Nordic and the Baltic countries accounting for the biggest share of the trades (Nord Pool, 2023a).

This discrepancy necessitates a second market, **Intraday** (Elbas), where producers and buyers can bid on contracts for power to be delivered in the following hour.

Balancing through ancillary services are procured by SVK through a separate system (SVK, 2023b).

2.7 Power reserves

ENTSO-E considers the kinetic energy capacity in Sweden to be 170 GWs compared to 390 GWs in the Nordics (ENTSO-E, 2018a). On 10th of April 2015 this number was 97.9 GWs in Sweden (ENTSO-E, 2018a) while the lowest level of inertia in the larger, Nordic system, was during the summer of 2009, being 115 GWs (ENTSO-E, 2018a). ENTSO-E concluded that in scenarios of low load and having a production consisting of wind, hydro and nuclear in equal parts, the nuclear power would have the highest share of inertia added to the system (ENTSO-E, 2018a). This means that removing nuclear power generation from a system impacts the inertia more than removing other types of electricity generation.

Generally speaking, the system mainly consists of primary, secondary and tertiary control reserves (ENTSO-E, 2022a). During the primary control, SVK, uses reserves to stabilize the frequency in the range of 50 Hz, which is done mainly through FCR (Frequency Containment Reserve). The secondary reserve is activated after the primary reserve, with a goal of restoring the frequency to 50 Hz after the stabilization (ENTSO-E, 2022a), this is done with aFRR (automatic Frequency Restoration Reserve) which can be seen in figure 18. The third type of control is a manual reserve, mFRR (manual Frequency Restoration Reserve), which takes over to relieve the first and secondary reserves. In practice, these reserves might be different power plants or virtual power plants that are able to comply with ramping specifications that are set by the operator. For instance, it could be a power plant that starts producing a specified amount of power with a low start-up time.

The amount of power reserve needed changes all the time as the system develops (SVK, 2023a).

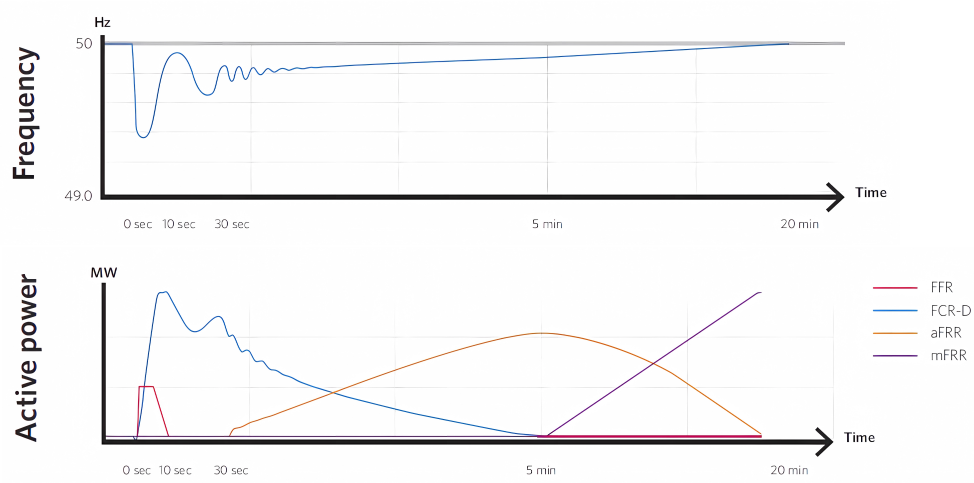

Figure 18: Frequency behaviours during a large disturbance and utilization of reserves (ENTSO-E, 2022a). FCR-N is not included.

2.7.1 RoCoF & nadir

As seen from figure 18, some type of disturbance caused a drop in frequency. The initial downward slope indicates the rate at which the frequency dropped, which serves as a valuable indicator of system resilience. This rate of change of frequency, **RoCoF**, is described by equation 7.

$$\text{RoCoF} = \frac{\Delta f}{\Delta t} \tag{7}$$

Another valuable metric is the **nadir**, which denotes the lowest frequency value the system reaches following a disturbance. Understanding and predicting this lowest point is crucial for system operators, since, if the nadir drops below certain thresholds, it could lead to system blackouts or critical damage to infrastructure.

2.7.2 FCR

FCR (Frequency Containment Reserve) is a type of frequency reserve composed of Frequency Containment Reserve for Normal Operation (FCR-N), which operates during minor deviations and Frequency Containment Reserve for Disturbances (FCR-D upward and FCR-D downward), which operates during disturbances (ENTSO-E, 2022a). The system is deemed to be in the normal operating range when the frequency lies between 49.9 and 50.1 Hz (ENTSO-E, 2022b). During this time, the FCR-N (Frequency Containment Reserve for Normal Operation) is operational. If the frequency increases above 50.1 Hz, then FCR-D downward is activated and deactivated when the frequency is back to the normal operating range. Similarly, if the frequency decreases below 49.9 Hz, then FCR-D upward is activated and deactivated when the frequency is back in the normal operating range, as illustrated in figure 18.

The upward FCR-D is dependent on the largest possible dimensioning error (the N-1 criterion), taking into account the failure of the largest generation unit in the network, which, in the Nordics, is the Oskarshamn 3 NPP (1450 MW) (ENTSO-E, 2022a). FCR-D down, on the other hand, depends on the failure of the largest transmission link, NSL or NordLink and is 1400 MW (SVK, 2023a).

2.7.3 FRR

FRR (Frequency Restoration Reserves) is a type of frequency reserve comprising automatic and manual reserves (aFRR and mFRR) designed to manage initial frequency deviations and assist FCR in restoring the frequency to 50 Hz (ENTSO-E, 2022b). The Automatic Frequency Restoration Reserve (aFRR) contributes power within 2 minutes and restores the frequency back to 50 Hz during a disturbance (ENTSO-E, 2022b). The Manual Frequency Restoration Reserve (mFFR) is activated on request by SVK within 15 minutes to restore the frequency back to 50 Hz. SVK procures mFRR on long-term contracts and its size must be larger than 1450 MW, which is the national reference incident (the gross size of the Oskarshamn 3 nuclear power reactor) (ENTSO-E, 2022a).

2.7.4 FFR

In 2020, the Nordics introduced an additional reserve, FFR, in response to the low levels of kinetic energy in the system affecting the activation time of FCR-D, to ensure proper stability during a disturbance.

FFR (Fast Frequency Reserve) is used as a very quickly dispatchable reserve to stabilize rapid transient-wise disturbances as seen in figure 18 (ENTSO-E, 2022a). This is often used when the level of inertia in the system is low. FFR is currently only able to up-regulate the frequency and is activated between 49.5 and 49.7 Hz with the activation time of 0.7 - 1.3 seconds while supporting the grid for 5 or 30 seconds (ENTSO-E, 2022b). According to ENTSO-E, SVK has an FFR share of 105 MW in 2022 (compared to 300 MW from the Nordic level). The biggest FFR-procurement was during 2022 with 71.5 MW on 2022-07-16 01:00, in 2021-08-15 01:00 that was 78.3 MW between 01:00 and including 06:00 and 43.2 MW in 2020-08-02 between 03:00 and including 04:00 (SVK, 2022a). This shows that FFR need is highest during the summer.

2.8 Duck curve

With increased shares of renewable electricity assets such as solar and wind power, system operators need to take into consideration new challenges for the system. Several system operators with different energy mixes saw the effects of high VRE penetration in their electrical systems. CAISO, California's independent system operator (ISO), coined the 'Duck Curve' which describes the net load that the system operator has to account for (CAISO, 2016).

As VRE resources generate electricity at full operational capacity during certain time frames, there is a need to reduce generation from other production assets in accordance with VRE generation and the electricity demand in the system. This, together with the natural consumption pattern during the day, leads to a net load pattern visually resembling a duck looking to the right, as seen in figure 19. The main issue for the system operator is the need to ramp up and ramp down the production of other assets other than VREs, especially where penetration of solar power is high. This can be seen in figure 19 where the TSO needs to first decrease production by 4 GW at 07:00 and then increase production by 6 GW at 13:00 in a few hours. In California, there is a high penetration of solar power and CAISO concluded that there is a need for ramping 13 GW in three hours (CAISO, 2016).

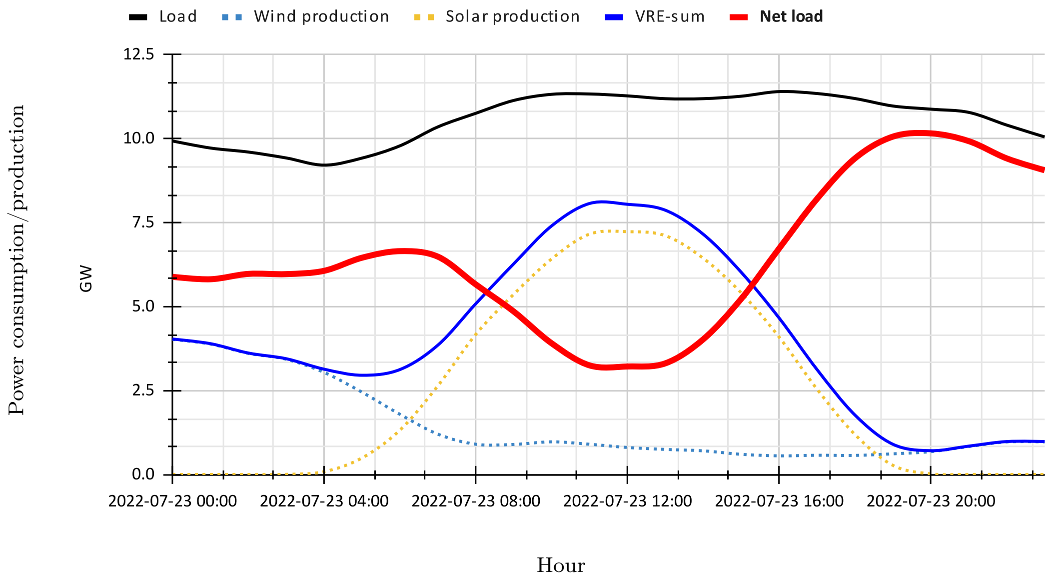

Figure 19: Total power consumption (GW) by hour during a summer day in Sweden where total variable renewable production (VRE) is subtracted from load to produce the net load (residual) on the "duck curve" form (SVK, n.d.). The solar production is scaled by a constant to illustrate a scenario with higher solar production in Sweden.

2.9 Energy storage

Energy storage is related to the ability of storing energy for future use. This can be done through the use of several technologies. This can be achieved through the use of different physical and chemical properties of materials and systems (Huggins, 2016).

The most used energy storage technology today is pumped hydro storage accounting for more than 95% of the stored energy (Svenskt Näringsliv, 2015). Other storage technologies on the rise are different batteries and hydrogen. What differs them on a technological basis are several factors, shown in table 5. The factors of interest are how much energy can be stored for a unit of volume together with the efficiency of the process. On a system scale the factor of interest is the efficiency, response time and the usual time for storage.

Table 5: Characteristics of storing energy through the use of pumped hydro storage, different batteries and hydrogen (Deloitte, 2015) (IRENA, 2019).

Storage type	**Efficiency (%)**	**Daily discharge rate (%)**	**Power density (W/l)**	**Energy density (Wh/l)**	**Storage time**	**Response time**
Pumped hydro	70 - 85	≈0	0.1 - 0.2	0.2 - 2	4 - 12h	sec - min
NaS *battery*	70 - 90	0.05 - 20	120 - 160	150 - 300	1 min - 8 h	ms
Li-ion *battery*	85 - 98	0.1 - 0.3	1300 - 10000	200 - 400	1 min - 8 h	ms
Flow *battery*	60 - 85	0.2	0.5 - 2	20 - 70	min	ms
Hydrogen	25 - 45	0 - 4	0.2 - 20	600 (200 bar)	min - week	sec - min

2.9.1 Pumped storage hydropower

Water is housed in two reservoirs separated by a height differential. In moments of electricity surplus the water is pumped from the lower reservoir to the higher where it is stored. When electricity is needed again, the pumped storage hydropower (PSH) releases the water through a turbine harnessing the potential energy (Svenskt Näringsliv, 2015), which, in essence, works like a two-way hydropower plant.

There are only three operational PSHs in Sweden today (93.6 MW), all being owned by Fortum AB and located in SE3: Kymmens kraftstation (55 MW), Lettens kraftstation (36 MW) and Eggsjöns kraftstation (0.6 MW) (Svenskt Näringsliv, 2020). Swedish PSHs are not closed systems by themselves and do not use the same water for pumping between the water reservoirs but it is the water used for other electricity production which limits the PSH capacity to yearly precipitation (Svenskt Näringsliv, 2020).

2.9.2 Batteries

The global electrochemical energy storage market is dominated by lithium-ion batteries with 92% of the market (Worku, 2022).

Batteries consist of anode, cathode and an electrolyte which transports the ions. During charging ions move to anode from the cathode and during battery operation these move in opposite direction (Goodenough and Park, 2013). Batteries offer a high power density and high efficiency. Several types of batteries are of interest for grid energy storage. Sodium-sulphur batteries are molten salt batteries that operate at high temperatures. They have a high efficiency have a high efficiency and last long time (Huggins, 2016) in this type, adding more storage tanks would increase the total available energy. Then by increasing the number of cell stacks would increase the rate at which this energy could be retrieved (power) (Huggins, 2016).

What is common among different battery types is that they provide high power density, fast response times and high efficiency although the storage time is low compared to other technologies. Li-ion batteries typically lose power at the end of their lifetimes. When they cannot be used in ordinary applications to the same extent they could be reused for other purposes like ESS (Energy Storage Systems) (Illa Font et al., 2023).

2.9.3 Hydrogen

Although molecular hydrogen is rare on earth, hydrogen atoms are abundant in chemical compounds such as water. Hydrogen in its gas form is highly combustible and hence of interest as both fuel and energy storage medium. It can be produced by steam methane reforming, coal gasification, renewable liquid reforming and water electrolysis (IRENA, 2019).

Even though 96% of the world's hydrogen is produced by fossil-fuel based processes (IRENA, 2019) there is a huge potential for renewable alternatives as electrolysis does not produce significant carbon emissions. On the contrary, hydrogen can be used to produce green fuels through carbon capture (IRENA, 2019).

During electrolysis, electricity can be converted into hydrogen and later converted back into electricity through the use of gas turbines or fuel cells and water. Since electrolysis is an endothermic process that requires energy to produce hydrogen, increasing the temperature can reduce the amount of electricity required.

There are three different types of electrolysers, each with their own advantages and disadvantages. The most common types are the Alkaline electrolysers and PEM (Proton Exchange Membrane) electrolysers; their characteristics can be seen from table 6. The Alkaline electrolysers are inexpensive and can operate in a wide range of temperatures. However, they are not as efficient as other, slightly more expensive electrolysers. The second type, PEM, are more efficient but are also more expensive and more sensitive to water impurities.

The third type is the SOE (Solid Oxide Electrolyser) but it is not as widely adopted as the other two. It is the most efficient and also the most expensive alternative of the ones mentioned. They operate at significantly higher temperatures than the previous alternatives.

What is of interest in this report are some of their characteristics that are seen in table 6. The PEM is the most recent, although more costly technology with the highest efficiency rating of them two. The

SOE has not yet reached adaptation phase, what is known is that operating temperature is much higher; 700 - 800^{o}C (IRENA, 2019).

Table 6: Electrolyser characteristics; operating temperature, start-up time and the ramping characteristics (IRENA, 2019).

Type	**Operating temperature (C)**	**Start-up (s)**	**Ramp-up (%/s)**	**Ramp-down (%/s)**
Alkiline	100 - 150	60 - 600	0.2 - 20	0.2 - 20
PEM	70 - 90	1 - 300	100	100

3 Results

3.1 Results question 1

In this section, the question 'How much electricity will Sweden need 2045?' is answered. The conclusion is that the electricity demand will increase far beyond today's number due to electrification, digitalization, electrification of the transportation sector together with push towards climate-neutrality which brings with it fossil-free steel production. The numbers vary greatly between the studied reports depending on the assumptions made but what remains clear is that the consumption will increase and will likely increase to 286 TWh or even higher, assuming a high degree of electrification.

The majority of Sweden's current electricity demand of 137 TWh today is mainly split into two sectors: Housing & Services and Industry as seen in figure 3 with the transport sector accounting for a very small part of electricity demand. As electrification of the society continues so will the rate of energy that is used as electricity as well as the energy efficiency.

The electricity consumption and production in the Nordic countries is heavily influenced by the weather conditions. Indicators such as temperature, rainfall and snowmelt with biggest indicators of consumption being temperature. Rainfall and snowmelt mostly influence the hydropower metrics, such as the available amount of water in the reservoirs, while solar irradiance will affect the production from solar power (SVK, 2021). In a long term market analysis report SVK concluded that the final outcome will mainly depend on the price and technology development (SVK, 2021).

To understand electricity demand in 2045 several reports were studied together with their assumption about the development of the sectors in figure 3 with compiled results being presented in figure 20. We see different stacked bars together which represent the result or span of results from each of the studied reports where results in the figure range up to 370 TWh. The studied reports used different complex system models under different assumptions and input variables to come to their conclusions which explains the different conclusions. The main conclusions and points of interest to this report will be presented below.

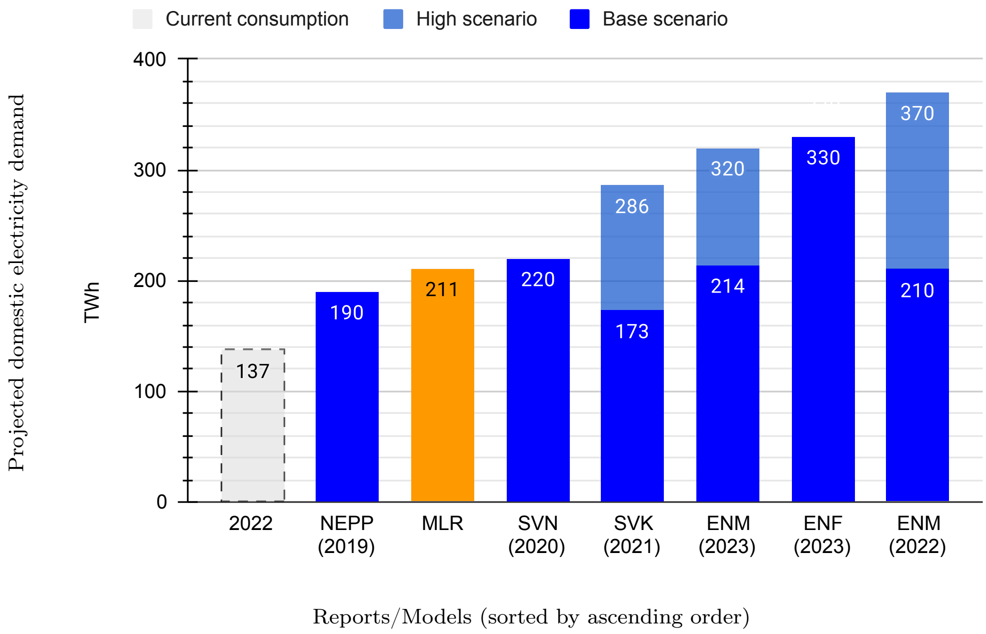

Figure 20: Projected electricity demand in Sweden in the year 2045, together with electricity demand in the year 2022 (leftmost column) (Energimyndigheten, 2023d). Values are originating from six reports and one model (MLR, drawn in orange). NEPP, SVN, SVK, ENM and ENF are abbreviations for: North European Energy Perspectives Project (NEPP, 2019), Svenskt Näringsliv (Svenskt Näringsliv, 2020), Svenska kraftnät (SVK, 2021), Energimyndigheten (Energimyndigheten, 2023f) & (Energimyndigheten, 2023e) and Energiföretagen (Energiföretagen, 2023) respectively. MLR is the multivariate linear regression model described in the method previously. Column chart sorted by ascending order, where presence of several stacked columns indicate several scenarios in the referred study.

In the long term analysis report by the Swedish TSO, SVK, several scenarios were studied for possibilities of the development of the energy system up to the year 2050. They study four different scenarios where the electricity demand is varied with respect to the assumed rate of transition, adoption of hydrogen production using electricity, energy efficiency development, rate of digitalization together with the dependency on imports versus self-sufficiency and the share of bio-fuels in the energy mix. The scenarios were constructed using BID3 and EMPS models (SVK, 2021). Additional models were used to perform network simulations but were not presented in the report. They concluded that the factor that will determine the true outcome will mostly be based on the price and technology development (SVK, 2021). The resulting range of models was 173 to 286 TWh where the higher number is associated with high degree of electrification.

There are also several reports present where Energimyndigheten (ENM) was one of the co-authors. One of the most recent reports was a joint agency report by Energimyndigheten, Ei, SVK and Trafikverket (The Swedish Transport Administration). The results were presented as a span of the results of joint assessments of the future electricity demand up to 2045 based on forecasts and compilations of electricity use in different sectors. They concluded that the electricity demand year 2045 will be between 210 and 370 TWh, depending on the degree of electrification (Energimyndigheten, 2023e). The upper bound from this report was gauged from SVK's transmission connection list. It is used when interested parties request to connect to the transmission system and draw or input a power of at least 100 MW (220 kV) or 300 MW (400 kV) (Energimyndigheten, 2023e). According to Energimyndigheten, the electricity demand of 370 TWh is given by this list, which includes the future known investments by industry (Energimyndigheten, 2023e). The lower bounds are, according to the report, built upon assumptions on lower degree of electrification, lower transition speed away from fossil fuels and the shortage of available transmission capacity together with decreased need for products coupled with increased electrification (hydrogen based steel etc.) (Energimyndigheten, 2023e). The uncertainty of 160 TWh will, according to the authors, be affected by political goals, energy prices on fossil fuels and commodities, availability of strategic minerals, availability of experienced specialists and available electricity (Energimyndigheten, 2023e).

In another report by Energimyndigheten, which used a Times-Nordic model with different assumptions on prices and economic activity in the system, a slightly different result was presented. The different scenarios resulted in a span of 214 and 320 TWh.

In yet an earlier report by Energimyndigheten from 2018, authors analyzed a few scenarios to reach a fully renewable system with shortfalls and potential for each of these scenarios. The scenarios where each of the following power sources: WP, SP, CHP; would be developed at a great pace and with a common theme that the nuclear power would be dismantled. The electricity demand in 2045 was according to this report 160 TWh (Energimyndigheten, 2018) which is at the lower end of the scenarios from figure 20 previously. The main reason for this low number is that it does not consider the major increase due to fossil free steelmaking and hydrogen electrolysis. This result was not included in the figure 20 since it is well outside the expected span of electricity demand presented by other, more recent reports.

The result in the report by NEPP (North European Energy Perspectives Project), was similarly made by analyzing variables that affect the consumption and making assumptions for the year 2045. The variables (like electrification, population increase etc.) were sorted by the degree of how much they affected the electricity consumption with the result 190 TWh (excluding losses). The notable difference from the other report was that the increase in the industry sector was only about 22 TWh in 2045 compared to 2020 which is on the low end, compared to other reports. The peak power consumption (peak load hour) year 2045 is considered to be 31.6 GW (with losses) (NEPP, 2019).

Another report was published by Energiföretagen (ENF), which is a trade association for about 400 energy producing companies, together with Energiforsk and Profu they published a report forecasting the electricity demand in 2045. They concluded that the electricity demand will be 330 TWh (Energiföretagen, 2023). Authors write that this number is calculated by assuming that all announced projects that are in the pipeline are completed, although they state this number is uncertain since any individual project's viability is not considered. They also forecast that peak load will be 49 GW, which is almost twice as high as it is today (Energiföretagen, 2023). They also predict that the industry will be the driver in the demand increase. Consequently, it is concluded that the majority of the increase will be housed in the north of Sweden, which currently has a production surplus with respect to other parts of the country. That would lead to a deficit of 125 TWh of electricity and 15 GW of power only in SE1 compared to today (Energiföretagen, 2023).

In a report by Svenskt Näringsliv, a much lower number was projected. Svensk Näringsliv, which is an employers' organization for businesses in Sweden commissioned a report from Qvist Consulting Ltd, where they modeled a cost optimized fossil-free system of the future. GenX model (The Optimal Electricity Generation eXpansion Model) was used together with a large set of assumptions about the future system which resulted in the result of 200 TWh electricity demand in 2045, without losses (Svenskt Näringsliv, 2020). Assuming a 9% distribution and transmission loss, this gives a total of 220 TWh electricity demand in 2045. They also predict that the majority of the electricity demand will come from a few sectors. These are the transport sector (16 TWh) where the majority of the transports are assumed to be electricity based in the future. Services and company sectors are also included along with processing industry, where majority of the processes are assumed to be electricity based. Steel industry, which transitions away from coal and fossil fuels, chemical industry and data centers might lead to an increase of the consumption of electricity (Svenskt Näringsliv, 2020). For the chemical industry, this number is predicted to be 22 TWh while data centers are predicted to increase their consumption by 10 TWh (Svenskt Näringsliv, 2020).

As the different reports have been presented one by one, some results of interest are presented separately below.

3.1.1 Major industrial projects

The majority of the studied scenarios and reports expect a major increase in electricity consumption. This increase is expected to come from the industry sector, for the production of hydrogen through electrolysis used to produce fossil-free steel, among other things. This addition alone is expected to require 22-100 TWh of electricity by 2050 (Energimyndigheten, 2023f).

Fossil-free steelmaking

Sweden is a major producer of steel. Since steel production is carbon intensive, a pilot project called HYBRIT (Hydrogen Breakthrough Ironmaking Technology) was initiated to make the process more climate friendly (REN21, 2022). This project is a cooperation between LKAB (mining company), SSAB (steel manufacturer) and Vattenfall (power company) (HYBRIT, 2021) and the impact of this project is estimated to reduce Sweden's emissions by 10% by 2026 (REN21, 2022).

The main idea behind fossil-free steel manufacturing is replacing blast furnaces that use coking coal with direct reduction shafts, which use hydrogen to produce sponge iron for steel (Vattenfall, n.d.).

HYBRIT is the overarching project name for the fossil-free steel produced by the triumvirate of SSAB, LKAB and Vattenfall. The company SSAB produces steel from iron ore that is mined and processed by LKAB, while LKAB is only one of SSAB's customers (Energimyndigheten, 2022c). Currently, the projected electricity demand for the add-on of the HYBRIT project is estimated at 15 TWh (Energimyndigheten, 2023f). However, based on LKAB's projection, 55 TWh of electricity is required to transition all of their processes to fossil-free production - a figure that includes 48 TWh to power the electrolysers and the aforementioned 15 TWh (Energimyndigheten, 2022c). Depending on the investment profile, the estimated power draw is expected to range between 7 GW and 13 GW (Energimyndigheten, 2022c).

In addition to HYBRIT, another competitive venture was initiated by other parties under the name H2 Green Steel (H2GS). This project launched a plan to build a factory for the production of fossil-free steel that is set to be completed in 2030 and is expected to require 13 - 14 TWh of electricity and a power draw of 1.8 GW (Energimyndigheten, 2022c).

Battery manufacturing

Northvolt is a project that aims to build lithium batteries for electric vehicles and ESS. Northvolt has written that their goal by 2030 is to have a production output of 150 GWh of battery capacity. As stated in an article in SVD, a site in Göteborg will require a power of more than 200 MW and use slightly less than 2 TWh of energy with a production capacity of 50 GWh (Törnwall, 2022). Assuming the same energy consumption for the rest of planned battery capacity would give an approximate additional electricity demand of 6 TWh by the year of 2030. As this is 15 years away from 2045, the real number is expected to be even higher.

Big data

Data companies such as Amazon Web Services (AWS), Microsoft and Google prefer to establish their datacenters in Sweden since it has one of the lowest electricity prices among OECD countries for electricity for industry (which is at the same rate as other base industry and is lower than regular, small companies would pay (Dolff, 2019). Another reason is the low emission profile from the Swedish electricity system.

Current expectation is that an addition of 10 TWh of electricity demand (Svenskt Näringsliv, 2020) would be added due to new datacenters. Furthermore, with the advent of artificial intelligence (AI), the electricity demand can increase even further as training AI models is an electricity-intensive computation process (Saul and Bass, n.d.). This is written about in the article where Google considers that about 15% of company's electricity consumption in 2021 was related to AI (Saul and Bass, n.d.).

3.1.2 Power need

The electricity demand can also be seen from the point of power availability during the peak load on a yearly basis. Between 2022 and 2023 the peak load hour was 23.9 GW on 2022-01-16 between 09:00 and 10:00 as seen from figure 5. Different reports come to different conclusions on the peak power demand in the future which is in large part affected by the load profile and flexibility assumption of each author. What is clear is that the peak load is expected to increase beyond today's number. Energiföretagen expects it to be 49 GW, which is almost twice as high as it is today (Energiföretagen, 2023). NEPP expects this number to be 30.5 GW (NEPP, 2019) while according to SVK it is expected to be between 42 GW and 47 GW assuming a high degree of electrification.

3.1.3 Temperature increase

The extrapolated temperature increase in the future will have an impact on the electricity system as the need for heating decreases, as well as the consumption of electricity for heating. In addition, as the temperature increases further so does the need for cooling which increases the need for electricity (Cruz Rios et al., 2017). This effect is due to the U-curve relation between electricity demand and temperature (Cruz Rios et al., 2017) (which can also be seen in California, where air conditioners are prevalent during the summer months).

Based on SMHI's model, the temperature can rise 2- 6 °C before year 2100 depending on the scenario of emissions according to the Paris Agreement (RCP2.6, RCP4.5 and RCP8.5) (SMHI, n.d.).

In the case of an increase of the temperature by 1.5 °C, that would lead to a decrease in heat production which in turn decreases the market for co-generation plants. According to Energiforsk this value will decrease by 0.5 TWh (Gode et al., 2021).

3.1.4 Result 1: conclusion

The electricity demand in Sweden for 2045 is expected to increase from 137 TWh in 2022 to as far as 370 TWh, where the majority of expected increase will come as a result from the industry sector and hydrogen based steel making which alone can increase the electricity demand by up to 100 TWh before 2050. Compiling numbers presented earlier is presented in table 7 and simply summing them up gives about 262 TWh.

Table 7: Table with compiled results representing a probable future increase in 2045 with respect to today.

Type	**Amount (TWh)**
2022	137
HYBRIT	55
H2 Green Steel	14
Transports	16
Datacenters	10
Battery manufacturing	6
Chemical industry	22
Total:	**262**

Considering the result from the multivariate linear model (MLR) and adding the industrial additions above results in 336 TWh. The decision in this report is made to adopt the high electrification scenario from the SVK report and hence the number 286 TWh in year 2045 since that result is the closest to the expected span of results together with the fact that a high degree of electrification is considered to be necessary to reach stringent climate neutrality goals set by the government.

3.2 Results question 2

In this section the question 'What is the share of each major electricity generation source in Sweden in 2045?' is answered.

The energy sources in relevance to this report will now be presented in a greater detail.

According to the IEA, Sweden is one of the global global leaders with a low share of fossil fuel and low carbon intensity of electricity generation (IEA, 2019). In 2040, as indicated in the report by Energimyndigheten, the share of renewable electricity is expected to be 78 - 80% (Energimyndigheten, 2023f) while in the future, the domestic, fossil free electricity production is expected to reach 99 - 99.5%. The number is not 100% due to the prevalence of fossil components in domestic waste burning (Energimyndigheten, 2023f).

Energimyndigheten concluded that, in short term perspective (up until 2035, land-based wind power plants seem to have the highest potential ability to add to the electricity production but that the acceptance among the public is a critical challenge (Energimyndigheten, 2023e). The long-term view leading to 2045 indicates a strong potential for nuclear power as well as offshore wind energy. In that case, several challenges are identified, among them are long lead times, long approval and certification times together with the need to reform the legislation and remove current restrictions (Energimyndigheten, 2023e).

According to Energiföretagen's worst case scenario, where no investments are made, only 40 TWh of production will remain 2045 compared to 170 TWh 2022 and only 4 GW of power will be available during peak load (Energiföretagen, 2023). They estimate that there is a need for investment of about 1000 billion SEK before 2045 which includes known investments by SVK of 170 billion SEK (Energiföretagen, 2023). Energimyndigheten identified the same potential challenge in their report for the long term scenario at 2045. They concluded that approximately 32 TWh of production capacity will reach the end of its lifetime (mostly CHP and WPP) while there is a need to build even more. In the case where the lifetime of existing NPP are not extended beyond 60 years, an additional 50 TWh of electricity production will disappear between 2040 and 2045 (Energimyndigheten, 2023e).

Over the years, even though the total installed capacity has increased, as seen in figure 16, the available production capacity during the peak load has decreased (Energimyndigheten, 2022a). This can also be seen through energy terms from figure 16 and figure 15. We can clearly see that, despite the fact that there is more installed capacity for wind than for nuclear power, there is still more electricity produced by nuclear power than wind power. This can be attributed to the low capacity factor of wind power and high availability factor of nuclear power plants compared to wind power.

The production share distribution of different sources is considered to be somewhat independent of the electricity demand, although not completely. The distribution of electricity shares is seen as dependent on the views in the society (SVK, 2021). A recent report concluded that the construction of new electricity generation plants and the transmission system has to be historically high to meet the assessed future electricity demand (Energimyndigheten, 2023e).

In addition, the public opinion figures on whether any further development should be done with respect to different energy sources presented in this report are as follows: solar power (81%), followed by wind power (58%), hydropower (42%), nuclear power (42%) and bio-fuels (32%) (SOM-institutet, 2020).

The energy potentials for power sources in relevance to this report will now be presented in a greater detail.

3.2.1 Solar power

In one report by Energimyndigheten the potential is seen as 40 - 50 TWh with only solar power on roofs and up to 130 TWh on agricultural land that is not being cultivated (Energimyndigheten, 2018).

In another report, the case that we develop a production of 25 TWh from solar power (25 - 30 GW of power) was studied. Energimyndigheten concluded that we would need an approximate area of 200 km^2 with solar cells (assuming a 0.15 efficiency), which corresponds to 15% of the total amount of roof-space in Sweden (Energimyndigheten, 2019). This is due to the fact that about half of the buildings in Sweden will have at least some solar cells on their roofs, since at least some space on the roofs will be filled with solar cells. This power source can also be built directly on the land, which would require 0.04% of Sweden's area. In that scenario that land could have alternative use (farming and similar) which would increase competition and difficulty to implement these projects. In the case of rooftops, there are little to no alternative uses of the roof-space (Energimyndigheten, 2019). In the case where only 5 TWh of solar power was developed, that would correspond to 3% of roof space and every tenth building having a solar panel (Energimyndigheten, 2019). In a different report by Energimyndigheten they concluded that in 2050, solar power production will be between 9 TWh and 32 TWh (Energimyndigheten, 2023f).

During the year 2021, there was only 52.26 MW ground mounted newly installed capacity out of nearly 500 MW, where the majority of the PV power was installed as BAPV (Building Applied Photovoltaics) (Lindahl et al., 2022). Which, in essence, means that the vast majority are modules added to existing structures and are systems that are below 20 kW (Lindahl et al., 2022). In total, there were about 133.84 MW of centralized installations out of 1.6 GW with the rest being distributed (or in a few cases off-grid) (Lindahl et al., 2022).

Solar power requires 15 to 40 times more land than wind power to generate the same amount of electricity (Energimyndigheten, 2019). However, when there are other buildings or infrastructure nearby, wind power requires 20 times more land than solar power (Energimyndigheten, 2019). This is because solar power can be placed in areas where wind power otherwise would create competition of interests.

The location of solar panels is not free from trouble due to the technological aspects of the power system that converts DC electricity to AC. The National Electrical Safety Board's (Elsäkerhetsverket) and The Swedish Armed Forces (Försvarsmakten) have conducted studies and concluded that some solar plants can interfere with the communication systems due to electromagnetic interference caused by poorly designed inverters and MPPT-optimizers (maximum power point tracker) which are usually part of many solar plants (Försvarsmakten, 2020).

An important point to note is that the availability factor for solar power during peak load is 0, meaning that solar power could not be counted on to produce power during peak load, as seen from table 2.

3.2.2 Nuclear power

SVK concludes that the energy system of the future will require different types of investments depending on whether nuclear power is present or not (SVK, 2021).

During the start of the 2040s, nuclear power will reach 60 years of operation (Energimyndigheten, 2023f). In the case where the lifetime of existing NPP are not extended beyond 60 years, an additional 50 TWh of electricity production will disappear between 2040 and 2045 (Energimyndigheten, 2023e). This is not impossible, as some nuclear power reactors in the USA operate beyond 80 years (SVK, 2021). In the case that the life-time is extended, the production is expected to be 28 TWh in 2050 (Energimyndigheten, 2023f).

In a report by Energimyndigheten it is estimated that new nuclear power has an approximate lead time of 10 years (Energimyndigheten, 2023e). In another report by Svenskt Näringsliv, they estimate that newly constructed conventional nuclear power will take 5 - 8 years to construct while SMRs based on the GE Hitachi BWRX-300 model will take 2 - 3 years to build (Svenskt Näringsliv, 2020).

Important law governing nuclear power potential in Swedish Environmental Code 1998:808 states that a new reactor must replace an existing electricity generating reactor, the older reactor must be permanently shut down when the new one begins operation and the new reactor must be constructed on the site where one of the current electricity generating reactors operates (OECD Nuclear Energy Agency, 2010).

In a recent report by Energimyndigheten the potential for nuclear power is considered to be 8.5 GW around the year 2050 (Energimyndigheten, 2023f).

In the case that nuclear power is developed and new generation reactors are built there are several possibilities of development due to the low energy efficiency of nuclear power and increasing demand for energy efficiency (Energy Efficiency Directive).

If nuclear power plants are converted to co-generation plants, then the newly supplied heat could potentially compete with that of combined heat and power (CHP) plants. The seasonal demand for heat, which correlates with and drives electricity demand, could in turn pose a challenge for the operators of nuclear power plants, since they are typically operated at full capacity most of the year in order to be profitable. This highlights the need for load following capability (adjusting their power output to meet changes in demand) and the risk of putting a down-pressure on heating prices in the pursuit of energy efficiency. Although, one possible solution is to generate a high-temperature heat from the NPP and use in high-temperature demanding processes, like the production of hydrogen. This adjustment will reduce electricity consumption of hydrogen production while not competing with ordinary district heating (and hence CHP) due to the high temperatures involved.

According to the report published by Energiforsk on alternative uses for nuclear power, in 2020 there were 71 out of 457 that produced heat for different processes (district heating, industrial heating and similar) (Wakter, 2022). What is of interest, is that in high temperature (HT) plants have a possibility to use that heat for high temperature electrolysis 550 - 950 °C (production of hydrogen) and other high-temperature demanding processes (chemicals production, iron & steelmaking) (Wakter, 2022). The production of hydrogen using high temperature is of interest in later chapters since, the higher the temperature the lower the consumption of electricity during hydrogen production (Wakter, 2022). The chosen electrolyser depends greatly on the efficiency, cost, output volume, heat, storage and other infrastructure. As SOE are able to operate in the area of 600 - 850 °C they are of great interest in high temperature applications (Wakter, 2022).

3.2.3 Hydropower

From 1986, the four rivers Torne älv, Vindelälven, Pite älv and Kalix älv were exempted from hydropower construction by law (Naturlagen) while in 1993 the government decided to call these lakes and 13 more areas as national lakes adding them to a list by the law (Naturresurslagen) further protecting these areas (Svenskt Näringsliv, 2020). According to the report we hence need two consecutive governments to overrule and increase installed capacity of hydropower in Sweden by any substantial amount. If that were to happen, the additional electricity production potential of the increase is additional 30 TWh annually, mostly in the two northern regions (Svenskt Näringsliv, 2020). According to the same report the potential is to increase capacity by 940 - 1580 MW (Svenskt Näringsliv, 2020).

In the beginning of 2019, a new law came into force which will review all HPPs in Sweden on the subject of their adherence to modern environmental standards in the next 20 years (Nationella planen, NAP). It is unclear how big the impact of this investigation will be but the subjects of interest that can be affected are production and capacity for power control (SVK, 2021). A target value for decreased yearly production was set at 1.5 TWh between the responsible authorities (Energimyndigheten & Havs- och vattenmyndigheten, 2014).

SVK assessment is that climate change will increase the filling rate of water reservoirs (SVK, 2021). In a report by Energiforsk it was concluded that due to climate change, the hydropower production can increase 2.8 - 4.8 TWh annually depending on the scenario of temperature increase (Scharff et al., 2023). Based on a report by Energimyndigheten the climate effects on hydropower together with the decrease due to NAP is considered to be a net increase of 0.5 TWh to the production by the year 2050 (Energimyndigheten, 2023f).

3.2.4 Windpower

The European Commission presented a strategy in 2020 regarding the increase of production capacity of offshore-wind power from then 12 GW to 300 GW (1200 TWh) in 2050, which is a 25 fold increase from today's number (SVK, 2021).

According to IRENA, in 2020, the installed power for offshore wind production in Sweden was 203 MW producing 0.67 TWh annually (IRENA, 2022). The corresponding number for onshore wind power is 9773 MW installed power producing 26.856 TWh annually (IRENA, 2022).

A recent review of wind power projects between 2014 and 2018 found that one-third of projects are rejected on average (Energimyndigheten, 2019). The review also concluded that it has become more difficult to obtain permits, which is a major hurdle for future development. Another hurdle is the long time it takes to complete the entire process (planning, permitting, development, construction), which Energimyndigheten estimates to be between 5 and 10 years or even longer in some cases (Energimyndigheten, 2019).

According to the Swedish Wind Energy Association (*Svensk vindenergi*), no new offshore projects have been initiated after 2013 (Kinning, 2022). However, there are currently approximately 366 TWh worth of projects under review (Kinning, 2022). The approval process for these projects is lengthy, spanning between 12.5 to 17.5 years. The earliest constructions, upon approval, are projected to begin in 2028 (Kinning, 2022), highlighting the extensive duration of the permitting process.

Analyzing the approval rates, during 2014 to 2021, only 45% of the wind turbine projects received the green light (Westander and Henryson, 2022). This suggests that the actual implementation of the projects in the pipeline might be considerably less than proposed. A decline in the acceptance rate of land wind power projects has been observed recently, possibly attributed to the municipal veto (Westander and Henryson, 2022).

Another factor is that a large part of the wind power projects that pass through the granting process are not developed, which Energimyndigheten considers to be a negative factor. It means that the resources for granting the permissions in the first place are held up by the many projects that are rejected (Energimyndigheten, 2019). According to Energimyndigheten, to build 90 TWh of wind power by 2040, there is a need of, on average, 1300 MW of projects granted each year and that the capacity to grant that amount is present (Energimyndigheten, 2019).

A different report concluded that there is a need for at least 100 TWh wind power until the 2040s, where 80 TWh of that is onshore and 20 TWh offshore (Energimyndigheten & Naturvårdsverket, 2021). However, the studied electricity demand is smaller than other reports along with the case where the whole electricity system is renewable and not fossil free (excluding nuclear power). As reported by Svensk vindenergi, the total need for wind power will be 33.3 GW installed capacity and 120 TWh annual production the year 2040 (Svensk vindenergi, 2021), which using an exponential extrapolation using other data-points in that report, yields 41.94 GW installed capacity and 157 TWh of production in the year 2045.

In the beginning of 2022 several areas were suggested that could house 20 - 30 TWh of offshore wind production in the future. Energimyndigheten was later tasked by the government to present potential areas where 90 TWh of production could be located (Energimyndigheten, 2022a).

A long-term analysis report on wind power predicts that it will be generating up to 179 TWh of electricity by 2050, with 122 TWh coming from land-based wind power (onshore) and 57 TWh from offshore wind power (Energimyndigheten, 2023f). Notably, production costs for offshore wind power are higher than onshore wind power, despite having a potential for high annual electricity generation (Energimyndigheten, 2017). A lower electricity price would have a greater negative impact on offshore wind power than on onshore wind power, due to the higher production costs of offshore wind power.

3.2.5 Combined Heat and Power

Today's production of electricity using co-generation is at around 15 TWh (Energimyndigheten, 2023b). According to Energimyndigheten this can be increased to 35 TWh and 10 GW installed power. In order to do that, there are several things that need to be implemented. Firstly, increasing the capacity factor from 0.46 to 0.8 and increasing the efficiency of power generation (Energimyndigheten, 2019). Additionally, transform heat plants (HP) into combined heat and power plants (CHPP) as there are hundreds of plants in Sweden that only produce heat without using the waste heat (Energimyndigheten, 2019). This number is also considering the sustainable biomass retrieval from forestry which, according to Energimyndigheten, is 27 TWh over today's level (Energimyndigheten, 2019). Furthermore, a potential of 70 - 90 TWh is considered sustainable by the year 2050 but has to compete with other interests (like production of bio-fuels) (Energimyndigheten, 2019).

A limiting factor is that the need for heat decreases due to increased efficiency of buildings and use of residual heat in industry (Energimyndigheten, 2019). This leads to a decrease in the market for services which CHP provides, making any further investments hard to make (Energimyndigheten, 2019). One more detail that adds to the complexity is that a low price of electricity which can also affect the investment climate (Energimyndigheten, 2019).

3.2.6 System outlook

In this section a few potential future system formats will be presented.

During the last date of December 2021, the total installed capacity in Sweden was 43.7 GW (Energimyndigheten, 2022a). However, the availability of power is not synonymous with installed power. The current available power production aligns with the demand. As the installed production capacity increased from about 35 GW in 2004 to today's number, the available production capacity has decreased from almost 30 GW in 2008 to 25 GW in 2021 (Energimyndigheten, 2022a).

Considering the potentials from these scenarios and keeping the expected electricity consumption from the previous chapter in mind, we obtain the potentials presented in table 8.

Table 8: Potentials in TWh for each power source, converted to TWh using system capacity factors for each source.

Type	**Potential (TWh)**
Hydropower	68
Solar power	25
Nuclear power	28 - 57
Wind power	100 - 157
CHP	35

Having these assumed potentials in mind the design of a system can be approached in various ways, considering different factors to create a very basic system model.

For instance, one could design a system optimized for electricity production in Wh-terms, ensuring production matches the annual electricity demand. However, this approach might not align production with consumption times, leading to increased reliance on imports from other countries and compromising self-sufficiency.

Another approach is to model the system concerning power availability during peak load, ensuring consistent or surplus power availability. This might lead to overproduction during off-peak times. Given the variability in wind power availability, as seen in table 2, there might be a need for significantly more wind power production to ensure consistent availability. Incorporating different energy storage systems can further complicate system design.

Yet another approach could be to build the ultimate ratio between the installed capacity of wind power and solar power that would minimise the variability of power generation. As indicated in a report by SVK, hydropower should be able to balance 13 GW of wind power (production of 30 - 40 TWh) under the assumption that the electricity can be delivered to consumers. For a higher amount of wind power, there is a need to increase other flexibility resources (Svenskt Näringsliv, 2015). Energimyndigheten indicates that daily and seasonal residual variations are highest for solar power, while wind power shows maximum day-to-day fluctuations (Energimyndigheten, 2019). A study aiming to reduce power fluctuations in Sweden computed an ideal solar-to-wind ratio to 3:7 or 2:8. Based on this, a system generating 25 TWh from solar would translate to between 58 and 100 TWh from wind (Widen, 2011). By the same rationale, a system generating 157 TWh from wind would align with a solar contribution of roughly 39 to 67 TWh of solar power.

The chosen approach for the simple model is to match consumption over the year and have an export of 26 TWh along with a domestic electricity demand of 286 TWh.

Creating a realistic system model is beyond the scope of this report. The primary goal of this section is rather to illustrate how varying amounts of intermittent sources can impact future system scenarios.

According to Energiföretagen, the power demand during peak load will be 49 GW. However, SVK estimates this number to be between 42 and 47 GW for high electrification scenarios (SVK, 2021), resulting in a range of 42 to 49 GW for peak load. Comparing this to the peak load in figure 5 indicates that peak load is set to double.

Initially, a demand of 286 TWh is assumed for 2045, based on SVK's report and the high electrification rate chosen in the previous section (SVK, 2021). Alongside this, an assumption of a slightly higher export in 2045 than in 2020 results in an export of 26 TWh. This leads to a total assumed electricity production of 312 TWh in 2045.

The assumed potential for each power source in 2045, as seen in table 8, was used as input variables for the model. Historic capacity factors for each power source were also considered to calculate the corresponding installed capacity. These values were then used to project future production using historic values, scaling the production to the corresponding value in 2045. This was done assuming the production pattern remains consistent with that of 2021 and that export levels in TWh remain the same as in 2020. Another assumption is that capacity factors do not see drastic improvements, with the exception of CHP, which is assumed to be 0.8, as previously discussed.

Subsequently, two main scenarios, labeled as Case 1 and Case 2, are represented. Each scenario comprises two sub-scenarios corresponding to peak loads of 42 GW and 49 GW, respectively. This hierarchical structure of all cases and sub-cases that were simulated is visualized in a tree diagram, shown in figure 21. The tree diagram reveals two primary cases at its topmost level (Case 1 and Case 2). At the deepest level, there are eight distinct sub-cases derived from different combinations of peak loads (42 GW and 49 GW) and energy storage system (ESS) sizes (2.7 TWh and 12 TWh).

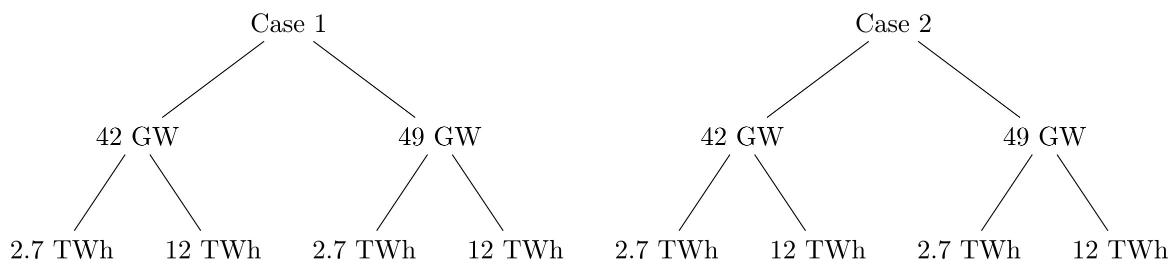

Figure 21: Tree diagrams for the simulated cases; Case 1 and Case 2. These two cases branch to different combinations of peak load and storage capacities culminating in eight sub-cases in total. For instance, one such sub-case is Case 1 with peak load of 49 GW and storage capacity of 2.7 TWh.

Detailed production assumptions for each case can be found in table 9. In Case 1, it is assumed that most nuclear power reactors won't operate beyond their 60-year lifespan. This would imply that only 28 TWh of nuclear generation remains, given the decommissions anticipated by the Swedish government (Regeringen, n.d.). In Case 2, on the other hand, it is assumed that nuclear power continues to operate with an installed capacity of 8.5 GW, equating to an annual nuclear power production of approximately 57 TWh. The power gap in Case 2 is expected to be compensated by wind power.

The values presented in table 9 show how production is distributed for each source in both cases along with the corresponding installed capacities. In this table, wind power varies between 46.2 GW and 56.8 GW, while nuclear power ranges from 4 to 8.3 GW while capacities of other power sources are assumed to remain constant between the cases.

In summary, these eight scenarios, as seen at the lowest level in figure 21, which yields eight distinct graphs. Each graph varies in terms of consumption (based on load), wind power contribution and the role of nuclear power in the electricity mix. Integral to each of these graphs is the inclusion of a virtual energy storage system (ESS). This ESS simulates charging and discharging activities based on the surplus or deficit in electricity production. The ESS-battery charges when production exceeds consumption and discharges in the opposite scenario. A flat line indicates an empty or full storage device. Charging and discharging are based on a predetermined round-trip efficiency of 97%, given that Li-ion vehicle batteries are utilized. These values are derived from calculations in the Vehicle-to-grid section, as seen in section 3.3.4.

Table 9: The two simulated cases for electricity system of 2045 showing the amount of expected electricity production in TWh by each source. Each case results in a sum of 312 TWh, which includes 286 TWh for internal electricity demand and 26 TWh for export. This table shows both expected electricity production (TWh) and corresponding installed capacity (GW).

	Case 1 (TWh)	**Case 1** (GW)	**Case 2** (TWh)	**Case 2** (GW)
Solar power	25	*26.3*	25	*26.3*
Wind power	**156**	*56.8*	**127**	*46.2*
Hydropower	68	*16.3*	68	*16.3*
Nuclear power	**28**	*8.3*	**57**	*4*
CHP	35	*5*	35	*5*
Sum	312	*112.7*	312	*97.8*

At first, a consumption and production pattern for 2021 is presented in figure 22. This figure illustrates that production closely follows consumption.

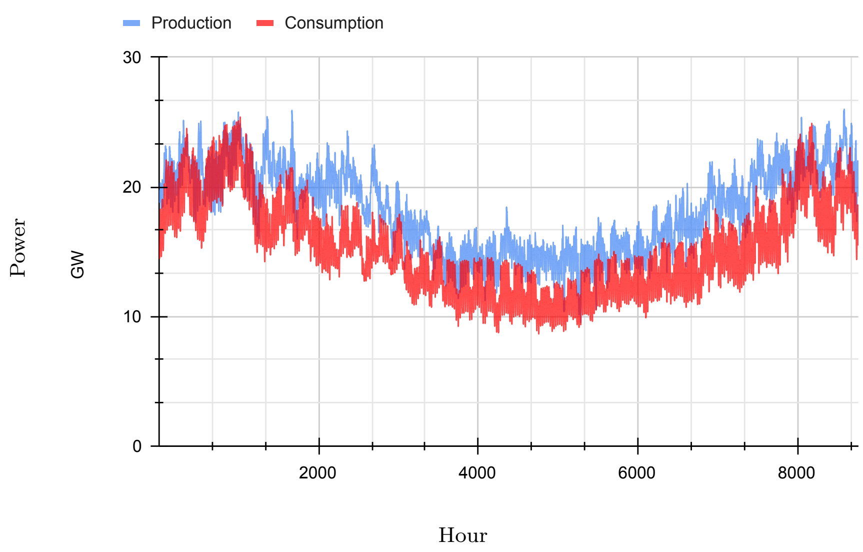

Figure 22: Total electricity consumption and production in Sweden during 2021 plotted as a function of hour during the year (Energimyndigheten, 2023b).

Simulating, using the method described in section 1.4 previously, two distinct cases and their sub-cases were studied. After simulating Case 1, we could observe the results seen in figure 23. Here, the production and consumption patterns are evident, especially during colder periods when consumption peaks. Notably, the production graph displays significant variability. In the simulation of Case 2, as shown in figure 25, the production graph still varies, but the spikes are less prominent due to decreased reliance on wind power.

For Case 1, the available power during peak load is calculated to be 30.7 GW, while for Case 2, it's 27.8 GW. This difference arises from the higher share of wind power but its lower availability factor. Solar power cannot bridge this gap as its availability is 0% during peak load. In a case where nuclear power were entirely excluded (0 TWh), this value would decrease further. To increase the availability of power during peak load, an additional 100 TWh of nuclear power could be required to achieve 42 GW available power during peak load.

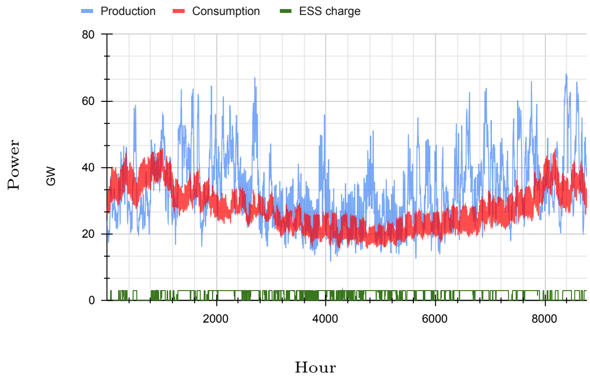

Figure 23: Simulation of a system considering **Case 1**; production, consumption with peak load of **42 GW** during the year 2045. ESS represents a V2G battery of **2.7 GWh**.

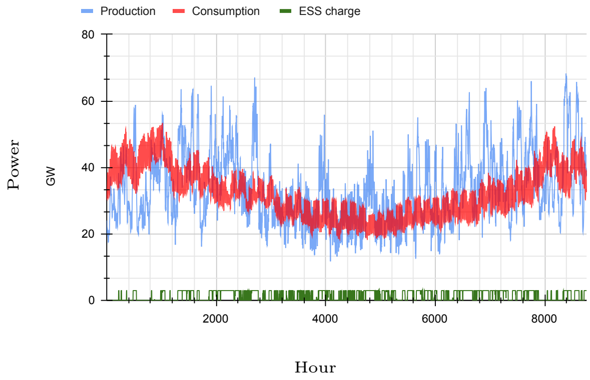

Figure 24: Simulation of a system considering **Case 1**; production, consumption with peak load of **49 GW** during the year 2045. ESS represents a V2G battery of **2.7 GWh**.

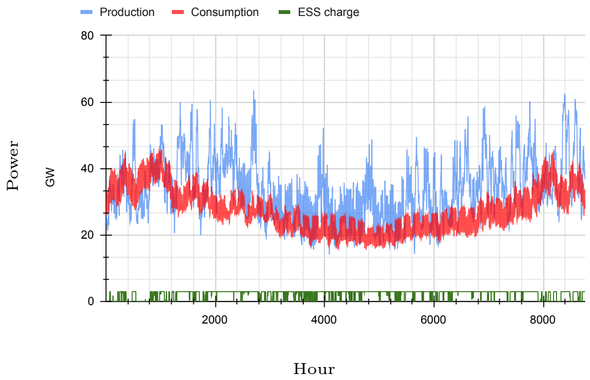

Figure 25: Simulation of a system considering **Case 2**; production, consumption with peak load of **42 GW** during the year 2045. ESS represents a V2G battery of **2.7 GWh**.

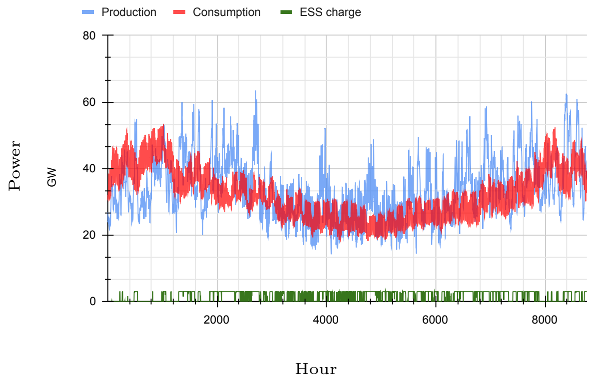

Figure 26: Simulation of a system considering **Case 2**; production, consumption with peak load of **49 GW** during the year 2045. ESS represents a V2G battery of **2.7 GWh**.

To assess the impact of ESS size on electricity import needs, the cases were simulated again with the same consumption and production patterns but with a larger ESS of 12 GWh, as suggested by SVK in their long-term analysis report (SVK, 2021). This resulted in four additional figures: figure 27, figure 28, figure 29 and figure 30. The number of hours requiring electricity imports was calculated for each of the eight sub-cases from figure 21 and presented in table 10.

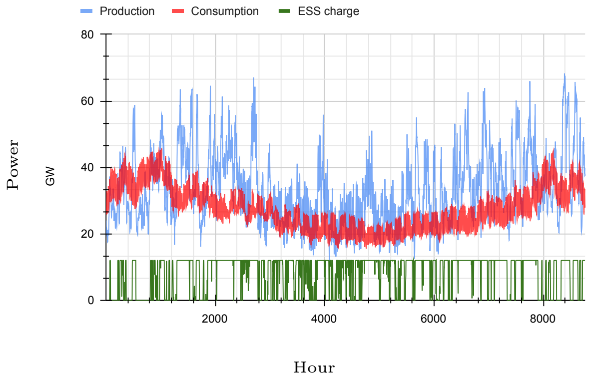

Figure 27: Simulation of a system considering **Case 1**; production, consumption with peak load of **42 GW** during the year 2045. ESS represents a **12 GWh** battery and its charge which does not affect the other results.

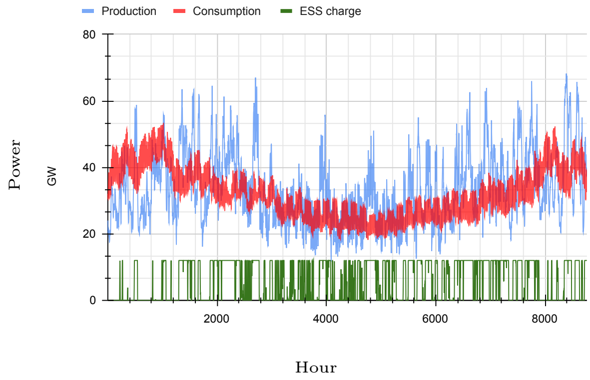

Figure 28: Simulation of a system considering **Case 1**; production, consumption with peak load of **49 GW** during the year 2045. ESS represents a **12 GWh** battery and its charge which does not affect the other results.

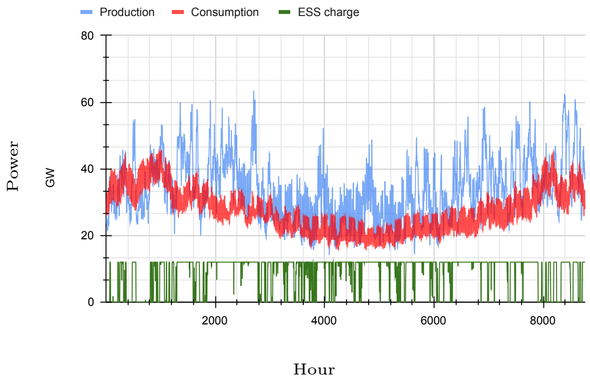

Figure 29: Simulation of a system considering **Case 2**; production, consumption with peak load of **42 GW** during the year 2045. ESS represents a **12 GWh** battery and its charge which does not affect the other results.

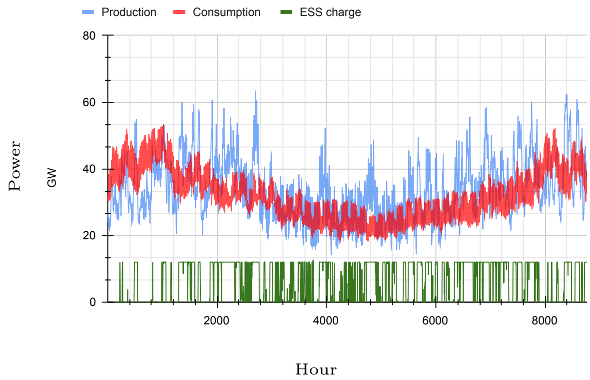

Figure 30: Simulation of a system considering **Case 2**; production, consumption with peak load of **49 GW** during the year 2045. ESS represents a **12 GWh** battery and its charge which does not affect the other results.

Table 10 lists the number of hours during 2045 when electricity imports would be necessary based on the aforementioned assumptions. It can be observed that the hours requiring imports decrease with reduced consumption (and consequently reduced peak load) and with increased ESS size. The highest number of hours requiring imports occurs when the ESS capacity is small, consumption is high (peak load of 49 GW) and there's a significant share of wind power (Case 1). Conversely, the fewest hours requiring imports are observed when the ESS capacity is large, peak load is 42 GW and there's a reduced reliance on wind power compared to Case 1 (i.e., Case 2). Assuming that a year has 8760 hours, the percentage of days that imports are needed would fall between 19% and 45%, based on the parameters of this model.

Table 10: Number of hours experiencing a need for import from other countries during 2045. Values are presented for two cases: peak loads of 42 GW and 49 GW, together with two ESS capacities, 2.7 GWh and 12 GWh.

	42 GW	**49 GW**
Case 1 (2.7 GWh)	2408	3939
Case 2 (2.7 GWh)	1937	3552
Case 1 (12 GWh)	2121	3665
Case 2 (12 GWh)	1663	3223

3.2.7 Result 2: conclusion

In conclusion, the shares of each power generation source is anticipated to align with the figures presented in table 8. This assumes an electricity export of 26 TWh by 2045, a domestic electricity demand of 286 TWh (including transmission losses) and a total demand of 312 TWh when including exports. An elevated share of IREs, predominantly from wind power, will result in increased fluctuations that the system must address using various flexibility resources. The higher the consumption and the lower the ESS size, the more hours the system will require imports from other countries.

3.3 Results question 3

In this chapter, the question 'What methods, technologies and strategies can be applied to increase stability and electricity availability in the Swedish system year 2045?' is answered. The preservation of the electricity system's stability is discussed. These results are based upon the recommendations and results from reports from Swedish government agencies, like Energimyndigheten and reports from other countries with a high share of VRE (variable renewable energy).

The evolving landscape of Sweden's electricity consumption is significantly shaped by large infrastructures, such as hydrogen production facilities and data centers. By strategically positioning these units in geographic areas where electricity production profiles align with their needs can lead to efficient energy use and reductions in system costs (Svenskt Näringsliv, 2020). Additionally, Svenskt Näringsliv has highlighted an anticipated trend: the industrial sector, with its steady load profile primarily based in the northern parts of Sweden, will likely drive a more evenly distributed electricity demand throughout the year (Svenskt Näringsliv, 2020). This is especially true in region SE1 (see figure), which currently has a surplus of hydropower generation, along with regions SE2 and SE3. This means that the power transfer from the north to the south of Sweden will change in the future and it is likely that there will be a greater power deficit in the southern regions.

Sweden's commitment to energy reliability is evident in its impressive 99.9% supply reliability track record (Sonnsjö et al., 2020). In 2022, the government underscored this commitment by mandating a norm: electricity production and imports should meet the country's demand 99.989% of the time, translating to potential unmet capacity for roughly 0.99 hours annually (Regeringen, 2022).

Yet, it's important to acknowledge the impending challenges. SVK's projections suggest that during peak consumption periods, Sweden will heavily rely on flexibility resources, demand management and imports (SVK, 2021). Meeting the government's stringent reliability standards will necessitate thorough planning and the utilization of all available flexibility resources.

Building on this, the International Energy Agency (IEA) underscores a significant concern. While they commend Sweden's ambitious goals for high renewable energy generation, they stress the importance of vigilance regarding grid stability and supply security (IEA, 2019). This sentiment is echoed in Energimyndighetens' report, which models various scenarios for a fully renewable power system. The findings indicate that a power landscape dominated by solar energy demands the highest degree of balancing, due to the amplified system operator ramping needs and diminished system inertia evident in both wind and solar scenarios (Energimyndigheten, 2019). In a separate report, CAISO, California's Independent System Operator (ISO), reports that in a system with 60% renewable generation and low load (demand) is more likely to experience instability. This conclusion is due to a combination of several factors. At first, VRE-sources are generating electricity at maximum available capacity while the demand follows a somewhat constant and predictable pattern. During the period of high VRE-generation, other conventional power generation sources have to decrease their power output to preserve the frequency. But, as these sources often are sources which provide inertia to the system (hydro etc.) the total inertia of the system decreases. This leads to a scenario where the grid may not be able to prevent uncontrolled frequency deviations due to a loss of a generator or transmission line. This is due to the fact that renewable generation does not have natural frequency response capabilities of conventional generation leading to a lower inertia in the system (CAISO, 2016). An important point is that California's hydropower comprises a small share of electricity generation, compared to Sweden (or Norway) and the renewable sources comprise solar and wind. Hence, hydropower does not assist with inertia in their system to the same extent. CAISO also concludes that flexibility is crucial for the electrical system in the future (CAISO, 2016). This conclusion is made by Energimyndigheten as well, which recommends restructuring the ancillary services market to encourage more participants to ensure electricity system flexibility, stability and speeding up permit processing and project completions to increase the electrification rate (Energimyndigheten, 2023e). Currently, local projects like Sthlmflex in Stockholm and CoordiNet in Upland, Gotland and Skåne have emerged to increase future market system flexibility (Energimyndigheten, 2022c).

Addressing the limitations of renewables, like lower system inertia, which highlights the need to explore the potential benefits of different power plant placements.

3.3.1 Siting

For solar power, the direction of solar panels can be changed to offset the time of day the majority of the production is happening (Energimyndigheten, 2019). Since the sun travels from east to west in the northern hemisphere, in case the panel is facing the west and not south, then the peak production during the day will be earlier than if the solar panel was tilted towards the north (azimuth = 0). Although this deviation from the optimal angle will affect the total electricity production (Dhimish and Silvestre, 2019).

If the peak production for solar power is earlier on a system level, this will lead to a slower ramp-up rate for the duck curve (seen in figure 19) towards the evening but might lead to a higher ramp down rate in the morning. As the azimuth angle is not optimal, the production will be slightly lower, making the duck's back, as seen in figure 19, be less protrusive.

Correlation

In a system with a great amount of power from intermittent sources, it is also interesting to know the correlation between power production from different units at different locations in the country. In a study, Widen concluded that the correlation is high between wind power plants that are close to each other, but as the distance increases, the correlation decreases to 0.2 - 0.4 for wind power plants farther away than 500 km. For even longer distances, the correlation is even lower, reaching 0.1 at 1500 km (Widen, 2011).

The correlation between solar power plants is much higher, reaching 0.8 for distances of 1500 km (Widen, 2011). Furthermore, they also conclude that the lowest correlation is on a 12-month basis, reaching -0.74 for combined solar and wind systems. The hourly variations in production are the highest in a system with more solar power due to the nature of irradiation compared to wind patterns (Widen, 2011). This shows the importance of interconnections with other countries once more as the longest distance between south and north of Sweden is 1572 km (Si, 2021), but the east-west distance is lower than 500 km, meaning that the correlation there is higher. Interconnections between different EU countries help even out the production by increasing the effective distance between power plants.

3.3.2 Interconnection

According to IEA, the interconnectivity of Nordic grids secures electricity supply (IEA, 2019). With interconnectivity being more important as the share of renewable power generation increases (IEA, 2019).

According to a study on a European level, where a 100% renewable system was simulated for the year 2050, they concluded that a higher degree of interconnection reduced the system cost by 9% and connection need decreased when small scale consumers and suppliers (prosumers) of solar power integrated energy storage systems by 6% (Child et al., 2019). Higher interconnectivity is also considered to be good as it connects solar generation in the south of Europe with wind generation in the north, reducing the variability, which reduces the need for storage capacity and installed capacity (Child et al., 2019).

While interconnected grids can help to reduce the cost and variability of renewable energy, a rule in the EU places new requirements on how this interconnection is implemented in practice.

The 70%-rule

A law called the "70% rule" (EU) 2019/943 came into effect at the beginning of 2020 and will gradually reach this target towards the end of 2025 in the EU (ACER, 2022a). It states that a country has to make 70% of its foreign connections (ACER, 2022a) available for the market for 30 % of the time (Sonnsjö et al., 2020). This applies between EU-bidding zones and those inside a country.

In practice, that means that Sweden is obliged to be able to export a certain amount of electricity. This also means that the higher the degree of interconnection and the more interconnections Sweden builds, the more electricity Sweden is forced to export.

According to the statistics from 2021, we can see that, for Sweden, the areas where interconnection of 70% is reached to the least extent are areas between Sweden and Denmark SE4 > DK2 (84 % of the time) and Sweden and Finland SE1 > FI (92 - 94 % of the time) (ACER, 2022b). For the internal borders between zones in Sweden (considering trade with other countries) the lowest two are SE2 > SE3 (49% of the time) and SE3 > SE4 (35% of the time) (ACER, 2022b). This shows that this rule is hardest to follow in the southern regions of Sweden.

While interconnection is a valuable tool for increasing grid stability, it is not a silver bullet. The ability to regulate consumption and production is also seen as essential for the future power system.

3.3.3 Flexibility

Flexibility in the electrical system refers to the system's ability to swiftly adapt to varying production and consumption conditions, especially with an increasing share of variable energy production. It involves balancing supply and demand for electricity using various resources such as demand-side management, energy storage and flexible electricity production (Ei, 2020).

Techniques, such as demand-side management (DSM), are seen as viable to reduce the power needed during the peak loads, which alleviates shortcomings in production and transmission capacity (Energimyndigheten, 2023e). According to Ei, the current potential for demand flexibility is currently 10.5 GW (where 7.35 GW comes from households) and the flexibility for production in Sweden is 0.45 GW (SVK, 2022b).

SVK, just as authors from other reports from previously, concludes that flexibility on both the consumption and production flexibility is essential to maintain supply and system stability. Pricing has to be adopted to incentivize consumers to change consumption habits (Svenskt Näringsliv, 2015) and further develop ancillary services (Svenskt Näringsliv, 2015).

According to the long term market analysis report by SVK, in a scenario where electrification was high, the amount of hours with LOLE (loss of load expectation) and EENS (expected energy not supplied) decreased from 889 hours to 40 hours if hydrogen was used (SVK, 2021). In cases where flexibility from data centers, industry and vehicles was used, then that amount dropped to 0.5 hours (SVK, 2021), which is within the *0.99 hour norm* introduced in the beginning of section 3.3.

An increased flexibility of power plants can increase the rate at which ramping can be done, that is, the plant's ability to increase or decrease production. This increases the system's ability to adapt to changing conditions (CAISO, 2016).

Nuclear power flexibility

Nuclear power is often considered a baseload power plant as it is being run at full capacity most of the time due to cost and reactor poisoning effects. Older generations of NPPs allow for a ramp rate to a limited degree, as seen in table 11, which is an order of magnitude slower than gas turbines. Reactors of newer generations are able to follow the load at an even higher pace (Bragg-Sitton et al., 2020), which is a desirable ability for a system with a high penetration of VREs. A study of the biggest reactor in Sweden - Oskarshamn 3 (BWR) for load following concluded that load following is possible to some extent but that it will increase wear and tear due to the design of operating at maximum allowed power (Bjurenfalk, 2020). In France, some reactors can vary their load from 100% to 20% several times a day in a matter of thirty minutes, adding to the frequency and voltage stability of the system (Wakter, 2022) by participating in the balancing of the system.

Table 11: Startup time, ramp rate and maximal ramp rate ability of older NPPs (Bragg-Sitton et al., 2020).

Startup time	Ramp rate 30 sec	Maximum ramp rate (per min)
2 hours - 2 days	0 - 5%	1 - 5%

Other developments of nuclear reactors have shown that about 17% of the world's nuclear fleet provide process heat in the form of district heating, desalination or other industrial applications (Bragg-Sitton et al., 2020).

A report found that Small Modular Reactors (SMRs), due to their flexibility to vary electricity production, could be used to increase their production to fill in the energy gaps created by Variable Renewable Energies (VREs), thereby reducing the need to curtail production (IAEA, 2009). Additionally, some other types of reactors, like molten salt reactors, are considered to be well-suited for load following and the ability to operate at high temperatures to produce heat for industrial processes (Bragg-Sitton et al., 2020). In the case of smaller distributed generators, it has been found that in a system with smaller generators, there is a 20% increase in the inertia response than a system with bigger generators of similar ratings (Qaid et al., 2021), meaning that a system with smaller generators but of similar total rating would increase the ability to perform a frequency recovery.

3.3.4 Energy storage

Energimyndigheten states in the report that high amounts of wind and solar power will lead to the need for increased energy storage systems (ESS) where batteries, hydrogen and pumped storage hydropower (PSH) are considered as viable options (Energimyndigheten, 2023e). Therefore, it is also these storage technologies that were considered in the results.

According to an article on energy storage, storage can be used for arbitrage when there are price differences, but also to decrease ramping on other generating sources and provide other ancillary services for grid stability (Schill, 2020).

The profitability of these virtual power plants is dependent on the price volatility of electricity and its duration. According to SVK, the increased need for flexibility does not automatically result in increased profitability of PSH. For instance, the increased amount of solar power in Germany has decreased the price difference between night and day, making the PSH operation less profitable (Svenskt Näringsliv, 2015).

Different storage types are found to have different potentials for the system (Worku, 2022). Lithium-ion batteries are considered to be good storage mediums for short-term electricity storage, while PSH is considered to be the best option for long-term energy storage, but it is limited by geographical constraints (Worku, 2022). Although super-capacitor ESS and superconducting magnetic ESS are recognized as viable options for short-term variations.

Pumped storage hydropower (PSH)

According to numbers in the report by Svenskt Näringsliv, the total capacity for new pumped storage hydro is 81 GWh in the north of Sweden. Another report by the EC finds this number to be 22 GWh (Svenskt Näringsliv, 2020). This is considering the current production capacity to be 96.8 GWh (IVA, 2015). The total PSH potential in the best-case scenario presented by Svenskt Näringsliv in terms of installed capacity is considered to be 624 MW compared to 93.6 MW today (Svenskt Näringsliv, 2020). There are currently projects looking into reopening and building new PSH, but they are yet to materialize (Svenskt Näringsliv, 2020).

Batteries

Batteries are seen as good short-term solutions, which can be used to deliver flexibility and improve frequency and voltage stability (Energimyndigheten, 2023e). According to SVK, the amount of battery storage available in 2045 will be between 2 and 12 GWh (SVK, 2021).

Vehicle-to-grid (V2G)

The amount of cars per person in Sweden is about 0.48 and the non-conventional cars (Battery Electric Vehicles, Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles) comprised 52% of the newly registered cars during 2021, compared to 5% in 2012. By the end of 2021, there were 189 thousand hybrids and 110 thousand electric vehicles on the roads of Sweden (Energimyndigheten, 2022a). This leads to a great number of batteries that are connected to the grid, which can be used to store energy and provide ancillary services.

The number of electric vehicles in the future will increase the risk of simultaneous charging during the hours of peak load of the day (which are close to the evening when people return from work). This can bloat "the duck curve", increasing the demand peak (the duck's head) and increasing the ramp rate demand on the system. This indicates the necessity to have a smart charging system for cars (Svenskt Näringsliv, 2015).

Cars still stand the majority of the time (approximately 96% of it) (IVA, 2019). As the population switches over to electrical vehicles with a battery inside, there emerges a potential source of distributed electricity storage, which can be used for peak shaving by the use of bidirectional charging while the cars are not in use.

According to Power Circle, there will be 2.5 million electric cars by 2030 and 4.5 million by 2045 (Power Circle, 2019). With the assumption that an average battery is 62 kWh (Power Circle, 2019), the available electricity will be 0.279 TWh, which is on the same order of magnitude as the current energy consumption in Sweden in one day. The unclear factor is the cycling depth of the batteries in the car, which affects the total available electricity for retrieval and the lifetime of the batteries. Assuming a battery discharge depth of 10% and that 96% of the cars are standing still would produce 0.027 TWh of available energy. Assuming that this energy would be used during an hour, that would generate 26.784 GWh/h, which is on the same order of magnitude as the current power need during the peak load.

This simple calculation shows how V2G not only can be used as a flexible resource supplying power but also as a flexible load which can draw power (by charging) when there are periods of overproduction. The major factor that governs how much energy is used is the adaptability of this technology. Even with the assumption of a 10% adoption, the available energy would be on the order of magnitude of the current power deficit during peak load.

In a long-term analysis report by SVK (Svenska kraftnät), they analyzed how price could be affected by V2G and concluded that the prices with V2G are evened out. They concluded that the maximum potential is about 19 GW (SVK, 2021).

One additional aspect of batteries in electric vehicles is that used car batteries that are no longer up to par can later be re-used in second-life scenarios in order to balance the grid (Energimyndigheten, 2019).

Hydrogen

Hydrogen production will play a very important role in the future energy system due to its ability to act as a storage medium and be used as a power source in the transportation sector and industry (SVK, 2021). The European Commission (EC) has recognized hydrogen as an important component of the future energy system and adopted strategies in 2020 that recognize hydrogen as an important part of climate-neutrality by 2050 and The Paris Agreement. It includes strategies for production, distribution and use. In Sweden, the use of hydrogen in the industry will be a major factor, together with the production of green fuels (green methanol through Power-to-X), which will also be important for Sweden becoming climate neutral (SVK, 2021). Moreover, hydrogen production through PEM electrolysers can provide ancillary services since the time it takes to ramp up, ramp down (when it acts like a load) and start up is vastly smaller than for the Alkaline counterpart (IRENA, 2019). This means that the Alkaline electrolysers are not likely to be used as frequency reserve (Alaswad et al., 2016).

Power-to-hydrogen (P2H)

Power-to-gas, also abbreviated as PtG, is a process of creating a gas from electricity. In this report, the gas of interest is hydrogen. When this hydrogen is produced by renewable electricity generation, it is called green hydrogen. The challenge of producing and storing electricity through hydrogen through electrolysis is twofold.

First of all, the production of hydrogen through electrolysis will depend on several factors such as temperature, pressure and type of electrolyte. This efficiency of electricity to hydrogen conversion in terms of energy is heavily influenced by the applied load as electrolysis has to operate at stable power. This means that the production of hydrogen through water electrolysis using variable renewable energy sources will not have as good efficiency as production of hydrogen through stable electricity sources (Amireh et al., 2023). Proton Exchange Membrane (PEM) fuel cell offers the most attractive future prospects, through its combination of simple design, high power/weight ratio and low working temperature (Alaswad et al., 2016). Not all electrolysers can provide grid services as the speed of load ramping is different.

A study was conducted to determine the optimal ratios of renewable generation to electrolysis power in the year 2020 to reduce the cost of hydrogen production. This determination was based on whether a power generation system possessed a low or high capacity factor, indicated by the number of full-load hours. The study took into account scaling effects and cost developments. It found, that for wind, the ideal ratio in relation to hydrogen production capacity ranges from 3.3% (for low capacity factors) to 143% (for high capacity factors). In contrast, for PV-systems, the ratio ranges from 14% to 73%. The variation is more pronounced for wind compared to solar due to differences in generation patterns (Hofrichter et al., 2023).

Another study came to a conclusion that in a system with high renewable generation penetration (PV and wind of 80%), the installed capacity needed decreased when increasing the amount of electrolysers capacity. Power-to-gas reduced the need for wind and solar capacity by up to 23% and the power curtailment up to 87% (Lyseng et al., 2018).

In a study from Japan, the integration of 70 GW of solar and 50 GW of wind was studied. They came to a conclusion that even though the surplus produced was 20 TWh, the load factor of said electricity was 5-15% (Shibata, 2015). The low capacity factor of production of hydrogen increases the hydrogen production cost. They conclude that it is better to use the stable part of the power generation output from renewable power generation to produce hydrogen even if that electricity is at a higher price (Shibata, 2015). This is since the capital cost of production due to low capacity factor. The suggested capacity factor of power generation is according to the report 40-70%, but in general a capacity factor of 90% is desirable (Shibata, 2015). Authors also suggest utilizing the oxygen from electrolysis to decrease the production cost of hydrogen (Shibata, 2015).

According to a report on Hydrogen by Energimyndigheten, in order to get a low production cost for hydrogen, the full-load hours have to be above 2000 - 3000 hours a year and it is not economically feasible to produce hydrogen when electricity prices are negative as they are present occasionally (Energimyndigheten, 2022c). Despite this, the report states that the potential due to hydrogen flexibility is still great (Energimyndigheten, 2022c). In a different report by IRENA a similar conclusion is stated; that in order to achieve competitiveness during low investment costs, 3000 - 4000 operating hours per year can be sufficient to get the largest decrease in production cost of hydrogen (IRENA, 2020). It is also suggested that the use of hybrid PV-wind farms could be used to generate a high number of high full-load hours (IRENA, 2020).

Despite low efficiency, hydrogen has multiple uses (not only as a storage medium) but is a fuel in itself. Hydrogen can later be converted to green fuels or even used to drive gas turbines at an efficiency rate close to fuel cells, which would add to system stability by inertia and ability to ramp-up power (Energimyndigheten, 2022c).

Power-to-hydrogen-to-power (P2H2P)

One of the potential uses of produced hydrogen is conversion back into electricity. This can be fed back into the grid using fuel cells (Energimyndigheten, 2022c). The challenges of using hydrogen as a storage medium to supply the system during high load are the total efficiency and the high capital costs of the hydrogen system (Shibata, 2015).

The efficiency of converting energy in the form of electricity into energy in the form of hydrogen is about 55 - 60% (Energimyndigheten, 2022c). Later, converting that energy into electricity would need a fuel cell which, currently, has an efficiency of about 50 - 60% (Energimyndigheten, 2022c). This leads to a total efficiency of about 32.5 - 43% (Energimyndigheten, 2022c). Despite the relatively low efficiency, the ability to store hydrogen for long periods without significant losses makes it a valuable energy source, especially during periods of high price volatility. When electricity prices are high, hydrogen can be used to generate electricity, offsetting the lower efficiency.

3.3.5 Stability

The number of minutes during which the frequency lies outside of the desirable frequency range has increased in recent times, which also means that the automatic frequency reserves use has increased (Svenskt Näringsliv, 2015). Low system inertia increases wear on the units that provide frequency regulation (like hydropower) (Saarinen et al., 2018).

SVK states that an increased amount of VRE is not necessarily the only reason behind the increased number of frequency deviations. Even though the installed capacity has increased, the deviations have not increased at the same rate. According to SVK, this can be due to the introduction of FRR (Frequency Restoration Reserve), which is an automatic secondary frequency control (Svenskt Näringsliv, 2015).

Synchronous production is the production which does not include wind and solar. This production is connected directly and is rotating with the same frequency, 50 Hz. This means that connected and rotating generators are contributing to system stability (SVK, 2022b).

During the time when the system operator has decreased the production of conventional electricity generators, there is a decrease in system inertia which leads to a greater risk of system failure during loss of production or transmission. This can be illustrated as the belly of the duck in figure 19 at 12:00 (CAISO, 2016).

During periods of oversupply, there is more generated electricity than there is demand, which can lead to negative prices. This can force producers of electricity to pay for consumers to utilize the electricity. Which, in turn, leads to market instability and can also require manual intervention to maintain stability and reliability of the system. This condition is manageable at small time scales with intrinsic market mechanisms but is not sustainable for longer time-frames (CAISO, 2016).

Synthetic inertia

Wind and solar are connected to the grid through power converters and are hence not synchronously connected, thereby not providing any stability to the system. In 2022, the synchronous production in the area of Sweden, Norway, Finland and DK2 is 80.1 GW and 30 GW in Sweden with the import capacity of 10.3 GW (SVK, 2022b).

Wind turbines are connected to the grid through converters which convert AC voltage (wind power) with variable frequency to a desired AC voltage with a stable frequency. The output voltage can be changed by regulating the duty-cycle and switching frequency in the controllers connected to the converter. To generate inertia, a different approach is taken from rotating synchronous generators in hydro and nuclear. To generate synthetic inertia, the angle of the blades at the turbine and angle in the power converter is changed. This results in that the output power from the wind turbines can be regulated.

The non-delivered energy due to curtailment becomes significant at 20 - 30 TWh of wind power. This is why the use of synthetic inertia is considered a necessity from 50 TWh of wind power production (Energiforsk, 2014). However, synthetic inertia does not contribute to rotor angle stability in the system (which is the ability of synchronous machines to stay synchronized during minor disruptions) (Energiforsk, 2014).

For a regular turbine, the optimal rotor speed is the rotor speed at which a wind turbine generates the most electricity given a specific wind speed (Adeyeye et al., 2021). An increase of the rotor speed above the optimal rotor speed decreases the yearly production. This increase in rotor speed increases the kinetic energy in a wind power plant and hence also the inertia, as the kinetic energy is proportional to the inertia times angular velocity squared. A slight increase in angular velocity increases the kinetic energy of the turbine. This energy can later be converted into mechanical power by decreasing the angular velocity of the turbine.

The idea is then to increase the angular velocity slightly above the optimal angular velocity (angular velocity at which the production is the highest at current wind speed) of the wind turbine. This results in an increased kinetic energy in the turbine which can later be harnessed when power is needed by lowering the angular velocity of the turbine.

According to a report from RISE on synthetic inertia, to ensure a worst-case scenario (a decrease of 1450 MW (Oskarshamn 3 going offline) without the frequency dipping below 49Hz) during a time of low inertia (100 GWs), there is a need for FFR-reserve of 250 - 270 MW with activation at 49.6 Hz and lasting 1s (Wickström, 2021). They found that an increase of the rotor speed by 2 rpm resulted in an FFR-reserve of 415 MW and a reduction in annual production by only 1.3% (Wickström, 2021). This was also compared to a different mode, where power curtailment at high wind speeds was studied. They concluded that to produce an 88 MW FFR-reserve resulted in a loss of production of 8.24%, which means that it produced a much higher production deficit and did not fulfill the FFR requirement (Wickström, 2021). They conclude that the best way to generate FFR-reserve is when wind power plants are at times of low wind speeds (below 9 m/s) (Wickström, 2021).

Furthermore, the operational impact on the wind turbines was evaluated. Implementing synthetic inertia would slightly increase the speed at which wind turbine is rotating, which would rotate at a higher pace compared to its optimal scenario. It is unclear how this operation would affect the life-time of the wind power plant as it could affect the wear and tear of the turbine.

A point of contention related to synthetic inertia is the fact that wind speed is not constant and may change during the time when the FFR reserve is active - thereby changing the optimal rotor speed for that specific wind speed and hence interfering with frequency regulation to the grid.

The limitation of employing synthetic inertia in this manner is that upon activation of the wind turbine's synthetic inertia response, there's a temporary surge in power as it reaches its optimal operating point to aid the system. However, to replenish the Fast Frequency Response (FFR) capability, there is a need to return to a lower power production operating point, thereby lowering the power output to the system. This loss of production will lead to a secondary frequency dip at a system level (Eriksson, n.d.). In the case when this is not handled properly, it can cause a secondary dip that is lower than the first dip, which can put the system at greater risk compared to a system where this is not implemented (Eriksson, n.d.).

Another issue with synthetic inertia is that the frequency quality during normal operation is not considered fully. In a report studying the Nordic synchronous system, the conclusion is to use linear synthetic inertia controllers, which would reduce the wear on frequency regulators such as hydropower (Saarinen et al., 2018).

3.3.6 Result 3: conclusion

The answer to 'What methods, technologies and strategies can be applied to increase stability and electricity availability in the Swedish system year 2045?' is enhancing system flexibility. Managing power generation spikes will be necessary due to increased reliance on wind power and the prevalence of wind (as seen from section 3.2). With significant wind power, distributing power plants to reduce correlation between them is essential. However, Sweden's limited geographical size and construction space due to competing interests restrict a significant separation of power plants. Interconnections with other nations could simulate a larger system area, but may lead to unfavorable export requirements during electricity need, due to the 70% rule.

Wind power introduces challenges as it connects to the system through converters, not directly. Utilizing synthetic inertia to cover Sweden's FFR need is advisable. Also, employing the battery inside electric vehicles as a larger flexibility resource (ESS) in a V2G framework is recommended.

While hydrogen can serve as fuel and be part of ESS, its low round-trip efficiency is a point of contention. Besides, the necessity for constant power during electrolysis, would further decrease the round trip efficiency while using variable power generation. This renders electricity storage, using hydrogen, through excess electricity from VREs rather inefficient.

4 Discussion

Niels Bohr famously said that "prediction is very difficult, especially if it is about the future". Despite this inherent difficulty, it's possible to identify potential factors that might shape future outcomes as some events can either pave the way for or hinder certain developments. For instance, a major advancement in production technology that results in the cost-effective manufacturing of PV-panels or another innovative breakthrough, could sway decision-makers to favor a particular technology. SVK points out the considerable uncertainty surrounding the transmission system's evolution past a decade into the future, given that planning primarily occurs within this 10-year timeframe (Energimyndigheten, 2023e).

4.1 Electrification rate

Most reports on electricity consumption's future make assumptions about society's electrification rate, which will dictate the base-case for future electricity demand. Politics can influence the electrification rate and, consequently, future electricity needs. For example, in 2022, the government eliminated the climate bonus for electric cars, impacting the rate at which electric cars are purchased (Energimyndigheten, 2023f). This reduces the electrification rate as fewer electric cars are purchased.

With this context on broad societal trends and policy decisions, it's important to also consider the role of single industries in shaping future demand.

4.2 Few industries behind vast increase of demand

The bulk of Sweden's electricity demand hinges on a handful of industrial giants and their withdrawal from further investment and participation could cause excess electricity production and unwarranted grid infrastructure costs.

For instance, the conflict between LKAB (HYBRIT participant and iron ore mining company) and H2 Green Steel (HYBRIT competitor) resulted in H2 Green Steel importing iron ore from Canada and Brazil instead of Sweden (Kärrman, 2023). This is an example of unforeseen events that could impact the viability of a large project and, consequently, Sweden's electricity production by many TWhs.

Furthermore, the large increase in the electricity demand due to fossil-free steel assumes that consumers are willing to pay a premium price for fossil-free steel, which is 20-30% higher according to an article in Dagens Industri (Industri, 2021). If CO2 (carbon dioxide) emission prices increase, this becomes more economical than the ordinary, fossil, steel. These prices in turn depend on economic, technological and political developments where single events can have significant and unforeseen impacts on previous forecasts (SVK, 2021).

In sum, this means that the global demand for fossil-free steel and carbon emission prices will likely affect the electricity demand in Sweden, which means that events requiring large amounts of steel at a slightly lower cost could divert attention from fossil-free steel.

Thus, as we consider the interplay between global demand for sustainable materials and local electricity needs, it's equally imperative to shift our focus to the economic factors underpinning these trends.

4.3 Pricing

A crucial point about this report is that future electricity prices and electricity production pricing (like LCOE) are not considered in great detail. In reality, these factors determine investment outcomes and the future electricity system.

According to an SVK report, the electricity price needs to be high to incentivize investments (Svenskt Näringsliv, 2015). This is understandable since solar and wind power production is cheaper compared to other electricity sources. As the number of VREs increases, this can put downward pressure on electricity prices, making further investments into renewable electricity less profitable. However, the electricity price is one of the determining factors of electrification speed and economic activity in the industry. This means that higher electricity prices reduce the incentive for the industry to electrify and make further investments requiring more electricity.

The prices of electricity certificates, which provide additional incentives, could also be meaningful. However, as certificate prices are low, they alone will not be a deciding factor in shaping the future energy sector (SVK, 2021).

As we delve deeper into the complexities of the electricity sector, it becomes clear that while some financial incentives may not be pivotal, the inherent uncertainties in our projection models further complicate predictions.

4.4 Projection model uncertainty

There are several factors governing the potentials for several fuel and power types. For instance, the assumption of a certain degree of sustainable fuel retrieval from the forest. This number can vary greatly depending on the assumptions made, which in turn affect the potential for CHP in Sweden.

As many of the potentials in this report rely on chains of assumptions in other reports, this adds to the uncertainty of the true future scenario. For instance, the total V2G potential which was used as ESS storage, which relies on the assumptions about number of vehicles, battery size, time of standstill and technology adoption. The discussion about each of these points in itself could be extended to several reports by themselves.

4.5 Political uncertainty

Uncertainty in investment is also affected by political changes and developments in the society and the world at large.

Many things are hard to predict due to political uncertainty, price volatility and so-called black swan events (the occurrence of something unlikely). As today's world is interconnected with linked supply chains, the amount of scenarios that could affect Sweden's energy market without the input of the Swedish government or people is great. These could be everything from black swan events, embargos, political events, subsidies, wars and conflicts between countries or third parties.

4.5.1 Internal politics

For instance, the report referred to The Paris Agreement in 2015 which got in effect on November 4, 2016. A few years later, in 2017, the 45th-president of USA (Donald J. Trump), the emitter of 15% of the world's greenhouse gasses, announced that the USA would leave that agreement (McGrath, 2020). As per the terms in that agreement, USA could not leave straight away, before the agreement had been in effect for three years - USA left the agreement on 4th November 2020 after a new political leadership got elected. A few hours after the 46th-president (Joseph R. Biden Jr.) got into office in 2021, he pledged that they would re-enter that agreement which came in effect 30 days later and USA formally reentered the agreement 19th of February, 2021. This illustrates how internal politics can affect the outcome of any projections in just a few years.

4.5.2 Wars and pandemics

Another black swan event of interest was the recent pandemic which put a strain on the global supply system and economy. This has indirectly led to the increase of production of electricity. For instance, the cost of solar panels has gone up slightly after decreasing for many years (Lindahl et al., 2022). This pandemic, together with an escalation of the Russo-Ukrainian war affected the Swedish energy system as the available supply of fuel decreased due to sanctions, increasing fuel and electricity prices in Sweden. This increased the number of people switching away from gas powered heating to heating pumps which leads to a slight increase in electricity consumption for heating.

4.5.3 Strategic and critical mineral supplies

As shown previously, the electricity use in the future will greatly depend on the degree of electrification. Electrification in turn depends on the availability of strategic materials which are required to produce devices and power generation sources. A few examples are neodymium magnets for wind power, tellurium for solar cells and lithium for batteries. This means that countries that control most of these materials will have leverage and strategic advantage over countries that rely on imports of these materials (Kommerskollegium, 2023).

4.5.4 Nuclear power

When discussing uncertainty, nuclear power is a topic that cannot be ignored. This is due to the accidents that have occurred in recent years, as well as its association with nuclear weapons and radioactive waste. The accidents in Fukushima Daiichi (2011), Chernobyl (1986) and Three Mile Island (1979) have played a part in swaying the public opinions in countries far away from them towards other power generation sources. In conjunction with these accidents some governments have decided to push decommissioning of existing power plants and abandonment of nuclear power altogether (Paddison et al., 2023). In Sweden, the opinion on nuclear power has shifted three times since the start of this century (SOM-institutet, 2020).

Yet another point, regarding nuclear power, is handling of nuclear waste. The lifetime extension and capacity upgrades of Swedish nuclear power plants have implications for nuclear waste management, as the country will produce more nuclear waste than originally planned. The increasing cost of nuclear waste disposal and the increasing amount of nuclear waste from nuclear power plants could create a future challenge. In the case when SMRs are more prominent than conventional nuclear power plants the nuclear waste costs could be even higher since SMRs can produce 2 to 30 times more waste, depending on their type (Krall et al., 2022).

Other countries (like France) use the waste fuel for reprocessing. This process involves separating the plutonium and uranium from other waste products and creating a MOX (Mixed Oxide) fuel (mix of uranium and plutonium) (SSM, 2023). This process is not free of controversy since plutonium can be used to create nuclear weapons.

Development of the fusion reactors can be considered the Holy Grail of electricity generation, since we would be able recreate the process inside the nucleus of the sun to generate energy. Although the development is underway and some projects have demonstrated the ability to generate more electricity than was put to use, the commercial adaptation is considered to be farther away in the future than the scope of this project.

4.5.5 Wind power

In the terms of wind power, there are multiple challenges that could hinder the development on both land and sea. As presented earlier, the majority of Sweden's land area is a subject of competing interests. This together with long lead times and permitting processes of many years introduces challenges for the industry. In addition, the fact that the licenses have to be renewed when placing a new wind turbine after the end of the lifetime at the same location, together with the short lifetime of wind turbine comparing to conventional power generation sources would mean that this permitting process could be considered as a bottle-neck for the future development of wind power in Sweden. In addition, the NIMBY (Not In My Back Yard) effects for wind power are not insignificant.

4.5.6 Solar power

In the case of solar power, the fact that it can be placed in locations of low or no competing interests makes it an attractive investment option compared to wind power. On the other hand, since the majority of the solar cells are produced in countries outside Europe, this can become an energy security concern.

4.6 Modeled consumption

The modeled result using the multivariate linear regression MLR is a result in itself but as the model is the simplest one and the electricity pricing was not added as variable it should be considered as the least reliable result of them all. Other, older reports from before 2020 have been studied but their conclusions for electricity demand are much smaller that recent reports since the hydrogen and fossil-free steel production is not considered to the same extent.

4.7 System complexity

In the majority of the reports, the projections are based on the future electricity demand being covered by the production within Sweden. In reality, the system is more complex as Sweden has a high interconnection factor with other countries like Norway, Finland and Denmark; this will affect both the flexibility and reliability of the system. For instance, Norway has a high share of hydropower, Denmark has a high share of wind power and Finland recently introduced a new nuclear reactor (Olkiluoto 3). In addition there are several hydropower magazines in Europe which all add to the complexity of modeling a system.

The electricity use will depend on the assumption on how much hydrogen based iron Sweden will be exporting due to the amount of assumed electricity demand for hydrogen production for these processes (SVK, 2021).

4.8 System development

Along with massive investments into the electricity system there is a need to decrease the lead times for transmission times, the permit processes for wind power needs to be lowered as it is currently longer than ten years. When nuclear power was built in Sweden during the mid 1900s, in a span of 14 years almost 11 GW of installed capacity was introduced. Assuming a capacity factor of 0.82, this would correspond to an addition of 5.6 TWh to the electricity production per year during this period. Comparing this number to the amount of energy needed to build before 2045 assuming 26 TWh of export and 286 TWh internal demand yields 312 TWh of production and would hence correspond to about 6.9 TWh of added production per year. This means that the addition of production needs to be even higher than during the time when Sweden built the majority of its nuclear power plants and this does not include the power-plants that approach the end of their lifetime and are planned to be decommissioned. According to the CEO of Energiföretagen, market-forces would not be enough to accommodate this doubling by themselves and the government has to improve the investment climate drastically by giving guaranties (Tidningen Näringslivet, 2023).

4.9 Climate neutrality objective

Even though the direct production of electricity by renewable electricity sources as wind and solar do not cause direct emissions - their life-cycle emissions are not completely negligible. These sources are dependent on the energy mix of the countries where the components are produced, affecting the carbon intensity (grams of CO2e released per produced kWh of electricity) (Svenskt Näringsliv, 2020).

This means that the goal of being carbon neutral, forces decision-makers to take into consideration the lifetime emissions of increased electricity production by the newly installed renewable sources together with increased need for recycling after the end of their lifetime but also the need to offset the non-direct emissions caused by lifetime emission profile.

Even in the case where all electricity production is climate neutral and all sectors have gone through extensive electrification there will still be a need to account for carbon intensity introduced by lifetime emission of different devices, which will require additional methods to reach climate neutrality goal by 2045 (SVK, 2021). Carbon dioxide can be captured and used in CCS (carbon capture and storage) and CCU (carbon capture and utilization and Power-to-X). This process also requires electricity (SVK, 2021) which means that the electricity demand might increase further depending on the need of CCS.

Under the assumption that the majority of wind and solar panels are produced outside Sweden, the amount of resulting emissions will depend on foreign countries' commitment to climate neutrality goals and the carbon intensity of their energy-systems.

5 Conclusions

To comply with climate neutrality goals of the future a vast amount of electricity will be needed. These values range as far as slightly more than twice the electricity production of today by 2045. This number is mostly dependent on the electrification rate of the society. The biggest increase is set to come due to the expected demand by hydrogen-based, fossil free steel making industry where only a few stakeholders will represent the majority of the increase. The conclusion in this report is that the domestic electricity demand will be 286 TWh (including transmission and distribution losses) assuming a high degree of electrification. On the other hand, the total production of electricity in Sweden is projected to be 312 TWh assuming that the export to other countries will be 26 TWh.

According to some reports the highest potential for electricity production in the long term scenario for Sweden comes from wind power (onshore and offshore) and nuclear power. The opinion towards nuclear power has changed but to increase the production substantially or use SMRs would require a change to current legislation. The share of nuclear power production in the future will greatly depend on whether old units are allowed to operate beyond 60-year life time as is possible in other countries. Furthermore, a few laws will limit the number of reactors and their placement in case nuclear is further developed. The hydropower production is unlikely to produce more energy and will likely be on roughly the same level or add 0.5 TWh to current production due to climate change.

The production of electricity through CHP will likely not be the biggest contributing factor since the need for heating decreases in the future due to increased temperature and higher efficiency of buildings. Solar power production has a low theoretical potential in Sweden but as it can be placed in locations with low or no competition it might still have potential. Although, a system with a high amount of PVs needs to consider and remedy the effects of the Duck Curve, especially during the summer and low availability during off-season and peak load. Wind power is considered to be the power source, which will add the most to the electricity production in Sweden despite the long permit application period and uncertainty relating to the process.

In order to preserve stability and power availability, several methodologies need to be implemented. These are flexibility but also solutions to increase resilience to unforeseen events threatening the electricity system. According to the results of this report the implementation of a majority of the flexibility resources (such as energy storage, demand and production flexibility) are essential to reduce the number of hours where Sweden cannot supply internal electricity demand below the 0.99 norm set by the government.

In the case when both nuclear power and solar power are present in the system and solar power production is high (usually during the summer when nuclear power is offline for maintenance), the combination of high production and low electricity demand can pose a stability risk to the electricity grid.

In the case where nuclear power is not further developed, synthetic inertia from wind turbines can be used as a fast frequency restoration reserve (FFR) which could cover the need in Sweden. To facilitate the development of these and similar services there is a need to further develop the ancillary services market to incentivise producers of electricity to curtail their production.

Summary

In summary, developing the energy system for a climate-neutral future represents a historic challenge for Sweden. This transformation demands substantial investment, coupled with political and public backing, as well as collaboration across various sectors. Nonetheless, this shift is vital for Sweden to achieve its ambitious climate objectives and cater to the rising electricity demand.

The core points and recommendations from this report are outlined in the bullet points below.

- A historically unparalleled build-out of power generating resources and the overall electricity system, including transmission and distribution, is required.
- It is essential to use all available flexibility resources (storage, demand management and ancillary services) in order to preserve system stability and power availability within the norm.

- Establishing interconnections with neighboring countries enhances the system's resilience and stability. However, this can have adverse effects in southern regions, where there's a high consumption-to-production ratio, due to the 70%-rule.
- In the long-term perspective, wind and nuclear power have the highest production potentials in Sweden.
- The laws concerning nuclear power require a reevaluation, alongside a consideration of potential nuclear waste increases.
- Wind power is anticipated to become the dominant electricity generation source in Sweden.
- The process for obtaining permits for wind power plant construction needs simplification to reduce the overall permitting time and increase the number of approved projects.
- Wind power has the potential to at least partially cover FFR using synthetic inertia (assuming there is wind present). The technology should be developed and implemented in future WPP projects.
- While solar power's potential in Sweden is limited, it remains significant, especially in areas with few competing interests.

6 Recommendations for Future Work

An interesting aspect is to model a more complex system that would use a model like TIMES-NORDIC and include different parameters such as the price for electricity production for different power sources and model different parts of the system for different penetration levels of the renewable electricity and include some ancillary services.

Another case study of interest could be researching the optimal way to run virtual inertia systems with respect to different consumption patterns. For instance, running wind power plants in the synthetic inertia mode during the summer sacrificing a bit of production and returning to maximum production during the winter months. This is done when production of electricity from solar is the highest and the system inertia is at its lowest as system operators need to ramp down conventional generation and nuclear power plants undergo revision.

Yet another aspect could be to analyze how much flexibility should be included in the case that the natural day cycle is slightly altered on a system level - in essence - incentivising people to slightly shift their routines to off-set morning and evening peaks in order to perform peak shaving (demand side management).

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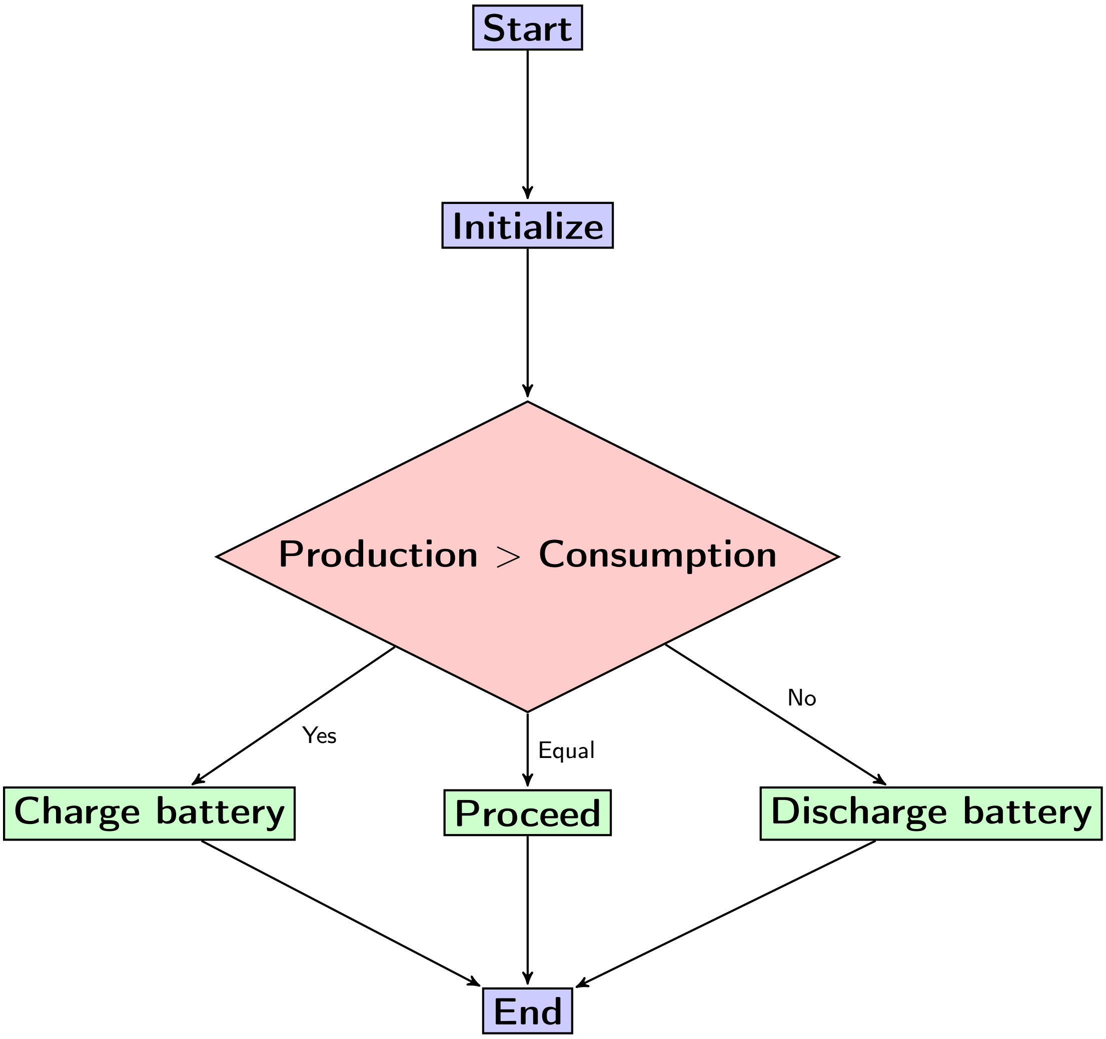
Appendix A: Flowchart for ESS-charging using AppScript



Appendix B: Populärvetenskaplig sammanfattning

Sverige har ambitiösa mål för att bli mer hållbart, inklusive att ha en fossilfri elproduktion 2040 och nollutsläpp av växthusgaser 2045. Examensarbetet utforskar möjliga utmaningar som systemet kan ställas inför genom att titta på landets framtida elbehov och potentialen för de energikällor som kan byggas i Sverige.

Rapporten visar att elbehovet kommer att fördubblas, främst på grund av det tillkommande behovet av den fossilfria stålproduktionen. Men det finns osäkerhet kring hur stor denna ökning exakt kommer att vara. Vindkraft förväntas bli den största energikällan, men det finns utmaningar med att bygga ut den då endast en liten del av Sveriges yta är tillgäglig för vindkraften. Dessutom visar det sig att en stor del av projekten inte godkönns i den långa ansökningsprocessen. Solkraft har också potential trots Sveriges låga solinstrålning. Detta beror främst på att den kan byggas på platser där andra energikällor inte får vara.

En del av kärnkraften når slutet av sin livlängd och om inte mer kärnkraft byggs ut kan det uppstå problem med elnätets stabilitet. En lösning kan vara att offra en liten del av vindkraftenens produktion för att hjälpa till att stabilisera systemet. Detta sker genom att justera hastigheten med vilken vindturbinerna roterar.

För att säkerställa att det alltid finns tillräckligt med el, även när det inte blåser eller solen inte lyser, behövs flexibilitet i systemet. Flexibilitet introduceras exempelvis genom energilagring samt genom tillfällig sänkning av förbrukningen.

Sammanfattningsvis visar detta arbete att även om det finns utmaningar framför oss, finns det också lösningar som kan hjälpa Sverige att uppnå de satta hållbarhetsmålen men att denna omställning kräver en del investeringar i både utbyggnad samt flexibilitet.