Implementation of Large-scale Grid Storage in Malmö

Potential economic gain and effects on the electricity system in the region

Gustav Johansson & Siri Nordberg

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Sammandrag

Denna rapport undersöker möjligheten till implementering av en storskalig energilagringslösning i Malmö och dess effekt på elbalansen. Arbetet utgår från Texel Energy Storage AB:s termokemiska batterilösning som lagrar energi i form av värme, vilken sedan utvinns som elektrisk energi genom en Stirlingmotor. Texel planerar att implementera en 400 MW-lösning i Malmö år 2027 - introducerad i tre faser, med en första och andra fas på 2 respektive 50 MW. En studie av elsystemet i Sverige såväl som i Malmös elprisområde SE4 genomförs med hjälp av produktions-, konsumtions-, pris- och transmissionsdata för 2022. För att undersöka ekonomisk lönsamhet och effekterna av dessa implementeringar skapas två scenarier utöver 2022 - år 2027 samt ett framtida scenario bortom 2030 där SE4 producerar tillräckligt med el från vindkraft för att täcka regionens elunderskott på årsbasis. Detta görs genom att titta på framtida marknadsanalyser för SE4 och därefter extrapolera data från 2022 för att skapa scenariot 2027 samt det bortom 2030. Driften av batterilösningen som ger störst ekonomisk lönsamhet i de olika faserna med två olika lagringskapaciteter (6- eller 12 timmars enheter) beräknas där driften bestäms utifrån marknadspriset på el. Därefter bestäms insättning och uttag av el på nätet, antalet drifttimmar, bruttovinst, nettovinst, genomsnittlig vinst per såld MWh, kostnad per lagrad och levererad MWh, återbetalningstid samt effekten på SE4:s elbalans för de olika scenarierna. Genom att driva lösningen baserat på SE4:s elpriser uppnås ingen uppenbar balansering av den regionala elbalansen då regionens elsystem ser en svag korrelation mellan elbalans och elpriser. Samtliga faser visar på lönsamhet, där 400 MW-lösningen ger störst vinst i alla scenarier, men även störst ökning av elunderskottet i SE4 eftersom lösningen är en nettokonsument av el. 2 MW-lösningen ger lägst vinst men har en försumbar påverkan på elbalansen. Vidare pekar resultaten på svårigheten med att driva en lagringslösning utifrån målet att maximera vinst och samtidigt hjälpa effektbalansen.

Nyckelord

Energilagring, nätansluten lagring, termokemiskt batteri, elsystem, elbalans, SE4, förnybar el, elpris, transmission av el, energiomställning

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Abstract

This report investigates the possibility for an implementation of a large-scale grid storage solution in Malmö and its effect on the electricity balance. The work is centred around Texel Energy Storage AB's thermochemical battery solution that stores energy as heat, which is converted to electricity through a Stirling engine. Texel plans to introduce a 400 MW storage solution in Malmö in 2027 – introduced in three phases, with a first phase of 2 MW and a second of 50 MW. A study of the electricity system in Sweden as well as Malmö's electricity price area SE4 is carried out using production-, consumption-, price- and transmission data for 2022. To investigate economic profit and the effects of these implementations two scenarios in addition to 2022 are created – the year of 2027 as well as a future scenario beyond 2030, where SE4 produce enough electricity from wind power to cover its electricity deficit on a yearly basis. This is achieved by looking at future market analyses for SE4 and then performing an extrapolation of the 2022 data to create the scenario of 2027 and the one beyond 2030. The operation of the battery solution to optimize economic profit for the different phases, with two storage capacity units (a 6 hour unit or a 12 hour unit), is calculated where the operation is determined by the market price of electricity. Thereafter, input and withdrawal of electricity to and from the grid, number of operational hours, gross profit, net profit, average profit per sold MWh, levelized cost of storage, payback time as well as the effect on the electricity balance of SE4 is determined for the different scenarios. No apparent balancing of the regional energy system is achieved by operating the solution based on SE4's electricity prices, as the regional electricity system see a weak correlation between electricity balance and electricity prices. All phases show profitability, where the 400 MW solution gives the highest profitability in all scenarios, but also the largest increase in electricity deficit due to it being a net consumer of electricity. The 2 MW solution yield least profit but has a negligible effect on the electricity balance. Furthermore, the results point to the difficulty of operating a storage solution with the aim of maximizing profit and helping the electricity balance at the same time.

Keywords

Energy storage, grid storage, thermochemical battery, electricity system, electricity balance, SE4, renewable electricity, electricity price, electricity transmission, energy transition

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Preface

This master thesis was conducted during the spring semester of 2023, as the finishing part of a MSc in Environmental Engineering at Lund University, Faculty of Engineering. The report was conducted under the supervision of the Division of Environmental and Energy System Studies, in collaboration with Texel Energy Storage AB in Gothenburg.

First and foremost, we would like to thank our supervisors Max Åhman (LTH) and Hanna Granath (Texel) for your support throughout the development of this thesis, and for the many constructive and valuable comments. Thank you also to our examiner Lars J. Nilsson (LTH) for taking the time to read and give feedback on our work.

We would like to thank the people at Texel for giving us the opportunity to shape this project to our mutual interest, and for the help you have given us along the way. A special thank you to Lars Jacobsson, Ludvig Andersson, and once again Hanna Granath for inviting us to your beautiful office in Gothenburg, and for the enthusiastic and educational conversations we have had.

We would also like to thank the people at LTH who helped us overcome problems when our expertise was not enough. Joel Johansson, Anton Wiklund, Isac Lazar and Marcus Klang - without your guidance, this thesis would not have become what it is.

Lastly, we would like to thank our friends and family for your enthusiasm and support throughout our education and in this work.

Abbreviations

AC - Alternating Current

CAPEX - Capital Expenditure

Cogeneration - Combined Heat and Power Generation

HTMH - High Temperature Metal Hydryde

IPCC - International Panel on Climate Change

LCOS - Levelized Cost of Storage

LTMH - Low Temperature Metal Hydride

OPEX - Operational Expenditure

SE1 - Luleå's Electricity Price Area

SE2 - Sundsvall's Electricity Price Area

SE3 - Stockholm's Electricity Price Area

SE4 - Malmö's Electricity Price Area

SvK - Svenska Kraftnät

TCES - Thermochemical Energy Storage

TSO - Transmission System Operator

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1 Introduction

Humanity faces the challenge of slowing down climate change as well as handling and adapting to the effects already seen today. According to the latest IPCC report, 79% of the global greenhouse gas emissions in 2019 originated from the energy-, industry-, transport- and building sectors (IPCC, 2022). Hence, decreasing the emissions from the energy sector is of great importance, and increasing the share of renewable energy sources is a key to achieve this reduction.

The Swedish energy system consist of a mix of renewable and non-renewable sources, with hydropower and nuclear power accounting for the largest share of production on an annual basis. The rest is made up by wind, cogeneration and solar power. The majority of the installed power capacity is located in the north where consumption is low compared to that of the more southern parts of the country. To promote establishment of new power sources in areas where consumption of electricity is high, Sweden was divided into four electricity price areas, from SE1 in the north to SE4 in the south, in 2011 (Svenska Kraftnät, 2022a).

Historically, the area of SE4 has had a large share of its electricity generation coming from nuclear power as Barsebäck and Oskarshamn's nuclear power plants are located in the region. However, in 1999 and 2005 the reactors of Barsebäck were shut down and later on in 2017 Oskarshamn shut down two out of their three reactors (Strålsäkerhetsmyndigheten, n.d.). As a consequence, expansion of renewable sources and transmission and import of electricity has been increasingly more important for the region as the area does not produce enough electricity to cover its consumption.

In Sweden in the nearby future, a larger share of renewable electricity is projected to be produced to the grid due to up-scaling and expansion of wind power and photovoltaic power, especially in SE4 where there is great potential for off-shore wind. As a result of an increase in intermittent production, a larger volatility in electricity supply as well as consumer electricity prices will be observed throughout the day and year. Additionally, the political situation in the world has created an unstable energy market which highly affects energy availability and electricity prices, especially in a widely connected electricity system such as the system of Europe. This became obvious when Russia invaded Ukraine in early 2022, which caused volatility on the electricity price market. With an increasing expansion of renewable power sources, the volatility seen in electricity prices will most likely remain.

A more volatile electricity market increases the demand for energy storage services and solutions such as large-scale grid storage[1] and frequency balancing to decrease electricity price volatility and ensure security of supply. By implementing a grid-scale storage solution with high capacity, these services can be provided. There are several energy storage technologies available as of today, however, the most promising ones out on the market are associated with high costs or are dependent on the use of rare

[1]Storage in direct connection to the electricity grid.

earth metals. In the light of this, Texel Energy Storage AB has developed a thermochemical energy storage solution.

Texel's storage solution is a battery which stores electricity from the grid as thermal energy. The battery operates by the heat-induced transport and storage of a working gas between two metal- or carbonate hydrides during charge and discharge, where electricity can be derived from the process through the operation of a Stirling engine. The heat not converted into electricity can for example be used as district heating. By making use of both heat and electricity, the efficiency can reach 90%. Texel plans to introduce their solution, with the capacity of 400 MW, in what used to be Öresundsverket in Malmö. The battery will be introduced in three phases, with the first having an electrical effect of 2 MW, the second 50 MW and the final phase 400 MW.

1.1 Purpose, Aim and Research Questions

The purpose of this report is to investigate what effects the implementation of a large scale grid storage solution, such as Texel's thermochemical battery, would have in Malmö when the need for energy storage solutions is growing as intermittent electricity production continue to see a strong increase. Furthermore, the aim is to understand how the energy balance in Malmö's electricity price region will be affected by such a storage solution and the economic viability for a company operating the solution.

To make this analysis possible, data regarding the production, consumption, transmission and price of electricity in the southern part of Sweden have been collected. This coupled with economical and technical data of Texel's thermochemical battery will paint a picture of the possible economic gains as well as services it can supply to the area and its consumers. Using this data, the mismatch of production and consumption will be both graphically and numerically presented which shows the possibility of storage in the area. Further, by analyzing the price of electricity in the area for a year the optimal storage pattern, potential for profit and stability for consumers will be found. Finally, a model will be developed using Excel and Python that interprets the mismatch between production and consumption in relation to the price of electricity to be used by Texel in the future when investigating new sites for their storage solution.

The research questions that form the basis of this report are the following:

- How would the electricity balance in southern Sweden be affected by the implementation of Texel Energy Storage AB's storage solution the year of 2022, 2027 and in a potential future scenario beyond 2030, where the southernmost price region becomes self-sufficient on electricity due to an increase in wind power production?
- What is the economic viability for Texel Energy Storage AB when implementing their storage solution in Malmö the year of 2022, 2027 and in a potential future scenario beyond 2030, where the southernmost price region becomes self-sufficient on electricity due to an increase in wind power production?

1.2 Delimitations

The very time frame of this project has implied some limitations in this report. As energy and electricity systems are complex, taking into account and analysing all factors affecting the energy flows and electricity prices requires a lot more time and resources than this project had.

A delimitation that is related to Texel's solution itself is the disregarding of the potential profit obtainable from heat utilization. In reality, the energy generated as heat could provide additional profitability as well as benefit to the district heating grid. As such, the project has only been investigating the economic viability in relation to the buying and selling of electricity. Other delimitations cover the flows and prices of electricity. When simulating future energy balances in Malmö, analyzing transmission has been neglected, it is instead assumed to follow the regional deficit of electricity. Furthermore, energy flows and prices outside of Malmö's price region have not been analyzed even though these prices and energy transports strongly affect the situation in the Malmö region as the area has grid connections both nationally and internationally. In other words, the market spot price does include the influence and is as such accounted for, but the physical flows outside of SE4 are not further investigated. The results in this report are only based on spot prices on the day-ahead market, and no consideration has been taken to the other markets of electricity when obtaining the results. Moreover, the solutions effect on the market price is neglected, even though this in theory would increase market spot prices when charging and decrease market spot prices when discharging. This is due to the delimitation of not analysing regions outside of SE4.

1.3 Disposition

In Chapter 2 the background information needed for the analysis is provided. It introduces the electricity system in Sweden's southernmost region SE4 including production and consumption, the electricity market, the transmission grid and the use of electricity price areas. This followed by a broad description of energy storage and the most promising technologies as of today, including Texel Energy Storage AB's technology. Chapter 3 explains the methods used to answer the research questions of the thesis. It introduce how, and from where the data was gathered, how the scenarios were determined and the methods used to optimize and simulate the results. In Chapter 4 the obtained data regarding SE4 and the future projected scenarios are presented. Chapter 5 presents the results of the simulation and analysis. This includes the optimal operation of the storage solution, potential for profit and the solution's effect on the electricity system of SE4. Chapter 6 contains a broad discussion about the results, prerequisites for energy storage, the electricity system of SE4, and future outlooks. Lastly, in Chapter 7, conclusions of the report are given along with proposed further research.

2 Background

This chapter provides the background information for the analysis of this report. It explains the current state of Sweden's electricity system including production and consumption, the electricity market system, the transmission grid and the division and use of electricity price areas. It includes a brief description of what influences the need for energy storage and the most promising methods for storage of electricity as of today, among them the proposed solution from Texel Energy Storage AB that is analyzed in the report.

2.1 The Swedish Electricity System

2.1.1 The Year of 2022

In both political and energy aspects, 2022 was an unusual year. The war in Ukraine, starting in February, caused gas prices to reach all time high levels and created an unstable energy market with high electricity prices as one of many consequences. Additionally, the natural gas pipelines Nordstream 1 and 2 were sabotaged which decreased the natural gas supply from Russia to Europe, which caused additional volatility on the gas price market with rippling effects on the electricity market. Due to the international grid connections in the south part of Sweden, and insufficient transmission capacities to the north, SE4 has been the area experiencing the highest electricity prices in the country. Apart from political instabilities in the nearby area during the year, the energy system in Sweden was also strongly affected by a decreased nuclear power production. In August 2022 the nuclear power reactor Ringhals 4 with an installed capacity of 1130 MW (Vattenfall, n.d.) located in Varberg, was taken out of operation due to a damage. The reactor was shut down and not brought into operation until late March 2023 (SVT, 2023). The south price region in Sweden is strongly dependent on transmission of electricity from the region located just north of it (where Ringhals is located), and the decreased power capacity caused by the reactor damage affected electricity prices in Sweden, especially in these two regions.

Statistics

On February 27th 2023, the Swedish Energy Agency published energy statistics for Sweden in 2022. During the year, the domestic production of electricity increased with 1% compared to 2021, while the total consumption decreased with 5%. A decrease was seen throughout the whole year, but was highest from September to November (Energiföretagen, 2022). The top three sectors with the highest consumption was housing and service, followed by mineral extraction and production, and electricity-, gas-, heating- and hydropower plants (Energimyndigheten, 2023). The electricity consumption by sector from 1970 to 2021 is presented in Figure 2.1 below.

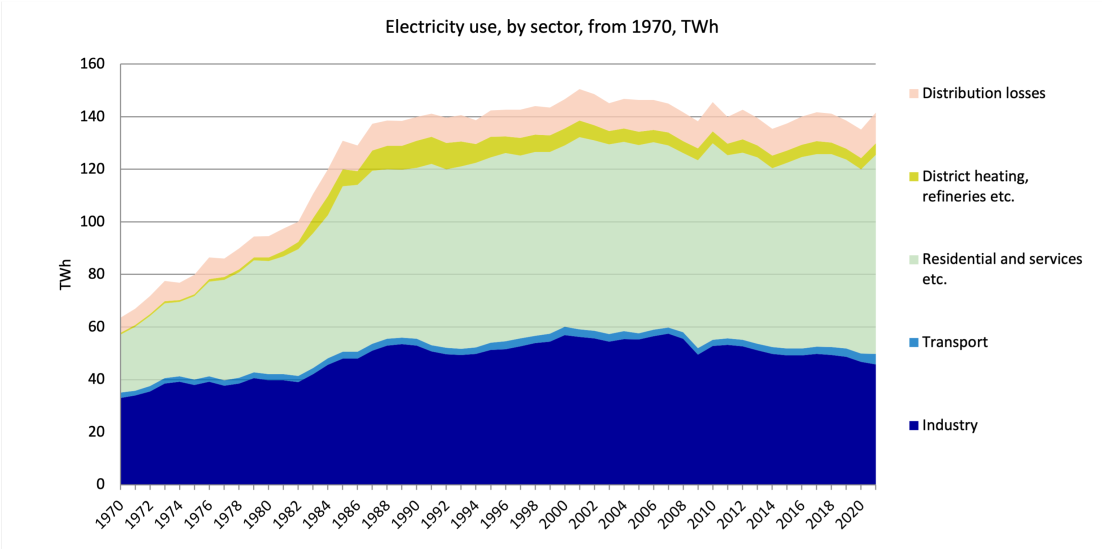

Figure 2.1: Electricity use in Sweden by sector from 1970 to 2021 in TWh. (Swedish Energy Agency and Statistics Sweden, 2023)

In Sweden, consumption of electricity varies depending on season as temperature has a large variability over the year, and an increase is seen during the colder months when there is more need for heating. Consumption also varies nationally, as the largest share of population lives in the middle and south part of Sweden. Therefore, transport of electricity from the north to the south is crucial.

In 2022, the production amounted to 170 TWh and the consumption 137 TWh, resulting in a net export of 33 TWh, which is the highest on record for Sweden and marked the twelfth year in a row with a net export. The total import was 6.2 TWh, which is a 26% decrease compared to that of 2021. Finland was the country Sweden exported most electricity to, while the majority of the import came from Norway. (Energimyndigheten, 2023)

The Swedish electricity production consists of a mix of renewable and non-renewable resources. The production statistics for 2022 by power source are presented in Figure 2.2, based on data from Energimyndigheten, 2023.

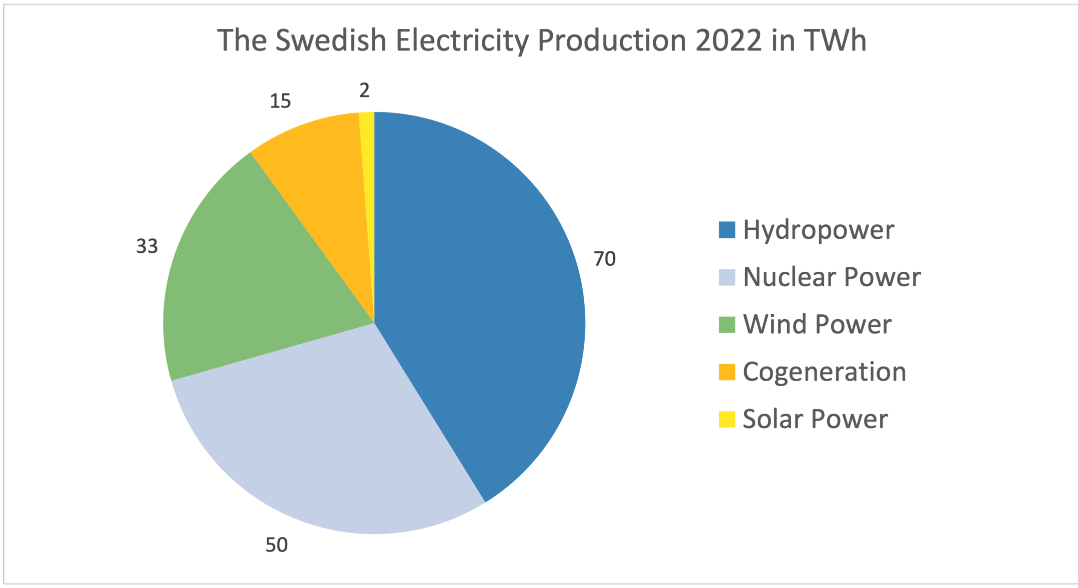

Figure 2.2: The Swedish electricity production by power source in TWh for the year of 2022. (Energimyndigheten, 2023)

The majority of the produced electricity came from hydropower, where the bulk of the production takes place in the north of Sweden. The power source is flexible and plannable, and hence it accounts for an important part of the electricity production as it can help balance the electricity system in times of higher consumption. Availability of water determines its production, and in case of heavy flows production increases. Nuclear power was the second largest electricity producing source in Sweden 2022. The reactors in use are located in the middle part of the country. The third largest share of the electricity production 2022 consisted of wind power, where the majority of the production came from on-shore turbines in the northern parts of Sweden (Energimyndigheten, 2022). Wind power is strongly weather dependent, and production is highest during winter. Cogeneration followed by solar power produced the least share of electricity. Cogeneration is mostly used as a reserve, and solar power has a low production compared to the other sources. Compared to 2021, hydropower production saw a slight decrease. So did nuclear power and cogeneration. Wind and solar power saw an increase, where wind power production increased with 20% and solar power production with 75%. All statistics are summarized and presented in Table 2.1 below.

Table 2.1: Electricity production in Sweden 2022 in TWh by power source. The share of Sweden's total production by source as well as the increase or decrease since 2021 is also presented. (Energimyndigheten, 2023)

Power Source	Hydro	Nuclear	Wind	Cogeneration	Solar
Production 2022 (TWh)	70	50	33	15	2
Share of total production	41%	29%	19%	9%	1%
Increase/Decrease since 2021	-6%	-3%	+20%	-1%	+75%

The South of Sweden - SE4

The trend with increased production and decreased consumption was seen in the southernmost price region (hereby mentioned as SE4) as well. SE4 produced 7.96 TWh during 2022, which is an increase with 0.63 TWh (8.6%) compared to 2021. The region's final consumption 2022 was 21.87 TWh, which is a decrease by 3.0 TWh (12.1%) compared to 2021. A major reason for this is that many households have reviewed their energy consumption (Krisinformation.se, 2023). The electricity production statistics for SE4 2022, including shares of the total production, are presented in Table 2.2. Wind power accounted for the majority of the produced electricity, followed by cogeneration, hydropower and solar power. The least share of the production consisted of unspecified production (Svenska Kraftnät, 2022d). Unspecified production is defined as production and input from cites with several electricity production types, or electricity input from railway services etc (Svenska Kraftnät, 2021a).

Table 2.2: Electricity production in SE4 2022 in TWh by power source. The share of SE4's total production by source is also included. (Svenska Kraftnät, 2022d)

Power Source	Wind	Cogeneration	Hydro	Solar	Unspecified
Production SE4 2022 (TWh)	4.9	1.5	1.0	0.4	0.16
Share of total production in SE4	61.6%	18.8%	12.6%	5.0%	2.0%

2.1.2 The Electricity Market

The Swedish electricity market is operated by Nord Pool. Their aim is to maximize competition within the market, make sure that the electricity is distributed within the price areas as efficiently as possible, and to ensure security of supply to all consumers. Unlike other free markets, the electricity market needs to be monitored so that supply and demand always match.

The electricity market, like all other competitive markets, act on the basis of supply and demand. The demand is determined based on both predictions of the day ahead and real time production and consumption during the day. Producers in the electricity price area auctions the amount of energy they can produce at the lowest cost possible and the transmission system operator (TSO) accept the highest bid that meets the demand, setting the price for electricity on the market. Further, due to the presence of a transmission grid, the TSO can make sure that the demand is met throughout the system regardless of the production in a given electricity price area. This also affects the price since transmission leads to additional expenses (Svenska Kraftnät, 2021b). A supply and demand curve for the electricity market is presented in Figure 2.3 below, where CHP refers to cogeneration plants. The price of electricity is found as the intersection of supply and demand for a given hour.

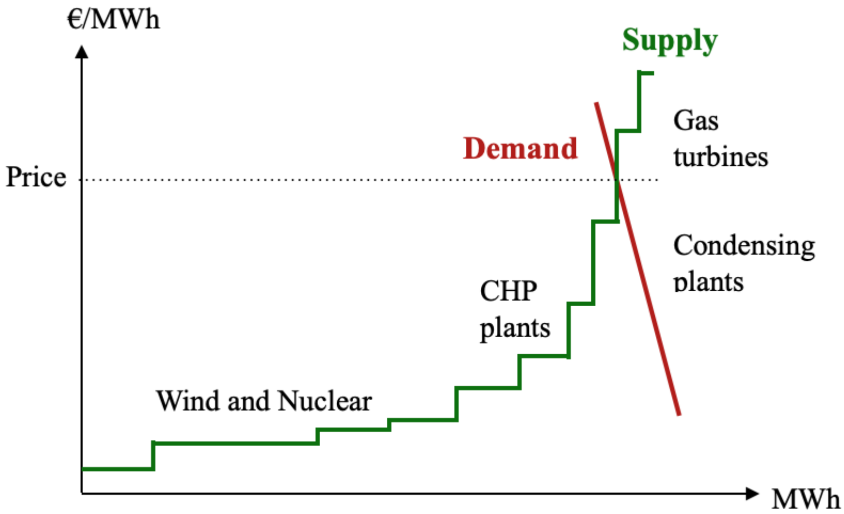

Figure 2.3: Supply and demand curve for the Nordic and Baltic electricity market Nord Pool.

Electricity in the grid is in the form of alternating current (AC) and is always moving in a certain frequency which is determined by the amount of electricity in it. In Sweden, the frequency of the grid needs to be maintained at 50 ± 0.1 Hz to operate. If the frequency drops below or above this specific value, more power capacity is needed to avoid system failure – this is called balancing (Svenska Kraftnät, 2023b). Due to this, the consumption of electricity needs to be predicted in advance so that the right amount of electricity can be bought to maintain the balance. This is regulated through three main markets of electricity.

Day-Ahead Market

On the day-ahead market the largest portion of electricity is traded. It is operated through a blind auction, which means no sellers of electricity knows the bids of other sellers. This auction takes place once a day, every day throughout the year, where electricity is bought for the 24 hours of the following day. Based on predictions of consumption and the buy-orders, the TSO establishes a demand curve, and based on the sell-orders they establish a supply curve, with the help of an algorithm, for each hour of the day. The price of electricity is then determined by the highest sell-order accepted that meets the demand of each hour (Nord Pool, 2020a).

Intraday Market

The intraday market handles much smaller volumes than the day-ahead market, but makes sure the system is in balance with the hourly variations not accounted for by the day ahead predictions. On the intraday market participants trade continuously with delivery the following hour, with electricity being traded as close to as 5 minutes before the delivery hour. This allows for a higher flexibility which can help mitigate the mismatch between consumption and production closer to real time (Nord Pool, 2020b).

Balancing Market

On the balancing market, ancillary services are sold and bought such as frequency control and voltage control to maintain the stability of the electricity system. This is electricity that usually is produced from high inertial sources and is usually not sold on other markets, as for example electricity from gas turbines (Mazzi and Pinson, 2017).

2.1.3 Electricity Price Areas

Sweden is divided into four electricity price areas ranging from Luleå SE1 in the north down to Malmö SE4 in the south, see Figure 2.4. The price within each area is determined by the production, consumption and transmission to and from that area. In Sweden, most of the electricity is produced in the northern parts, mainly due to the vast capacity of hydropower, while the largest consumption occurs in the southern parts. This leads to a large amount of electricity being delivered from the northern areas down south. Division into electricity price areas was made to promote new production in areas with a large consumption, such as SE4 and SE3, and to encourage heavy energy consumers to establish their operations up north where electricity is cheaper and more available. (Svenska Kraftnät, 2022a)

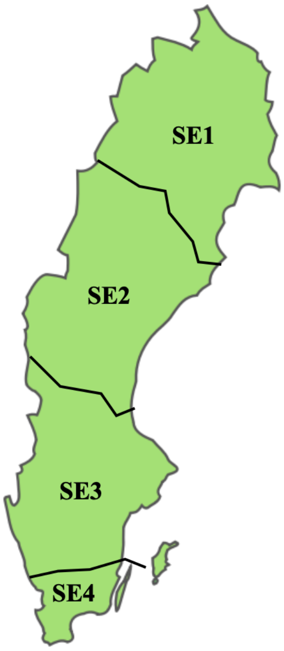

Figure 2.4: Map of the division of the four electricity price areas in Sweden as of 2022.

2.1.4 The Transmission Grid

The national electricity grid in Sweden is maintained by Svenska Kraftnät (SvK) and consists of around 17 000 kilometres of power lines, including about 200 switching stations and substations, with connections to 16 other countries. When the physical transmission grid cannot transfer the amount of electricity that the market requires, bottlenecks in the system arise.

Sweden is a net exporter of electricity with connections to Finland, Norway, Denmark, Lithuania, Poland and Germany. The southernmost price region SE4 has connections and exports a large portion to Denmark, Lithuania, Germany and Poland. With the exception of Denmark, the electricity production of these countries is much less intermittent than that of SE4. Due to the market being competitive, electricity flows to the place where it is most valuable, as long as there is capacity in the grid. As a result of this, the export to Lithuania, Germany and Poland usually operates at max capacity or not at all. In contrast, the transmission to and from Denmark is much more variable due to the intermittency in their production.

2.2 Energy Storage

Energy storage refers to a variety of solutions that capture energy produced at one time for use later on to reduce imbalances between demand and supply. The principle of storage is presented in Figure 2.5, illustrating the process of storing electricity when prices are low (blue areas) and outtake when prices are high (green areas). Furthermore, the aim is to decrease the electricity price peaks, at the expense of increasing the bottoms, creating a more even price curve which is shown in red. Under the condition that prices reflect the deficit within a region, the storage process based on price will help even out the energy balance.

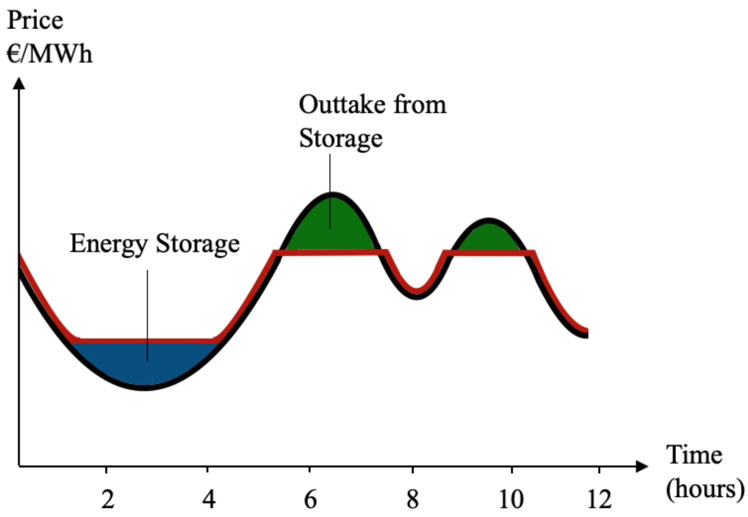

Figure 2.5: The principle of energy storage with storage and outtake at different prices over a 12 hour time period.

Energy storage is especially important in the electricity system since, as previously mentioned, electricity is always in motion and has to be kept at a certain voltage and frequency. With more renewable electricity production being introduced into the Swedish system, maintaining the frequency and voltage is becoming more difficult as the most used renewable production types solar and wind vary greatly in their supply throughout the day, week and year. This does not only cause problems with voltage and frequency, but also affects price volatility and security of supply to consumers. The margins in the systems are becoming smaller, and prices are becoming more fluctuating, leading to higher and more frequent peak prices. To counteract the growing instability caused by the increasing renewable production – storage solutions are needed.

There exist many different types of energy storage solutions that differ in their scalablility, response time as well as rate of delivery. To obtain a fully renewable electricity system, large scale grid storage solutions are needed to help mitigate the intermittency of production, as well as storage at smaller scales with a fast response time that can help reduce smaller imbalances at shorter timescales. In addition, long-term storage will be needed to help mitigate the seasonal variations. The sections below will provide an overview of the current most promising energy storage solutions, as well as Texel Energy Storage AB's solution that is analyzed in this report. In addition, it will provide a comparison between their relevant characteristics.

2.2.1 Pumped Hydro-, Hydrogen- and Battery Storage

Pumped hydro is a storage solution that is comparable to conventional hydro power, and is today the most widespread technology for storage of energy, amounting to 94% of the global installed storage capacity in 2018 (IHA, 2018). Instead of using run-off from one or many catchment areas to supply the turbine with water and generate power, it uses excess electricity to pump water from one reservoir to another to be used for later peak electricity demand. The round-trip efficiency of pumped hydro is generally around 70-85% with losses mainly originating from hydraulic losses due to friction during pumping (Rehman et al., 2015).

Storage through electrolysis of water into hydrogen is today one of the most promising methods of storing electrical energy. The main reason is due to the possibility of it being completely carbon neutral in its process and the many functions of hydrogen as an energy source. Using an electrolyzer with an efficiency of 90% in combination with a power plant converting it back into electricity using a fuel cell with an efficiency of 60%, the overall efficiency becomes 54% excluding losses in storage and transportation (Breeze, 2018).

Batteries are the most scalable grid storage solution and has seen a strong market growth in recent years. As of today, based on cost and energy density, lithium-ion batteries are the preferred choice of grid-scale battery storage, specifically lithium iron phosphate batteries (IEA, 2022). Lithium-ion batteries have a high round-trip efficiency, electricity to electricity, of about 92%, however, costs are still high which limits their application for grid storage (Han et al., 2023).

2.2.2 Texel Energy Storage AB's Solution

The storage system developed by Texel Energy Storage AB is a thermochemical energy storage system (TCES) combined with a Stirling engine, illustrated in Figure 2.6. The solution does not contain any heavy metals or rare earth metals and is almost 100% recyclable. The storage capacity of the Texel battery is adaptable to the implementation, and in this analysis a storage capacity of 450 kWh and 900 kWh have been used. The 450 kWh storage capacity unit is related to a 6 hour operation at full effect, and the 900 kWh storage capacity unit is related to a 12 hour operation at full effect, hereafter referred to as the 6- and 12 hour storage units. The Stirling output delivers up to 30 kW electric power, and as of today, the solution can only charge and discharge at maximum electrical effect. To increase the storage capacity and energy output, multiple storage units can be connected. The scalability of the solution therefore allows for numerous applications – from small scale household storage to large scale grid solutions with outputs of hundreds of megawatt hours. The system allows for long storage duration, with the possibility to store energy with minimum losses. According to Texel, in comparison to other thermal storage solutions, the Texel battery has a high energy density – up to 20-40 times higher compared to molten salt for example.

The capital cost (CAPEX) of Texel's solution differs if the solution has a 6 or 12 hour storage capacity, so does the operational costs (OPEX). According to Texel, the solution that will be implemented in Malmö has a CAPEX of $104 330 and an OPEX of $34 600 for the 12 hour storage capacity unit and for the 6 hour storage capacity unit a CAPEX of $44 220 and OPEX of $16 800. The OPEX is defined as the total maintenance cost for the operational lifetime, and does not include the cost of electricity. The costs related to the three phases proposed for the site are presented in Table 2.3, converted from US dollars to Euros. Further, according to Texel, the predicted levelized cost of storage (LCOS) with the metal hydride technology, defined as CAPEX + OPEX divided by the output of energy, can be as low as $0.0198/kWh for the Texel solution when not considering heat utilization. The economical data is based on a production of 100 000 units each year and an operational lifetime of 40 years (McWhorter, 2020).

Table 2.3: CAPEX and OPEX for the different phases and storage capacities, presented in million Euros.

	Phase 1		**Phase 2**		**Phase 3**	
Storage Capacity	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**
CAPEX (MEUR)	2.683	6.329	67.07	158.2	536.5	1266
OPEX (MEUR)	1.019	2.099	25.48	52.48	203.8	419.8
Total (MEUR)	3.702	8.428	92.55	210.7	740.4	1686

The Texel storage system operates by the transfer of a working gas between two metal hydride or metal carbonate beds. In the metal hydride system, the working gas is hydrogen, while in the metal carbonate one it is carbon dioxide. The process described in this section, and the one used in the analysis of this work, is for the metal hydride system, but the process is similar for the metal carbonate one. When using metal carbonates, the system has a lower equilibrium pressure, and a pressurized gas tank replaces the low temperature metal hydride (LTMH).

In the metal hydride system, the high temperature metal hydride (HTMH) contains a bed that has a high enthalpy and an equilibrium pressure of $\leq$60 bar at the desired temperature of operation. The LTMH consists of a low enthalpy bed, operating at a lower temperature compared to the HTMH at an equal equilibrium pressure. The metal hydride material's equilibrium pressure is the pressure at which the uptake (exothermic) and release (endothermic) of hydrogen is equal. A reversible metal hydride's equilibrium pressure is elevated with an increase in temperature and decreased with a reduced temperature.

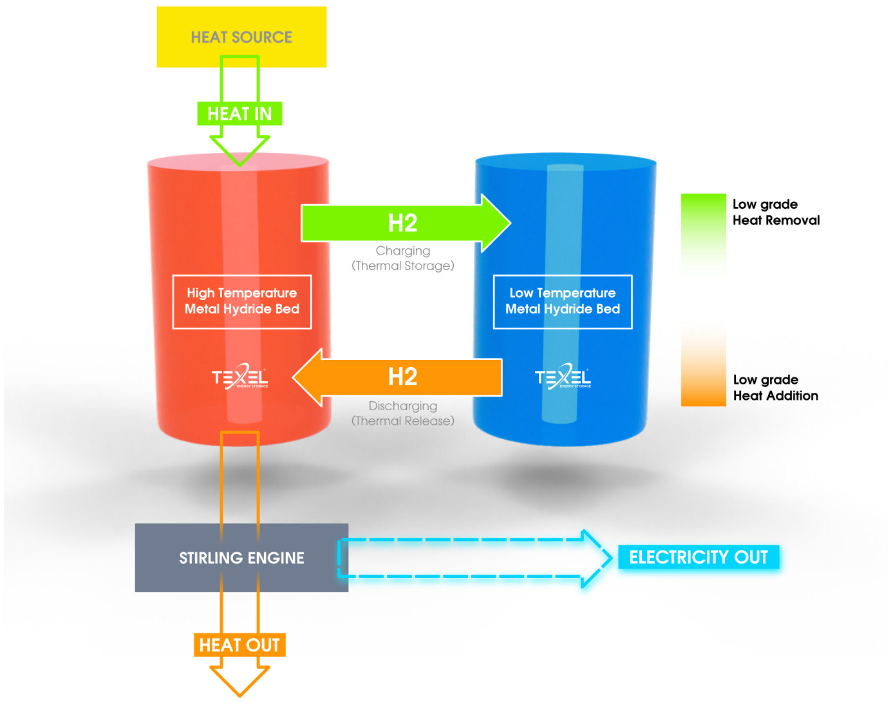

Figure 2.6: A schematic illustration of the Texel energy storage solution with hydrogen as working gas.

The energy storing process is illustrated in Figure 2.6, and starts with an addition of heat to the HTMH bed, causing a hydrogen release from the material. The temperature will then rise, making the system pressure increase above the LTMH material's equilibrium pressure, a process which causes the released hydrogen to react with the LTMH. Hence, the thermal energy is stored in the chemical bonds between the hydrogen and the LTMH material. To maintain the lower temperature and equilibrium pressure in the LTMH bed, the low grade heat produced in the material is rejected. The release of the stored energy starts when the LTMH bed's temperature is increased, making the working gas release and react with the HTMH material. The large enthalpy of the reaction generates a large amount of heat which is fed into the Stirling engine to receive electricity. 40% of the total energy output is electricity, but when using a combined heat and power application, the overall efficiency can reach 90% if the generated heat through the cooling loop in the Stirling engine is utilized.

Different storage solutions provide different services to the grid. Some have a fast response time and some are able to store energy for longer periods of time. To put this in to perspective, a table has been made that presents the round-trip efficiency, response time and typical time scale of storage for the presented storage technologies, see Table 2.4.

Table 2.4: Promising grid storage technologies of today, including Texel's technology, with their round-trip efficiency, response time and typical time scale of storage.

Storage Technology	**Pumped Hydro**	**Hydrogen**	**Battery**	**Texel**
Round-trip Efficiency	70-85%[1]	54%[2]	92% [3]	40%
Response Time	Minutes[4]	Minutes[5]	Seconds[6]	Hours
Typical Time Scale	Minutes - Seasonal	Minutes - Seasonal	Seconds - Hours	Hours - Seasonal
References	[1] Rehman et al., 2015 [2] Breeze, 2018 [3] Han et al., 2023 [4] EERA, 2016 [5] Andrzej and Daniel, 2019 [6] Koltermann et al., 2023			

In comparison to the other solutions, the one developed by Texel has a lower round-trip efficiency from electricity to electricity and a slower response time. However, if the heat from the loop is utilized, it reaches an efficiency of 90% which competes with the lithium-ion battery. In addition, it provides the possibility to store on a seasonal scale due to the minimal losses during storage.

3 Methods

This chapter will provide a description of the methodologies used to obtain the results of this report. Firstly, the choice of spot price as a basis for operating the Texel solution will be described, followed by an explanation of the scenarios used in the analysis and why these were chosen. Furthermore, the data gathering process will be outlined as well as a description of the working process of developing a model as well as parameters for obtaining the optimal operation of Texel's solution. Lastly, the calculations for obtaining the results will be given.

3.1 Spot Price as a Basis for Storage Operation

A storage solution operating on the electricity market earns profit on what is called arbitrage. In other words, it buys electricity when the market price is low and sells electricity when the market price is high. Currently, no extra incentive is given for a storage solution of Texel's response time to aid the grid with stability. Therefore, the economic viability is only defined by the arbitrage. However, with enough variations between peak- and off-peak prices there is a substantial potential for profit. The price of an electricity region should correlate with the electricity balance, meaning that a low market price corresponds to high availability of electricity and a high market price to low availability of electricity. Essentially, a solution withdrawing electricity from the grid at times of low market price and inserting it at times of high market price, should aid the grid in mitigating the discrepancy of production and consumption while gaining profit. As such, the decision was made to use the market spot price of electricity as a basis for operation with the aim to maximize the arbitrage for the period analyzed.

3.2 Development of Scenarios

One of the research questions asked to investigate what the impact would be if the Texel thermochemical battery was implemented in SE4 in 2022, 2027 and in a future scenario beyond 2030 with a much higher production of wind power. To answer this, data regarding the 2022 electricity system needed to be found, and then used to make projections for the future systems. The reason for development of these future scenarios was mainly due to the trend of an increasingly intermittent electricity system. This due to the up-scaling of wind- and solar power in Sweden, which most probably will affect the market price of electricity, hence affecting the operation of the Texel solution. In addition, the storage solution is expected to operate for 40 years, which makes the future profitability as important as the current profitability for the analysis.

The Texel storage solution operates on the hour, meaning that the future hourly data needed to be estimated regarding production, consumption and spot price to find the optimal operation for maximizing profit as well as determining the effect on the electricity balance in the region. Projecting a future electricity system is difficult, but with a sufficient amount of information in combination with assumptions, the future scenarios could be established. These scenarios were not developed to predict the consumption, production or price of a certain hour, but rather to find the general trend. If the consumption were to increase more than the production, it is reasonable to assume that the spot price on the market would increase as a consequence. With the aim of maximizing profit, the storage solution will buy electricity when the market price is low, and sell electricity when it is high. Therefore the trend in market price and, more importantly, its variation throughout the year was needed.

The process used to find an estimation of the hourly consumption, production and market price for 2027 will be explained in detail in Section 4.2. In short, an estimation of the electricity balance, based on the projected increase in capacity of power production sources, was developed. This was then used to find the excess or deficit of electricity in the system for each hour which was then applied on the data of 2022 to find the hourly market price of electricity. With a higher capacity of intermittent power sources, this method of projecting yields a larger variation between peak- and off-peak prices, due to an increased mismatch of production and consumption. As for example, when wind speeds are high, production of electricity from wind will drive prices down and vice versa when wind speeds are low.

To find an estimation of the hourly consumption, production and market price beyond 2030, the same process of extrapolation was used. However, this scenario assumes that the annual residual deficit of electricity is zero, i.e. that the region is self suppliant on electricity on a yearly basis. For this to be possible, a large increase in production is needed, which was assumed to be covered by an expansion of wind power, mainly off-shore. How this scenario was developed is explained in detail in Section 4.3. As for the scenario of 2027, this resulted in the hourly production of wind being a precursor for the market price, with periods of low wind seeing amplified peak prices, and periods of high wind seeing reduced off-peak prices.

3.3 Gathering of Data

The data gathering process started out with an examination of public data sources containing information about the Swedish power system for the year of 2022. The data of interest was the hourly electricity production from different power sources in SE4, the consumption, the transmission as well as market prices of electricity.

Production and consumption data were gathered from SvK, including profile settlement losses and consumption. Transmission data were gathered from ENTSO-E and includes the hourly transmission to and from SE4. Market prices of electricity in Euros were extracted from eSett and compared to spot prices from SvK in Swedish Kronor (SEK) to verify the data. Furthermore the data were put together to obtain the total hourly consumption, production, transmission and an electricity balance in SE4 for 2022.

Statistics and data regarding the Swedish power system as a whole and the energy situation the year of 2022 as well as statistics for SE4 specifically were collected from the Swedish Energy Agency. Installed capacities for all different power sources within the price region, except from solar power, were gathered from SvK's short term market analysis 2022 (Svenska Kraftnät, 2022b). The solar power data was found in SvK's power balance report for the Swedish electricity market 2022 (Svenska Kraftnät, 2022c). In order to simulate the future scenarios in SE4, the projected installed capacities as well as the consumption for the year of 2027 were needed. This data was also found in SvK's short term market analysis 2022.

Data relating to Texel's storage technology was provided by Texel through a public report published at Savannah River National Laboratory in the U.S (McWhorter, 2020).

3.4 Data Processing and Optimization

The Texel solution can only charge and discharge at its maximum electrical effect, which means that the battery for a specific hour can choose between one of three actions; to charge, to discharge, or to do nothing. The exception is hours of replete storage where charging is not an option, and hours of deplete storage where discharging is not an option. When discharging, due to the round trip efficiency, the solution will insert 40% of the electricity it consumed during charging to the grid and get paid according to the hourly price. Depending on the storage capacity used, it can be charged a total of 6 or 12 hours before it needs to discharge in order to continue its operation. With these physical constraints a model using an algorithm to simulate the maximum arbitrage from a period with hourly price data was developed. This algorithm was formulated in Python and utilizes the concept of dynamic programming which is a method of mathematical optimization. The algorithm looks at one hour with a specific storage level and decides what the best outcome is, with the aim of maximizing profit, based on all the actions available. This decision is made by looking at the previous hour with a specific storage level, 0 to 6 or 0 to 12, depending on the storage capacity unit used. For example, to figure out what the profit would be if the decision is to discharge, the algorithm will take the total profit up until the previous hour with one higher storage level and add the additional profit made if you discharge at the current hour. To get the best outcome, the algorithm will then compare all three actions available for the specific hour. Once the algorithm has reached the end, it will return the maximum profit obtainable at each storage level for every hour that is simulated. The maximum profit for the period will then be the maximum profit found at the final hour with a depleted storage, i.e. a storage level of 0. The complete code is presented in Appendix A

Along with the profit such as arbitrage, which is calculated using Equation 3.1 below, and the physical effect on the electricity balance, a few economical results were of interest to be found.

$$\text{Arbitrage} = \sum (p(t_{discharge}) \cdot \text{Discharge Effect} - p(t_{charge}) \cdot \text{Charge Effect}) \qquad (3.1)$$

Where $p(t_{discharge})$ is the spot price of the hour discharging was performed, and $p(t_{charge})$ is the price of the hour where charging was performed. Again, it should be noted that the discharge effect always is 2.5 times lower than the charge effect due to the round trip efficiency of 40%, which means that $\text{p}(\text{t}_{discharge})$ needs to be at least 2.5 times higher on average for the arbitrage to be positive.

The economical data were gathered from a techno-economic analysis conducted by Texel together with Savannah River National Laboratory that presented CAPEX and OPEX of a single storage unit during its entire lifetime of 40 years (McWhorter, 2020). It is essential to note that the cost data calculated by Savannah River National Laboratory mentioned above does not account for several important project economics including tax incentives, reductions in CAPEX and OPEX due to technological advancements, salvage money at the end of project and time value of money such as escalators and discount rate (Johnson and Arizona State University, 2021). The CAPEX and OPEX of every phase were calculated, and later used to find results such as net profit, levelized cost of storage and payback time. The net profit is defined as the gross profit, or arbitrage, of operating a year subtracted by the yearly cost where the yearly cost is calculated as the lifetime cost (OPEX + CAPEX) divided by the lifetime in years. See Equation 3.2 below.

$$\text{Net Profit} = \text{Arbitrage} - \text{Yearly Costs} \tag{3.2}$$

The LCOS is defined as the cost of storing and delivering one unit of electricity, and is calculated according to Equation 3.3 below. The delivered or stored electricity is defined as the results from operating a year according to the model constraints, and the yearly cost is again the sum of operational cost for the year and the capital cost divided by the lifetime. When determining the LCOS, the cost of electricity is not included, this is because it varies throughout the year based on the market price. As such, the LCOS is the minimum cost related to storing and delivering one unit of electricity which in reality should include the cost of that specific unit of electricity during charging.

$$\text{LCOS} = \frac{\text{Yearly Cost}}{\text{Yearly Delivered Electricity}} \tag{3.3}$$

The payback time is defined as the time it takes to earn back the CAPEX of implementing the solution. The OPEX are those of a year, and the arbitrage or gross profit is the profit earned from buying and selling electricity a specific year. The payback time is calculated according to Equation 3.4 below.

$$\text{Payback Time} = \frac{\text{CAPEX}}{\text{Arbitrage} - \text{OPEX}} \tag{3.4}$$

It should be noted that the results from the equation assumes that the future annual profit would be the same for each consecutive year following the one that is analyzed up until the initial cost is payed off.

Since the model only analyses and gives results for a specific year, no discount rate is used since it does not analyze the profit of future years. As such, a simplification is made that the capital costs are constant for each year and is not subject to inflation, and the LCOS is only given for a specific year.

4 SE4's Electricity System: Current State and Future Projections

To obtain the results of this report an analysis of the electricity system in Sweden's southernmost electricity region SE4 has been performed and will be presented in this chapter. First, in Section 4.1, the data for the year 2022 is presented, including consumption, production, transmission, the electricity balance and prices of electricity. In Section 4.2, projected data for 2027 is presented which was extrapolated from the data of 2022. Lastly, in Section 4.3, the future projected scenario beyond 2030 is presented and explained.

4.1 The Electricity System of SE4 in 2022

This section provides an explanation of the data gathered for the year 2022, along with several graphical illustrations. The year 2022 is used since it is the most recent full year up until this report is written and published.

4.1.1 Consumption

Since Sweden is divided into four price regions the potential storage and economical profit is also unique for each region. The consumption data is divided into five subcategories which are,

- Hourly measured consumption
- Hourly measured losses
- Standardized delivery consumption
- Standardized delivery losses
- Hourly measured consumption <50 MW

These together make up the final consumption of SE4. Standardized delivery consumption and delivery losses refer to the allocation of consumption and losses of user areas based on their consumption profiles, where direct measurements are not possible. This allocation is linear which means that every hour of the month is distributed according to the same percentage which theoretically leads to a slight underestimation of losses (Svenska Kraftnät, 2021a).

Sweden see vast variations in climate from season to season, with temperatures ranging from 0° in winter to 19° in summer on average (Moberg, 2022). This leads to a significantly higher consumption in winter due to higher amounts of heating. This trend is further amplified due to some heavy industries close operations during summertime, which lowers consumption in summer even more. The daily consumption also varies greatly. Generally, the consumption is higher during daytime than nighttime, since most people sleep at these hours and many facilities pause operations. On average during 2022, SE4 consumed about 2500 MWh of electricity each hour, with a peak hourly consumption of 4289 MWh, and a minimum hourly consumption of 1356 MWh. The total electricity consumption in 2022 was 21.87 TWh. The distribution of consumption throughout the year is presented in Figure 4.1.

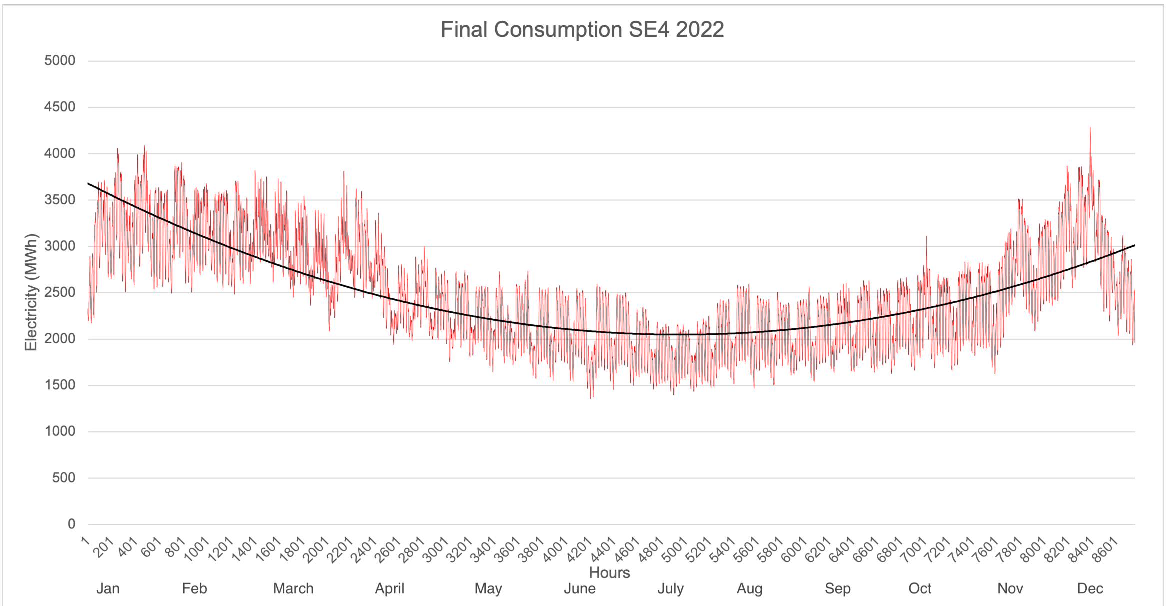

Figure 4.1: Final hourly consumption in SE4 for 2022. The black line in the middle is a trend line to show the seasonal variations in consumption.

From the graph, daily and seasonal variations in consumption becomes clear, ranging from an average consumption of 3000 MWh per hour in the winter and 2200 MWh per hour in the summer.

4.1.2 Production

In SE4, as mentioned in the background, the majority of the electricity produced in 2022 came from wind power (both on- and offshore) followed by cogeneration, hydropower, solar power and unspecified production. The installed capacities, the total installed capacity and the yearly production for the different power sources in SE4 are presented in Table 4.1. Unspecified production is not included.

Table 4.1: Installed power capacities (MW) and their yearly production (TWh) in SE4 2022. Unspecified production is excluded.

Power Source	**Wind**	**Cogeneration**	**Solar**	**Hydro**	**Total**
Installed Capacity (MW)	2180	760	372	240	3552
Production (TWh)	4.92	1.45	0.36	1.01	7.74

Solar Power

Power sources see variability in production pattern, especially those that are strongly dependent on weather and season. Solar power has a large intraday variability, but is also strongly dependent on season. Peak electricity generation is seen during the day and the summer months due to higher insolation. An example of the intraday variablities can be seen in Figure 4.2, where the solar electricity production a typical cloudy winter and sunny summer day in SE4 2022 is shown.

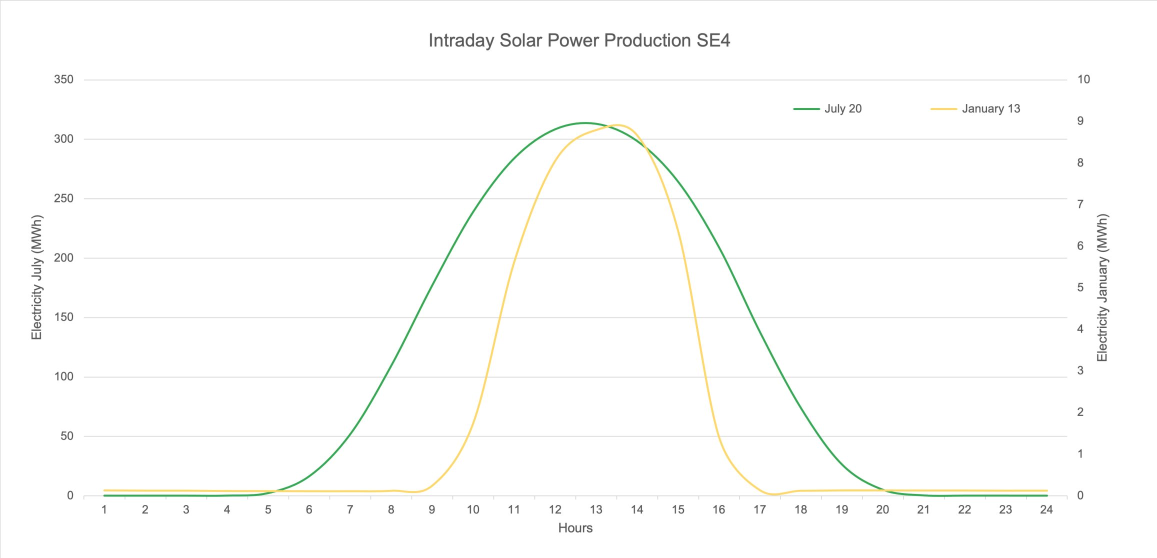

Figure 4.2: Hourly solar power production in SE4 a typical winter and summer day 2022. The yellow line represents the production January 13th (right axis), and the green line July 20th (left axis).

The peak hourly production during January 13th was 8.8 MW while the peak production on July 20th reached 313 MWh, which shows the major seasonal variations for this production type. To further show the intermittency, the annual solar production in SE4 2022 is displayed in Figure 4.3.

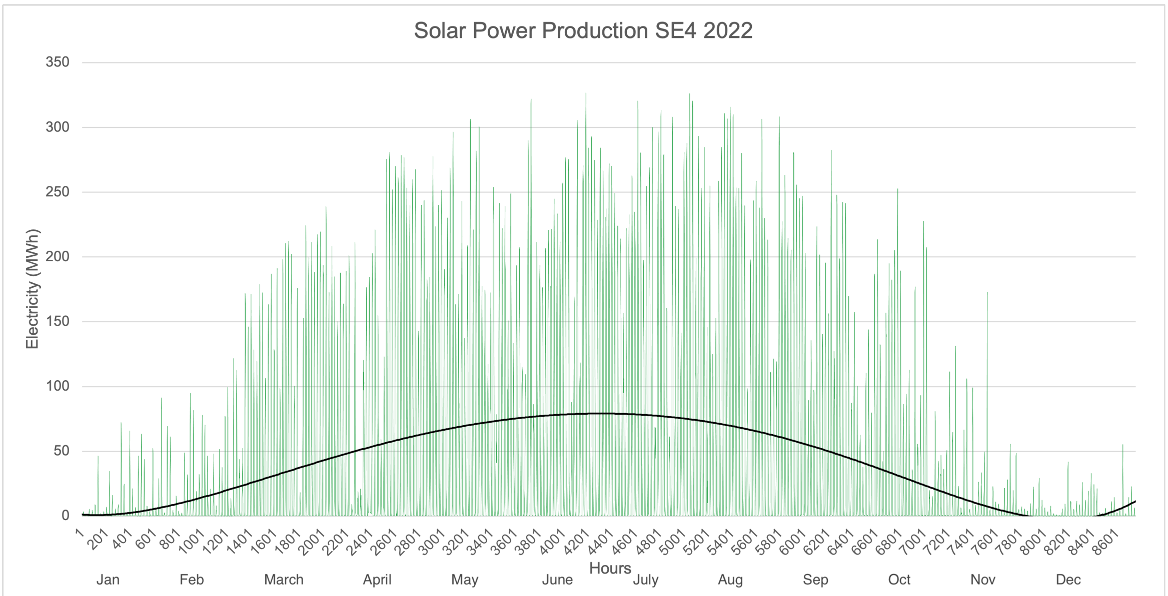

Figure 4.3: Hourly solar power production in SE4 2022. The highest electricity production is seen during the summer months.

These two figures point to that both intraday- and yearly variations in solar radiation will heavily affect the availability of electricity, especially when the installation of solar power see an increase.

Wind Power

Wind power is an intermittent power source, meaning that it only produce electricity when there is wind energy available for harvest. In Sweden, October to March are the windiest months while May to August generally have the least wind (SMHI, 2022). In Table 4.1 it was seen that there were a total of 2180 MW installed wind capacity in SE4 as of 2022. Approximately 92.2% of this capacity is onshore wind plants, and 7.8% offshore (Svenska Kraftnät, 2022b). The hourly wind production pattern in SE4 over the year is displayed in Figure 4.4, and the trend line shows a higher production in January and February and a lower production in the beginning of the summer. This also shows the large variations that arise from periods of more or less wind, resulting in weeks or days of high production and weeks or days of low production. The maximum hourly wind production in SE4 during 2022 reached 1757 MWh/h on December 31st.

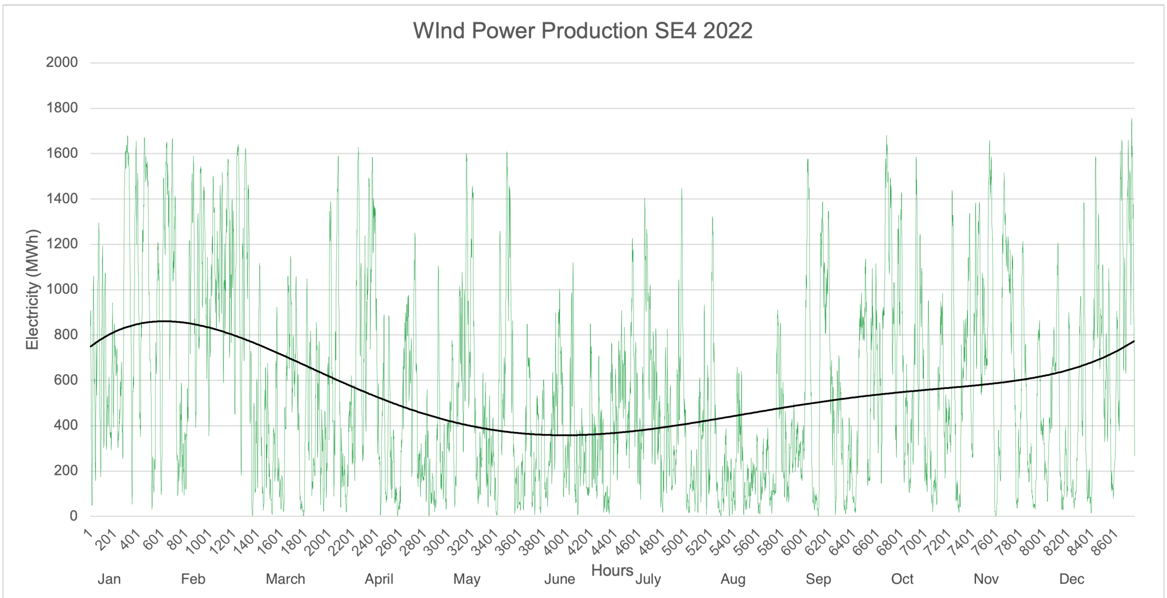

Figure 4.4: Hourly wind power production in SE4 2022. The trend line illustrates the seasonal variability of the power source.

Cogeneration

Cogeneration is combined heat and power, and in SE4 during 2022 it accounted for the third largest installed capacity, seen in Table 4.1. The power source can, as mentioned, serve as flexible and plannable, and is therefore an important resource in case of events with electricity imbalance and frequency drops on the grid. The cogeneration production in SE4 in 2022 is displayed in Figure 4.5, and was highest during the winter months. The trend line shows a peak production in the end of the year, and a lower production during the summer months.

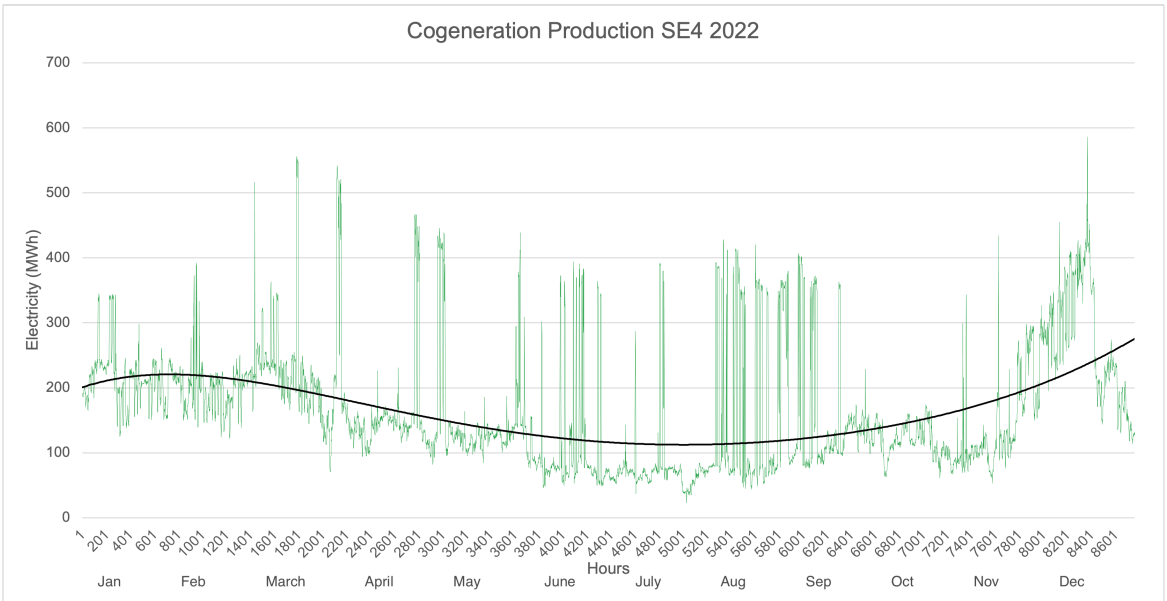

Figure 4.5: Hourly cogeneration production in SE4 2022. The trend line illustrates the variability of the power source over the year.

In the figure, some hours show a huge peak in production which has not been analysed but might be due to drops in frequency that needs to be mitigated through additional supply from gas turbines or similar technologies. These peaks mostly occurred in August which coincides with the shutdown of the Ringhals 4 reactor and a period of low wind production.

Hydropower

As seen in Table 4.1, there is a total of 240 MW installed hydropower capacity in SE4 as of 2022, which amounted to 12.8% of the produced electricity in the region. The hourly 2022 production in SE4 can be seen in Figure 4.6, with a maximum hourly production of 281 MWh.

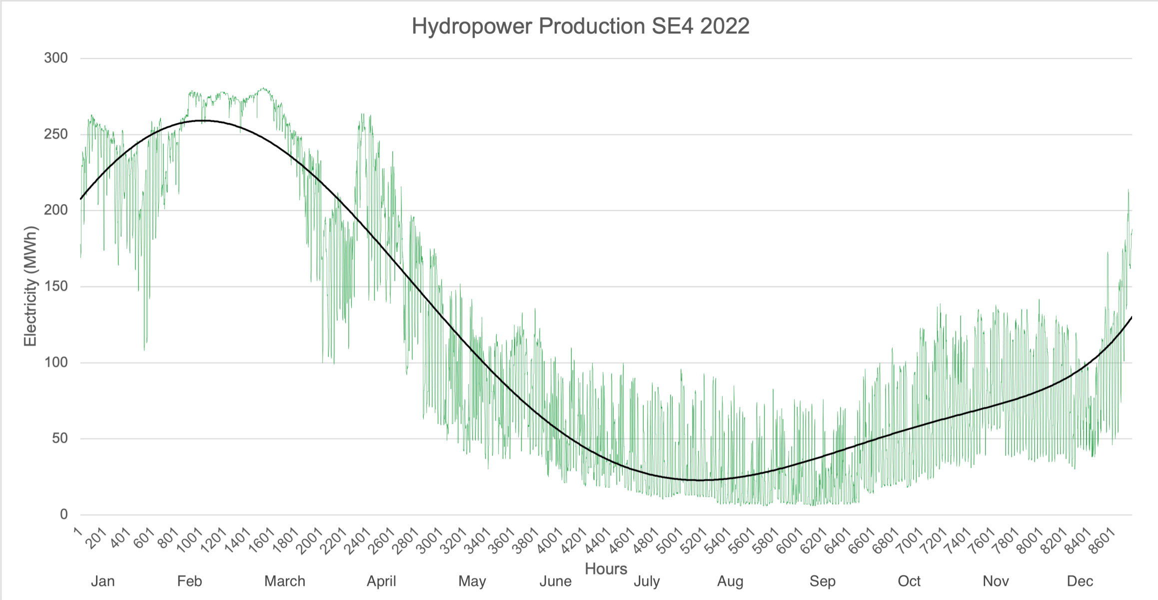

Figure 4.6: Hourly hydropower production in SE4 2022. The trend line illustrates the variability of the power source over the year.

The production reaches its peak in the beginning of the year, and contributes least during the summer months when the demand of electricity is lower. This is to refill the reservoirs with water to increase supply when the demand starts to increase in winter.

4.1.3 Transmission

In SE4, transmission to the region plays a crucial role as the region's own production is not sufficient to cover its consumption. There are physical restrictions for grid capacity when transferring electricity. Maximum transmission capacities for SE4, the percentage of grid utilization as well as the total import and export during 2022 are presented in Table 4.2 and 4.3 below. It should be noted that the utilization is based on a comparison between the actual utilization (MW) of the connections during 2022 and the theoretical maximum transmission possible during every hour of the year. Table 4.2 shows the maximum import capacities to SE4, and Table 4.3 shows the export capacities.

Table 4.2: Maximum import capacities to SE4, the percentage of utilization of the connections as well as the total import 2022 in TWh.

Import	**SE3 → SE4**	**DK → SE4**	**DE → SE4**	**PL → SE4**	**LT → SE4**
Max Capacity (MW)	6200	1700	600	600	700
Utilization 2022	57.2%	3.57%	1.77%	2.11%	0.634%
Total Import 2022 (TWh)	31	0.53	0.093	0.11	0.039

Table 4.3: Maximum export capacities from SE4, the percentage of utilization of the connections as well as the total export 2022 in TWh.

Export	**SE4 → SE3**	**SE4 → DK**	**SE4 → DE**	**SE4 → PL**	**SE4 → LT**
Max Capacity (MW)	2800	1300	615	600	735
Utilization 2022	0.091%	52.7%	58.8%	74.2%	78.8%
Total Export 2022 (TWh)	0.22	6.0	3.17	3.90	5.07

As can be seen in Table 4.2, the connection from SE3 to SE4 has the highest transmission capacity among the import connections, followed by Denmark, Lithuania, Germany and Poland. The utilization was highest for the transmission from SE3 to SE4, but only to 57.2% of its maximum capacity. The remaining connections were utilized to a very small extent. The by far largest import of 31 TWh, accounting for the majority of the imported electricity, came from SE3. This number is much greater than the consumption of 21.87 TWh within SE4 (see Section 4.1.1). Due to the fact that SE4 exports a great amount of electricity to nearby countries, and not only electricity from the region's own production, it points to the role of SE4 as a transmission gate out to Europe.

SE4's largest export connection capacity from the region is the connection to SE3 followed by Denmark, Lithuania, Germany and Poland in descending order. Utilization was highest for the connection to Lithuania (78.8%). Usage of the export connections were >50% for all except for SE3, see Table 4.3. Import connections were used to a much lower extent except for SE3, with a utilization of 57.2%, see Table 4.2. While import occurred almost exclusively from SE3 to SE4, export was more evenly distributed to the surrounding countries with the largest export of 6.0 TWh to Denmark.

Based on the information above, it can be concluded that SE4 is strongly dependent on import from SE3 while simultaneously acting as an exporter to its surrounding countries on a yearly basis. Consequently, these large flows of electricity through the region have effects on both the electricity balance and prices within SE4.

4.1.4 The Electricity Balance in SE4

SE4 suffers from a practically constant annual deficit of electricity, and during 2022 SE4 only produced 36% of its total consumption within the region. The system is kept in balance due to a significant amount of transmission to the area and utilization of reserves. In Figure 4.7, the electricity balance for SE4 2022, with transmission included, is illustrated. The balance was slightly negative for the majority of the months, with a multitude of minor variations over shorter time periods. During April and May, there were large variations where SE4 alternately suffered from a large negative or positive balance. Over the remainder of the months, variations were not that high, however there were some peaks in both positive and negative balance, especially a major negative peak in October.

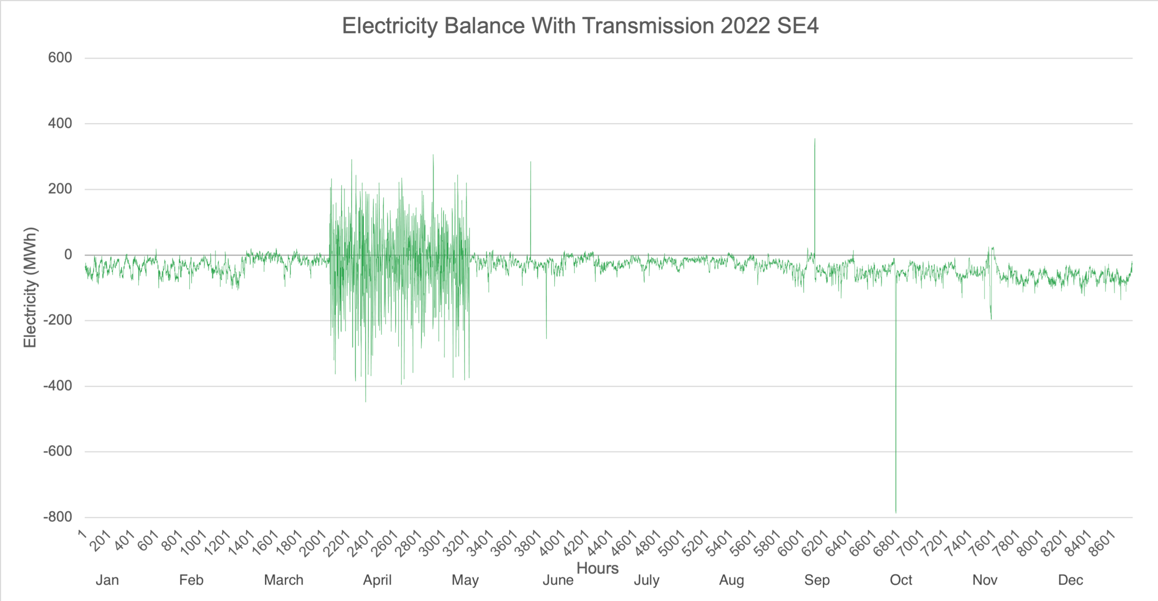

Figure 4.7: The hourly electricity balance in SE4 2022 with transmission to and from the region included.

In reality, the electricity balance should always stay around 0, with some minor variations that cause infrequence but, as mentioned above, the graph shows some large fluctuations in April and May. The reason for these have not been analysed in depth, but data shows that this period is related to a high export of electricity from SE4. The same is seen with the major negative peak in October, which seems to be due to a three hour long export at peak capacity to Germany. It could also be due to some reserve, not included in the graph, being used to cover up the deficit which could be excluded from the data, or some other data missing.

As mentioned, SE4 had an almost constant deficit during 2022, which was counteracted by either transmission or power reserves. To fully understand what effect a storage solution would have it is therefore more interesting to study the electricity balance within the region without transmission and reserves, since these should make up for the deficit at all times of the year, otherwise there would be a shortage of electricity or power outage in the system. The electricity balance in SE4 without transmission to and from the region is presented in Figure 4.8 below.

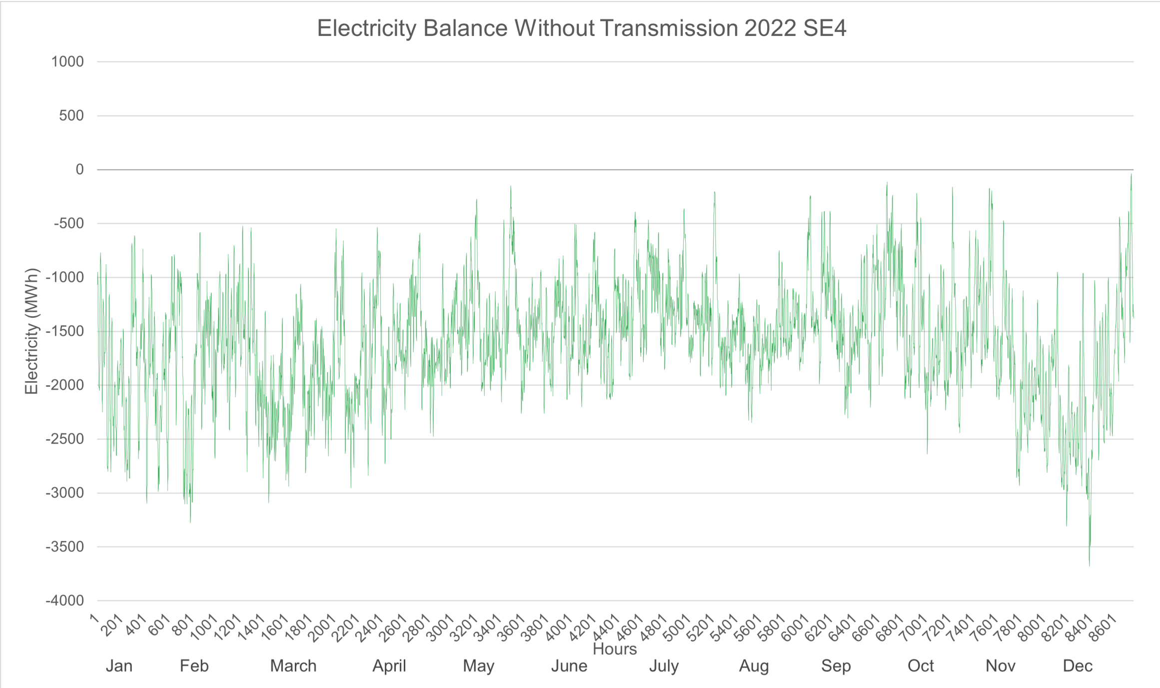

Figure 4.8: The electricity balance in SE4 2022 without transmission to and from the region included.

This shows how heavily dependant SE4 is on import and especially transmission from SE3. The balance is conclusively negative for all hours of the year.

4.1.5 Spot Price

The spot price is the price that electricity is bought and sold for on the day ahead market in the SE4 electricity price region. This means that it reflects consumption and the amount of energy that is available for transport to the area. Some hours might be related to high consumption and low production, but if there is a large excess of energy available for transport at a low price from one or many other areas, the spot price could still be lower than that of an hour with a lower consumption and larger production. Price variations are related to consumption patterns but also shifts in production, especially from the weather dependent power sources, both in SE4 and other price regions. Generally, prices are higher in the morning and in the evening when consumption is higher, and with solar power in the system, prices tend to be lower during daytime hours. Prices are also higher during the cold months, as energy use for heating is higher.

Figure 4.9 shows the spot price on an hourly basis in SE4 during 2022, and does not take into account electricity certificates, surcharges, energy tax, value-added tax or electricity grid costs. Prices range from a maximum of 800 EUR/MWh to a minimum of -2.1 EUR/MWh, with a mean value of 151.7 EUR/MWh. 2022 was an exceptional year in political and energy aspects which resulted in these high electricity prices. In addition, the general pattern with lower prices during summer was not seen in SE4 during the year, rather the opposite. As can be seen in the figure, the trend line point to high prices during the summer, and peak prices were seen during August and September. The reason for the major price peaks in August and September is most probably related to the shut down of the Ringhals 4 and a substantially lower wind production as seen in Figure 4.4. This can also somewhat be explained by the data which shows a high export throughout August and September coupled with a below average transmission from SE3.

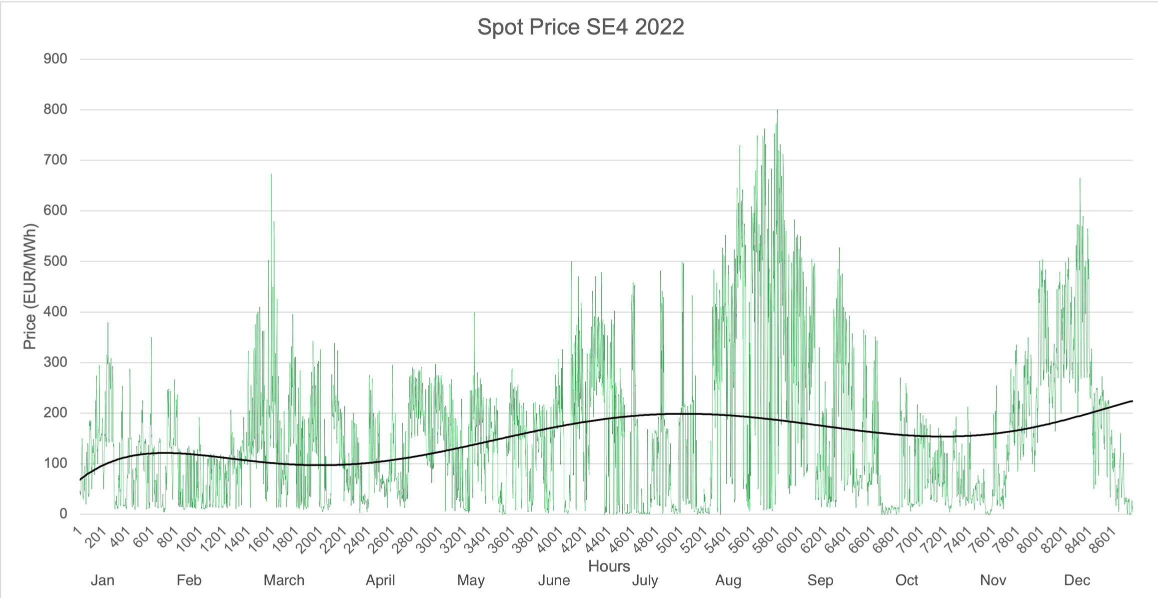

Figure 4.9: Hourly spot price in SE4 for 2022 in EUR/MWh. The trend line shows variabilities over the year.

The price differences graphically presented above in 4.9 is what later will be used to determine the potential economical gain through storage of electricity and the optimal charge- and discharge pattern. The storage solution acts as a consumer when the price of electricity is low due to excess electricity being available and bought, and a producer when price is high due to a deficit of electricity, hence influencing the supply and demand of the market.

In an isolated system the price of electricity is directly determined by the production and consumption, i.e. when production is higher than consumption the price would theoretically be low or negative and vice versa. SE4 is the price region in Sweden with the most international grid connections, and due to this, prices are only to some degree determined by the current conditions in the region.

4.2 Projection of SE4's Electricity System in 2027

This section presents a projected scenario of the 2027 SE4 electricity system. The scenario is based on the short-term market analysis composed by Svenska Kraftnät (Svenska Kraftnät, 2022b), as mentioned in Chapter 3. The short-term analysis contains data of installed capacity of different energy sources, and the consumption up until 2027. With this information, an extrapolation of the data between 2022 and 2027 was used to predict the hourly consumption, production, transmission and price of electricity in 2027. The aim with this was not to predict the hourly balance that would be seen in 2027, but rather to find the variations in production, consumption and price that could occur based on the information available. With this, the residual regional deficit in 2027 could be approximated and used to amplify the variations in price to see what benefit a storage solution would bring.

4.2.1 Consumption

The final consumption during 2022 was 21.87 TWh, with an average hourly consumption of about 2500 MWh, see Section 4.1.1. According to the market analysis performed by SvK Svenska Kraftnät, 2022b, the annual final consumption in SE4 in 2027 will be 26.34 TWh, which amounts to an increased consumption of 20%. This increase is mainly due to electrification and population growth, slightly counteracted by energy efficiency measures. To estimate the hourly consumption of electricity in SE4 during 2027, the increase in consumption was multiplied to each hour with the factor 1.2 (+20%), giving a new hourly consumption profile that linearly matches that of 2022, but higher. This especially increases peak consumption since this way of estimating using a percentage factor gives a higher increase in actual value when the consumption is high. The simplified formula used for the calculations is presented in Equation 4.1 below, where t is an hour.

$$\text{Consumption}_{2027}(\text{t}) = \frac{\text{Final Consumption 2027}}{\text{Final Consumption 2022}} \cdot \text{Consumption}_{2022}(\text{t}) \tag{4.1}$$

The new peak consumption was estimated to 5166 MWh and the minimum consumption was estimated to 1633 MWh, as such, resulting in a larger consumption variation compared to that of 2022, see Section 4.1.1. The projected hourly consumption of 2027 is presented in Figure 4.10 below.

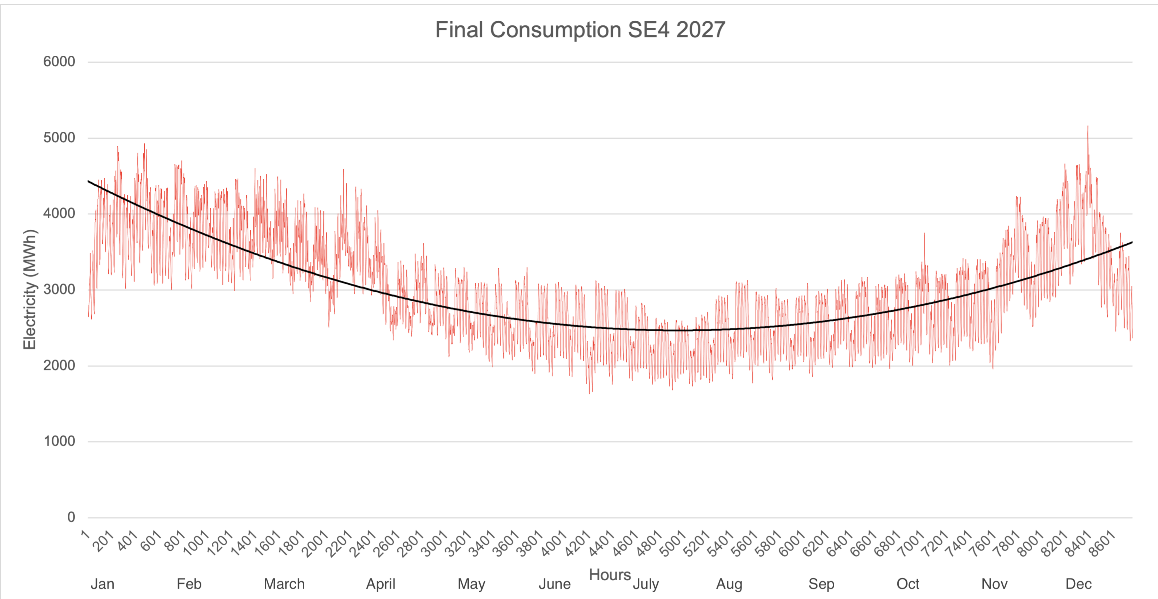

Figure 4.10: Projected final hourly consumption in SE4 for 2027. The black line is a trend line and shows the seasonal variations in consumption.

4.2.2 Production

The production was projected using a different approach than the consumption. Instead of estimating on an increase in produced quantity, an increase in production was instead found by using the increase in installed capacity of each production type up until 2027 in SE4. The assumed installed capacity of each production type in 2027 was gathered from SvK (Svenska Kraftnät, 2022b) and is presented in Table 4.4 below along with the installed capacities of 2022.

Table 4.4: Installed as well as projected installed capacity of each power source 2022 and 2027 in SE4. The table also shows the percentual increase in capacity.

Installed Capacity (MW)	**2022**	**2027**	**Increase**
Hydropower	240	240	0%
Cogeneration	760	780	3%
Wind Power	2180	2717	25%
Solar Power	372	1352	263%
Total	**3552**	**5089**	**43%**

With this information, the hourly production of each power source was multiplied with the projected increase in capacity. This method allows for the intermittency of the production types to be included and estimated accordingly, and the production to assume the same profile as in 2022, in accordance to the extrapolation of consumption, see Equation 4.2.

$$\text{Production}_X(t) = \frac{\text{Inst. Capacity}_X}{\text{Inst. Capacity}_{2022}} \cdot \text{Production}_{2022}(t) \tag{4.2}$$

The largest projected increase in capacity is seen in solar power, increasing from 372 MW in 2022 to 1352 MW in 2027 (Svenska Kraftnät, 2022b). Solar power as a source of production has strong seasonal dependency and also varies a lot throughout the day, as previously mentioned in section 4.1.2. As a result, the supply will increase substantially during daytime hours of the summer months in 2027, while the production during winter months stay more or less the same. The estimated hourly production of solar power in 2027 is presented in Figure 4.11 below.

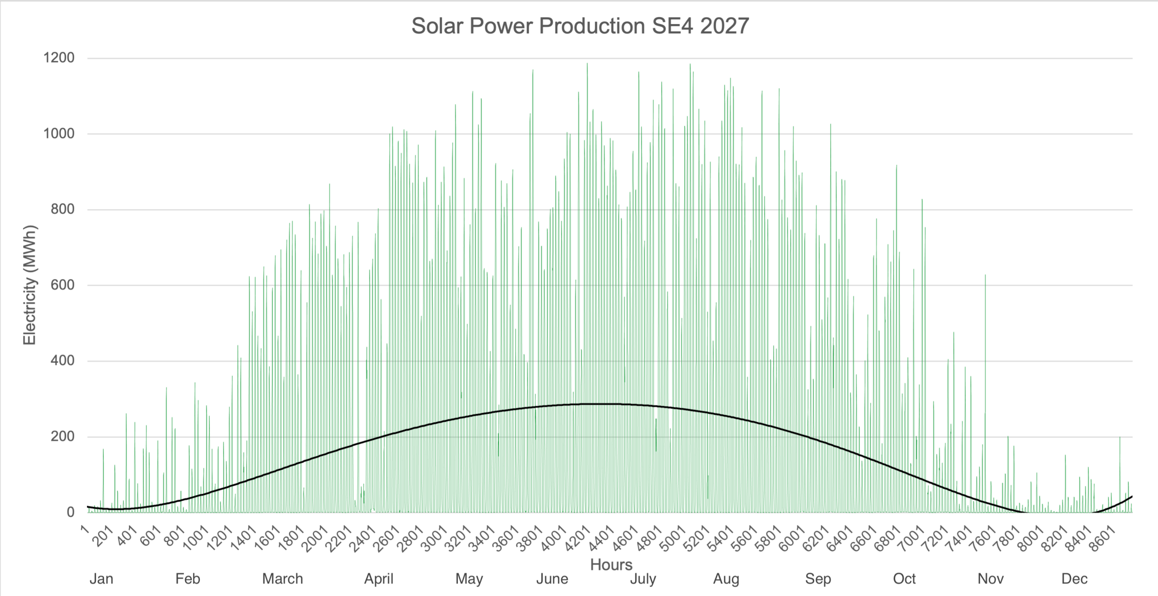

Figure 4.11: Projected hourly solar power production in SE4 2027. The black line represents the trend of production.

The second largest increase in capacity is projected to be seen in wind power, with an increase from 2180 MW in 2022 to 2717 MW in 2027 (Svenska Kraftnät, 2022b). The reason behind the rather small increase in wind power is mainly due to the problems with obtaining permits in SE4. As of 2027, none of the planned off-shore wind parks have been taken into operation. The first off-shore project to start its operation is Kriegers Flak, with a planned start of construction in 2027 and operation in 2029 (Länsstyrelserna, n.d.). This means that beyond 2029 there will be a larger increase in wind power capacity. The estimated hourly production of wind power in SE4 the year of 2027 is presented in Figure 4.12 below.

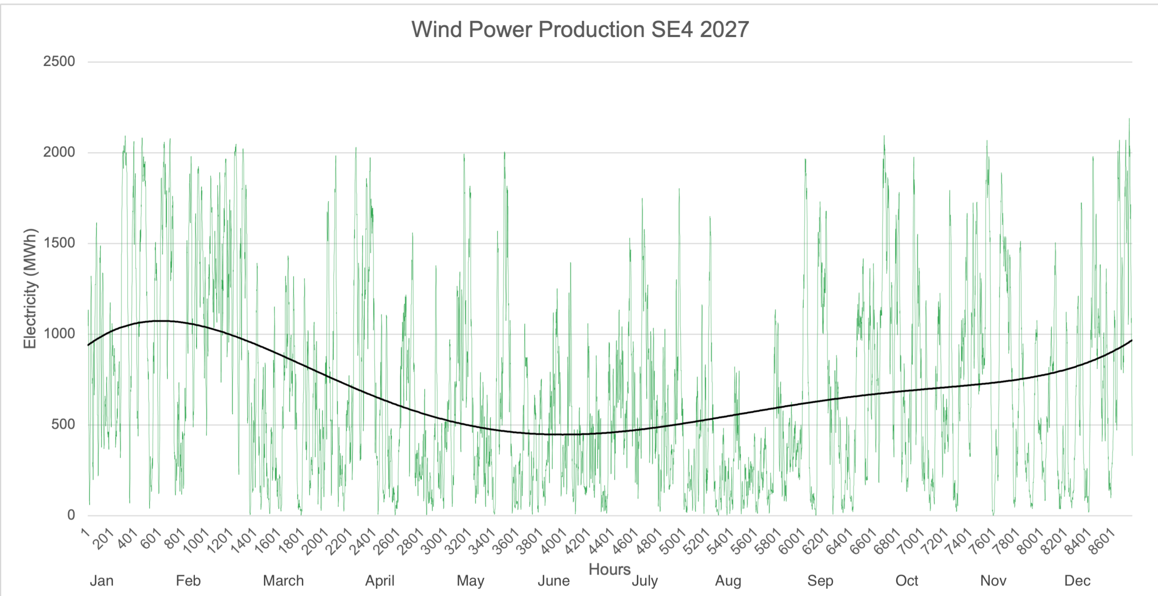

Figure 4.12: Projected hourly wind power production in SE4 2027. The black line represents the trend of production.

The installed capacity of cogeneration power see a slight increase of 20 MW, and installed hydropower capacity remain the same in 2027.

4.2.3 Transmission

When predicting the electricity situation in SE4 2027, the transmission to and from the region was neglected in a way where it was assumed to follow the deficit of electricity in the region. Just as for 2022, when there is a deficit of electricity it will be bought and transported from somewhere else to ensure consumers have electricity for all hours of the day. Therefore, extrapolating the transmission would make no sense, and it is instead assumed to be reflected in the extrapolated spot price. In addition, there are no major new connections to SE4 planned to be established up until 2027.

4.2.4 Electricity Balance

The electricity balance in 2027 closely resembles that of 2022 since it is derived from the same data. Here the transmission is not of interest since the transmission is assumed to follow the deficit of electricity in the region. As has been presented, the production of wind was projected to increase up until 2027 together with a larger increase in solar production, which results in a lower deficit during windy and sunny hours of the year. This increase is counteracted by a heavy increase in consumption of 20% which is applied to all hours of the year according to what was described in section 4.2.1. The deficit of electricity is calculated as the difference between the projected consumption and production, see Equation 4.3 below, where t is an hour.

$$\text{Deficit(t)} = \text{Consumption(t)} - \text{Production(t)} \tag{4.3}$$

With this, the hourly residual deficit of the region was calculated which resulted in the projected electricity balance in SE4 presented in Figure 4.13 below.

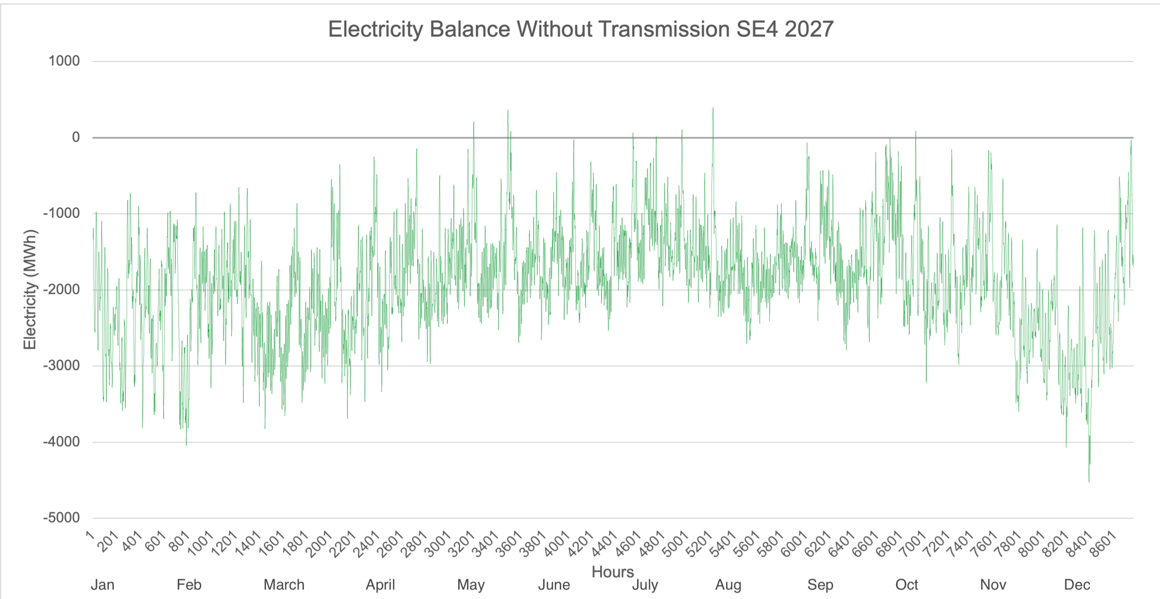

Figure 4.13: Projected hourly electricity balance in SE4 2027 without transmission.

The graph shows a slightly more negative electricity balance in SE4 compared to 2022. The exception is periods where the solar and wind production was high in 2022, resulting in more hours of the year where the production is equal or higher than the consumption.

4.2.5 Spot Price

Projecting future prices is a difficult task. This is because of the multitude of factors influencing the price of electricity. However, to complete the aim of this report and to find the effects of implementing a large-scale grid storage solution in SE4 in 2027, an estimation of future prices, or at least the trend, was needed. One option would be to simply use the prices of 2022 and assume that the prices in 2027 would be the same, but as has been discussed in the previous section, the growth of intermittent power sources in SE4 is high. As the intermittency of production increase the intermittency of prices increase as a consequence. Further, as the consumption of electricity increase, seen in Section 4.2.1, the prices should increase as well.

To estimate the future price and its variations on an hourly basis, the hourly deficit of electricity in SE4 was used, i.e. the electricity balance without transmission. This deficit is affected both positively by the increased consumption and negatively by the increased production, giving a relationship that should, to some degree, reflect the increase and decrease in the market price of electricity. The 2027 projection showed that the deficit on average increased, which means that the price should increase on average as well, see section 4.2.4. Additionally, a correlation analysis revealed that the most significant correlation with the market price of electricity was found in the changes in electricity balance, although the correlation was moderately weak. The projected hourly deficit was estimated for each hour of 2027 as previously explained using Equation 4.3. The resulting hourly deficit of 2027 was then divided by the deficit of 2022 for each hour resulting in a decrease or increase in deficit. This hourly percentage was then multiplied by the corresponding hourly price of 2022 to give an estimation of what the market price would be in the 2027 electricity system. As such, the balance of electricity within the region was used as a proxy to estimate the future prices. This should in theory simulate the increase or decrease the variation of the spot price for each hour. Equation 4.4 was used for the calculation, where the price and deficit is that of a specific hour, t.

$$\text{Price}_X(\text{t}) = \frac{\text{Deficit}_X(\text{t})}{\text{Deficit}_{2022}(\text{t})} \cdot \text{Price}_{2022}(\text{t}) \tag{4.4}$$

The estimated price of electricity in SE4 in 2027 is presented in Figure 4.14 below. Illustrated here is the increase in price but also the increase in price variations, i.e. the difference between peak and off-peak price. The mean price over the year is 175.8 EUR/MWh, with prices ranging from a maximum of 989 EUR/MWh to a minimum of -2.32 EUR/MWh.

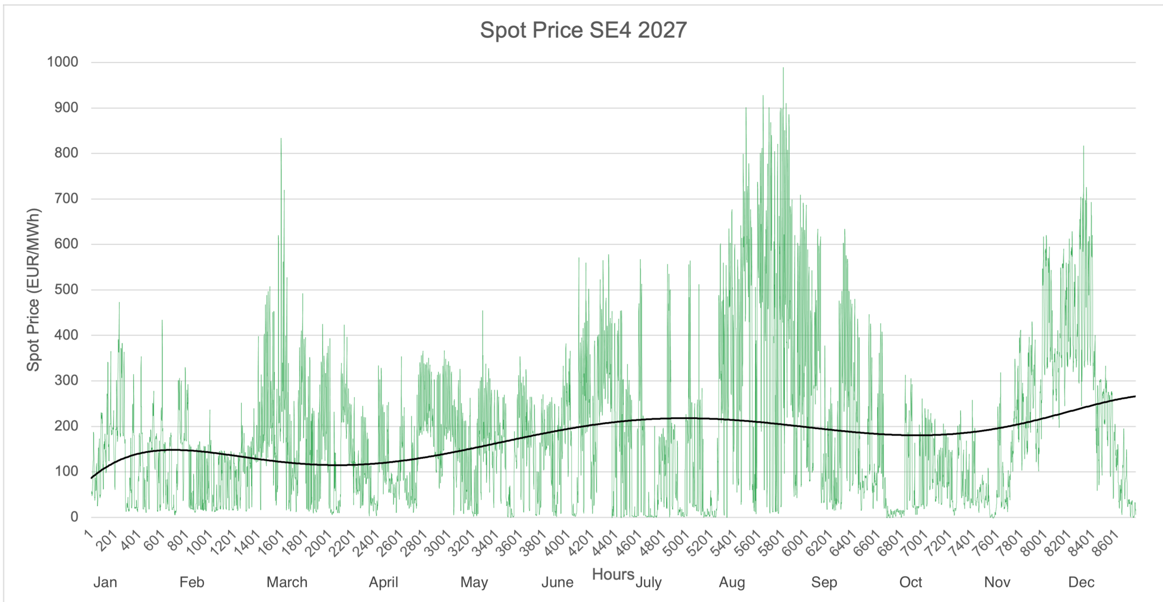

Figure 4.14: Projected spot price for 2027 in EUR/MWh. The trend line shows the variability over the year.

As can be seen in the figure, the spot price of 2027 is directly dependent on the price of 2022 and therefore they follow the same trend. The new price is generally higher due to the increased deficit, but it also has larger variations due to the higher production of wind and solar that was presented in Section 4.2.2. During periods in 2022 with high wind and solar production, the price in 2027 will be much lower, while periods with low wind and solar will see a high increase in spot price.

4.3 SE4's Electricity System Beyond 2030

This section will provide a description of a future scenario of the electricity system in SE4 beyond 2030. The scenario is not related to a certain year, bur rather based on a situation where SE4 produces enough electricity to have a yearly net residual deficit of zero, i.e. the production equals the consumption annually. This increase in production is based on a large expansion of wind that is assumed to take place beyond 2030, making SE4 self-suppliant in electricity. As a consequence of this, the transmission is not investigated but instead assumed to follow the balance of electricity – when there is an excess SE4 exports, and when there is a deficit SE4 imports. Hence, the export equals the import. Consumption within SE4 was assumed to be the same as for 2027, as it is difficult to estimate a consumption for an unknown future year. Even though the electrification proceeds, efficiency measures could mitigate the increase in consumption.

The power sources that most likely will see a major increase in installed capacity in SE4's future electricity system are solar and wind power. However, in this specific scenario, only wind power was scaled up in order to see how this type of intermittent production can affect electricity prices and thereby the operation and profitability of Texel's storage solution. It was found that to cover the deficit, the installation of wind power would see an increase by 355% compared to that of 2027, giving a total of 9915 MW installed wind capacity within SE4 in this future scenario. The increase of about 10 GW in capacity corresponds to a yearly increase in production of about 16 TWh, based on the production of 2027. With the many off-shore wind parks being investigated outside the coast of SE4, this is not at all unreasonable. As an example, the project of Aurora outside of Gotland projects a yearly production of about 24 TWh (Länsstyrelserna, n.d.). The capacity increase was multiplied with the hourly wind production for 2027 to receive the new production, in the same way as was done for the 2027 simulation. The resulting production can be seen in Figure 4.15.

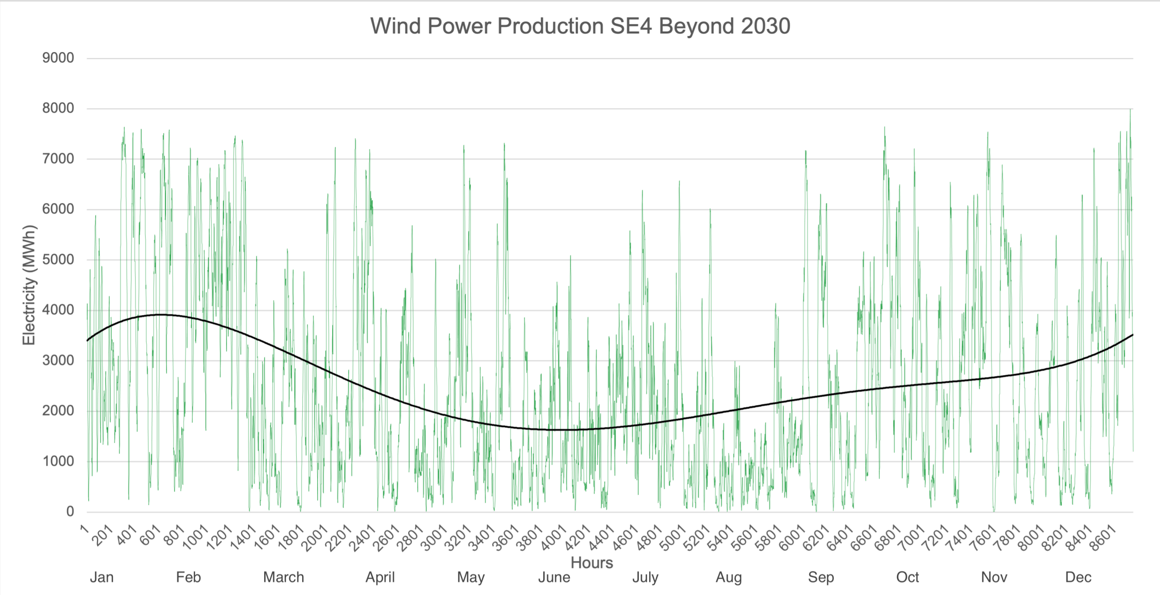

Figure 4.15: Projected hourly wind power production in MWh in SE4 in a future scenario beyond 2030, with 9915 MW installed capacity. The black line represents the trend of production.

As can be seen in the figure, the production of wind power has increased notably, with peak hourly productions of nearly 8 GWh, compared to the hourly peaks just above 2 GWh in 2027, and peaks of almost 1.5 GWh in 2022. This vast increase in wind power capacity and production gives an entirely new electricity balance in the system. As explained, this future scenario is based on the assumption that SE4 is fully self-sufficient on electricity on a yearly basis. The new electricity balance is thus net zero on an annual basis, but with large variations within it. The new balance is presented in Figure 4.16 below.

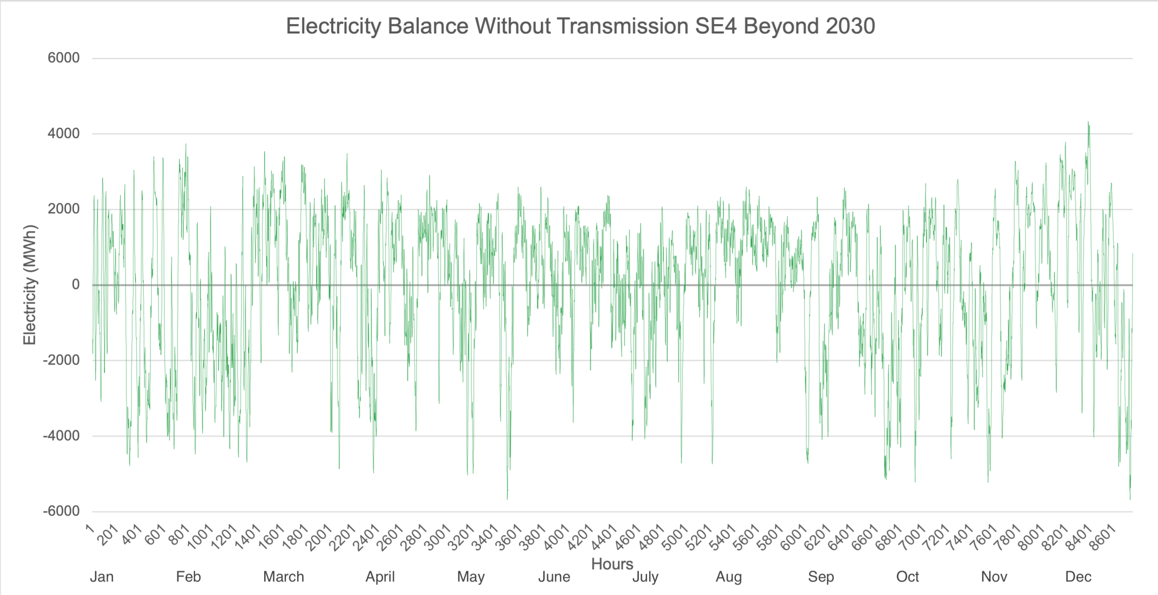

Figure 4.16: Projected electricity balance in SE4 beyond 2030 in a self-sufficient electricity system without transmission.

As can be seen, the electricity balance see periods of large excess but also periods of large deficit. The strong increase in wind power has a substantial effect on the price due to the periods of excess and deficit, which is illustrated in Figure 4.17. This impact on price is seen throughout all hours of the year except for the hours where wind production is low, where the price generally is the same as for the specific hour 2027. This is illustrated by comparing Figure 4.15 and 4.17 where periods of low wind – that is March, August to September as well as early December, are related to peaks in spot price. The spot prices for this scenario were calculated using the same methodology as for the 2027 projection, by first finding the hourly deficit of electricity and then applying this to the price of 2022.

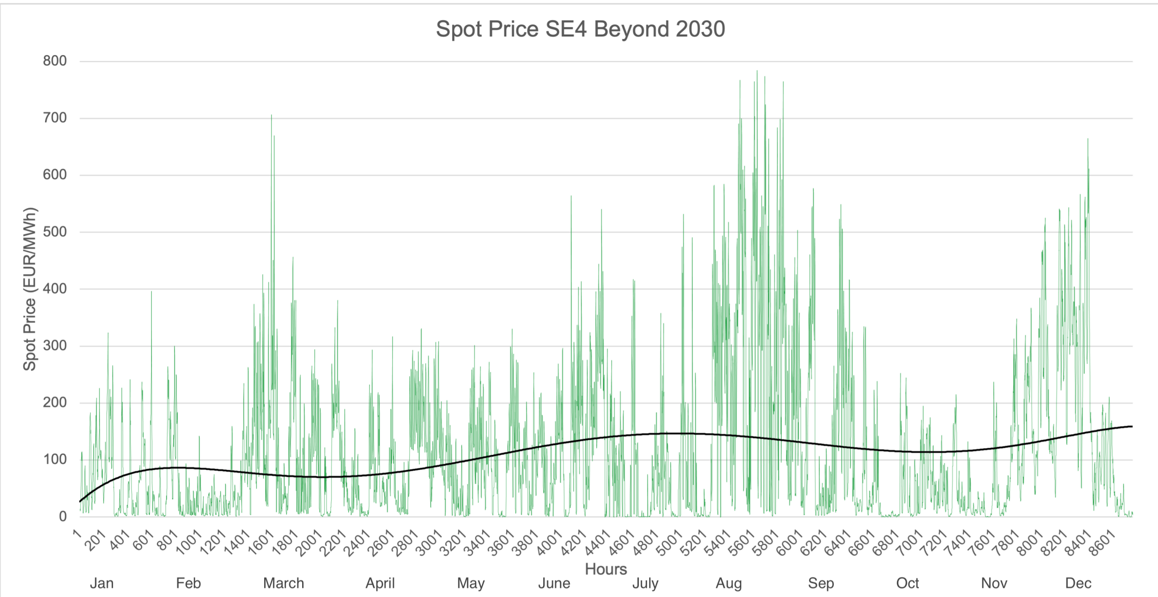

Figure 4.17: Projected spot price in SE4 beyond 2030 in EUR/MWh. The trend line shows the variability over the year.

Periods with higher production of wind power see a large increase in yield in the new scenario which decrease the hourly spot price considerably, such as in late February, late October and late December. This leads to larger variations between the peak and off-peak prices, and generally more periods of off-peak prices. Additionally, due to the substantial increase in annual production, the average price for this scenario becomes much lower than that of the other scenarios. The average hourly spot price in this scenario is 110.8 EUR/MWh compared to 175.8 EUR/MWh of 2027 and 151.7 EUR/MWh of 2022.

5 Results

This chapter is divided into three sections, which contain the results of each scenario with the operation of Texel's solution. Each section presents operational and economical results of the three phases and the two storage capacities including input and withdrawal of electricity, number of operational hours, gross profit, net profit, average profit per sold MWh, LCOS as well as payback time. The effect on the electricity balance in SE4 will be presented as a plot of the hourly balance within the region. In addition, a more detailed plot of the balance with and without the solution for each scenario will also be given.

In this chapter, when presenting the results, it is important to note that it is not the deficit or excess of energy that determines the solution's action (charging/discharging), but solely the price. As a result of this, some hours when the storage solution is charging might see a larger deficit than others when the solution is discharging. In other words, the charging occurs when the physical amount of electricity available for transport to SE4 or is present in the region is high, and discharging when the opposite is true, since this is what generally determines the price.

In order to obtain the results, a simulation was carried out by using the model explained in Section 3.4. As charge and discharge decisions are solely based on price, with no price variation impact accounted for, the operational hours will be the same for all three phases. An operational hour represents one hour of charging and one hour of discharging.

As a result of the operational hours being the same for each phase, the results display a linear dependency to the size of each phase when looking at input and withdrawal of electricity as well as the gross- and net profit. Due to this linearity, the average profit per sold unit of electricity, LCOS and the payback time will the same for each phase for each scenario.

5.1 Storage Potential 2022

This section presents the results for the three different phases and the two storage capacities for the year of 2022. The optimal charging pattern with the six hour charging capacity resulted in 1315 hours of charging and 1315 hours of discharging. For the twelve hour charging capacity, the storage solution was charged 1678 hours and discharged 1678 hours.

The simulated optimal pattern of action was used to find the input and withdrawal of electricity to and from the grid along with the gross profit (arbitrage) from bought and sold electricity. By combining these results with the economical data collected from Texel, additional results including net profit, average profit per sold MWh of electricity, LCOS as well as payback time could be calculated. These results are presented in Table 5.1 below.

Table 5.1: Simulation results for Texel's storage solution for the different phases and storage capacities in 2022. Input and withdrawal of electricity, operational hours, profitability, LCOS as well as payback time for the different phases are included.

2022	Phase 1		Phase 2		Phase 3	
Storage Capacity	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**
Input (MWh)	2630	3356	65 750	83 900	526 000	671 200
Withdrawal (MWh)	6575	8390	164 375	209 750	1 315 000	1 678 000
Operational Hours	1315	1678	1315	1678	1315	1678
			Economical Results			
Gross Profit (MEUR)	0.408	0.549	10.2	13.7	81.6	110
Net Profit (MEUR)	0.316	0.391	7.90	9.80	63.2	78.4
Avg Profit (EUR/MWh)	155.2	163.7	155.2	163.7	155.2	163.7
LCOS (EUR/MWh)	35	47	35	47	35	47
Payback Time (yrs)	7.00	8.49	7.00	8.49	7.00	8.49

As can be seen in the table, using the 12 hour storage capacity unit results in a higher number of operational hours than that of the 6 hour storage capacity unit, and hence higher numbers of input and withdrawal of electricity. The difference between the two is 363 hours of operation (both charging and discharging). The reason for this is due to the fact that the storage capacity is larger, which means there are more possible operational decisions to be made over the hours of a year. Additionally, with a higher storage capacity, there will be less hours when the solution is fully charged or fully discharged and cannot operate to increase profit. In other words, these reduced physical constraints leads to a better optimization of the data. As a consequence of this, the average profit gained from each MWh of sold electricity is higher, which leads to a higher arbitrage. However, since the 12 hour storage unit is more expensive than the 6 hour unit, see Table 2.3 in Section 2.2.2, the LCOS and payback time is higher.

Since the phase 3 solution with the 6 hour storage capacity inputs 526 GWh and withdraws 1315 GWh to and from the grid, which is a vast amount of electricity, it is interesting to see how the balance of electricity within the region is affected. The general impact the storage solution has on the electricity balance is displayed in Figure 5.1, using the 6 hour storage capacity since this performs best in terms of LCOS and payback time.

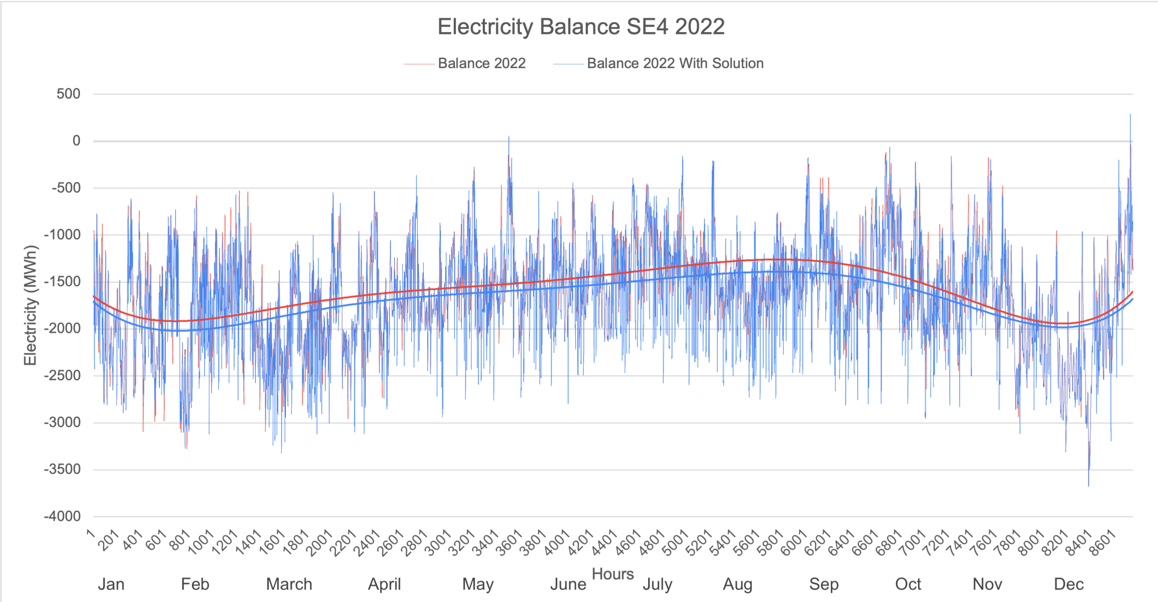

Figure 5.1: The hourly electricity balance in MWh in SE4 during 2022 with and without Texel's phase 3 solution (400 MW). The blue data shows the balance with the solution and the red data without. The colored trend lines corresponds to the data set in respective color.

The balance of electricity is shown on the y-axis, with the red line representing what was seen during 2022 and the blue line representing what would be seen if the phase 3 was installed and operated optimally to maximize profit. The trend lines show that the average hourly amount of electricity in the region would decrease with phase 3, as the storage solution acts as a net consumer of electricity.

To more accurately show how the balance would be affected by the solution, a graph has been made to illustrate the electricity balance of an arbitrary week with high operation, with and without the phase 3 solution, see Figure 5.2. In this case a summer week ranging from the 29th of July to the 5th of August was selected.

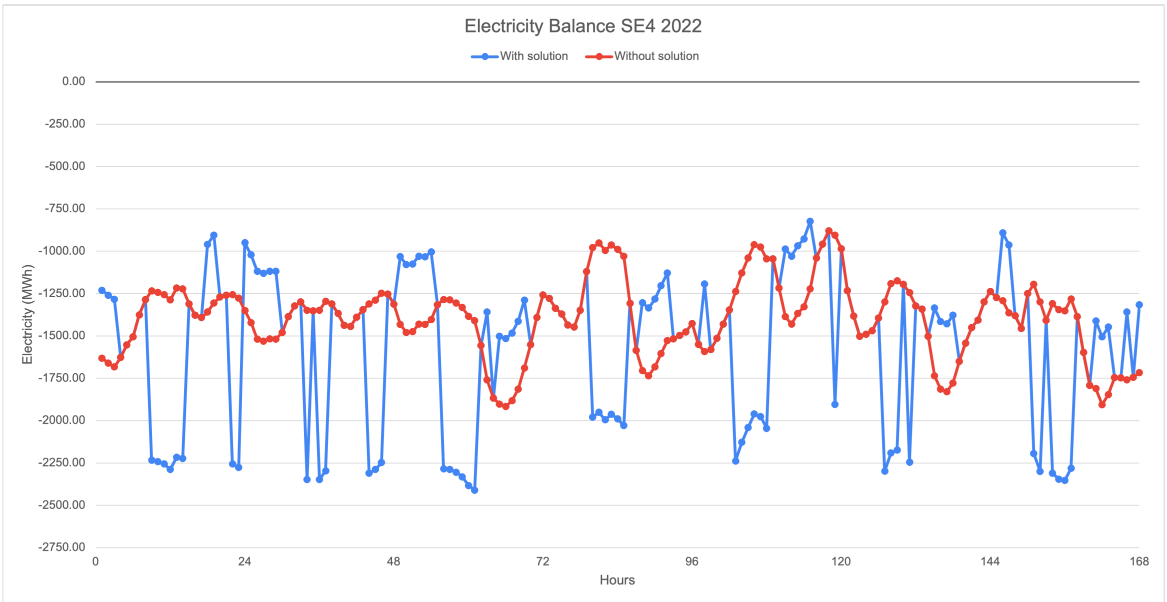

Figure 5.2: The hourly electricity balance in SE4 for a summer week (29/7 - 5/8) in MWh in the scenario 2022 with and without Texel's phase 3 solution.

Each dot in the graph represents an hour with or without operation, with the blue line representing the balance with the solution, and the red without. When the solution charges the blue line drops below the red line, since 1000 MWh of electricity is withdrawn from the grid. When the solution discharges the blue line peaks above the red line due to an input of 400 MWh of electricity to the system. When the lines coincide the solution does not operate and the balance stays unaffected. The solution's operation for this specific week shows the general trend of discharging when the available electricity is low and charging when the available electricity is high. The net consumption of operating is also apparent since the balance with the solution generally is lower. It should be noted that the trend of charging at high availability is not always seen. The reason for this, as previously mentioned, is that the solution operates based on price which does not always correlate with the electricity balance in SE4.

5.2 Storage Potential 2027

This section will provide the results for the three different phases for the year of 2027. Similar to the 2022 results, the effect on the electricity balance in SE4 for phase 3 and a higher resolution figure of the balance with and without the solution will also be presented. The operational and economical results for the 2027 scenario, including all three phases with the two storage capacities, are given in Table 5.2 below.

Table 5.2: Simulation results of Texel's storage solution for the different phases in 2027. Input and withdrawal of electricity, operational hours, profitability, LCOS as well as payback time for the different phases are included.

2027	**Phase 1**		**Phase 2**		**Phase 3**	
Storage Capacity	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**
Input (MWh)	2722	3412	68 050	85 300	544 400	682 400
Withdrawal (MWh)	6805	8530	170 125	213 250	1 361 000	1 706 000
Operational Hours	1361	1706	1361	1706	1361	1706
			Economical Results			
Gross Profit (MEUR)	0.498	0.663	12.4	16.6	99.5	132
Net Profit (MEUR)	0.405	0.505	10.1	12.6	81.1	101
Avg Profit (EUR/MWh)	182.8	194.4	182.8	194.4	182.8	194.4
LCOS (EUR/MWh)	34	46	34	46	34	46
Payback Time (yrs)	5.67	6.91	5.67	6.91	5.67	6.91

The optimal charging pattern of action for 2027 with the 6 hour storage capacity unit resulted in 1361 hours of charging and 1361 hours of discharging. For the 12 hour storage capacity unit, the solution was charged and discharged 1706 hours – an increase of 345 operational hours compared to the lower storage capacity. The reason for this is explained in Section 5.1. Input and withdrawal of electricity is also higher for the 12 hour solution as a result of the increase in operational hours. The 6 hour solution performs the best in terms of LCOS and payback time, but the 12 hour performs better if it is preferable to maximize the net profit.

Below in Figure 5.3, the hourly electricity balance for 2027 with and without the 6 hour storage capacity unit phase 3 solution is shown. Again, as for the year of 2022, the 6 hour solution was chosen to illustrate the effect on the balance of electricity within the region as it performs best in terms of LCOS and payback time.

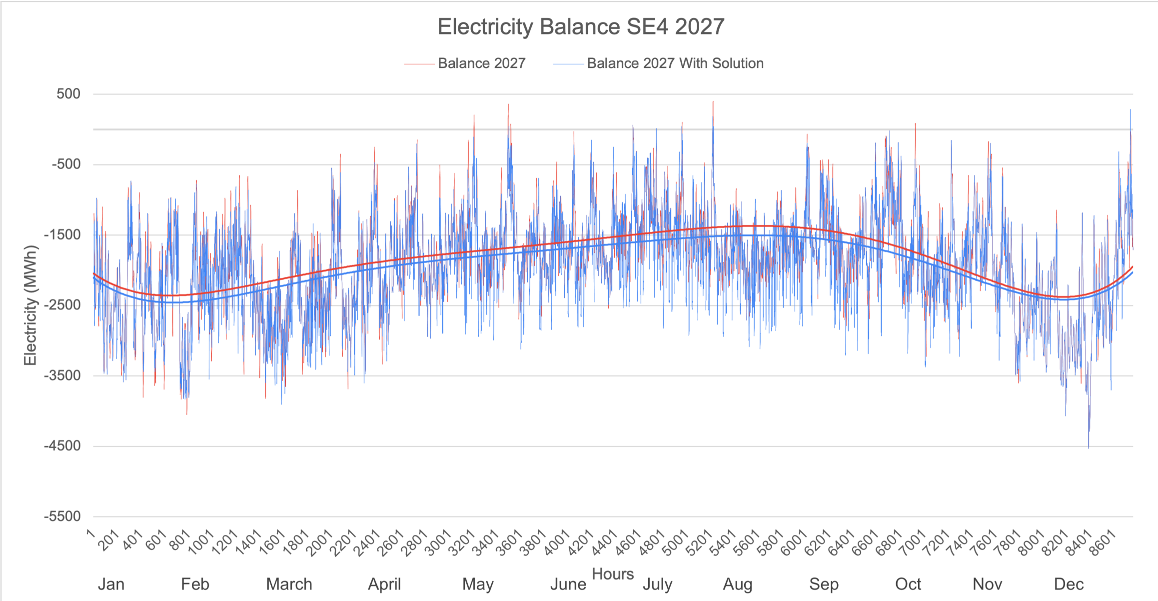

Figure 5.3: The hourly electricity balance in MWh in SE4 during 2027 with and without Texel's phase 3 solution. The blue data shows the balance with the solution and the red data without. The colored trend lines corresponds to the data set in respective color.

As was seen in Table 5.2, the 6 hour phase 3 solution inputs 544 GWh and withdraws 1361 GWh – on average increasing the electricity deficit in SE4. This is visualized in the figure above where the balance of electricity in SE4 is seen on the y-axis. The red data set shows the projected balance 2027 without the solution, and the blue data set shows the balance with the phase 3 solution installed and operated to maximize profit. The lines with respect to the colors indicate the trend throughout the year, illustrating the decrease in average available electricity caused by the phase 3 solution. Again, a more detailed view of the operational effect on the electricity balance was made and can be seen in Figure 5.4. The same week as was used to illustrate the 2022 result was used in this scenario as well for continuity.

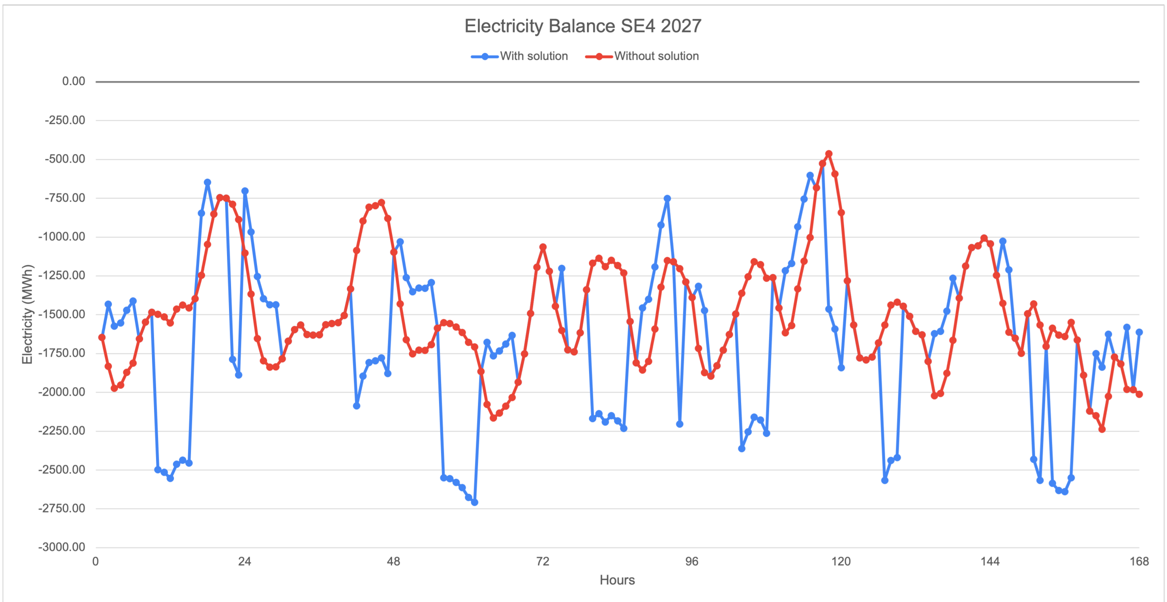

Figure 5.4: The hourly electricity balance for a summer week (29/7 - 5/8) in MWh in SE4 in the 2027 scenario with and without Texel's phase 3 solution.

The pattern of charging when the electricity balance is higher and discharging when the electricity balance is lower was seen here as well, which is reasonable since the electricity balance of the 2027 scenario is similar to that of 2022.

5.3 Storage Potential Beyond 2030

In this section, the results for the three phases and the different storage capacities in the scenario beyond 2030 are presented. The simulated effect on the annual electricity balance and a more high resolution figure with and without the phase 3 solution for a weekly operation will be given. The resulting operational and economical data are presented in Table 5.3 below.

Table 5.3: Simulation results of Texel's storage solution for the different phases and storage capacities in the scenario beyond 2030. Input and withdrawal of electricity, operational hours, profitability, LCOS as well as payback time for the different phases are included.

Beyond 2030	**Phase 1**		**Phase 2**		**Phase 3**	
Storage Capacity	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**	**6 Hour**	**12 Hour**
Input (MWh)	3026	3888	75 650	97 200	605 200	777 600
Withdrawal (MWh)	7565	9720	189 125	243 000	1 513 000	1 944 000
Operational Hours	1513	1944	1513	1944	1513	1944
Economical Results						
Gross Profit (MEUR)	0.395	0.545	9.87	13.6	78.9	109
Net Profit (MEUR)	0.302	0.387	7.56	9.69	60.5	76.5
Avg Profit (EUR/MWh)	130.4	140.2	130.4	140.2	130.4	140.2
LCOS (EUR/MWh)	31	41	31	41	31	41
Payback Time (yrs)	7.25	8.57	7.25	8.57	7.25	8.57

The resulting optimal charging pattern with the 6 hour storage capacity unit resulted in 1513 hours of charging and 1513 hours of discharging. For the 12 hour storage capacity unit, the operational hours increased by 431, resulting in 1944 hours of charging and 1944 hours of discharging - the highest operation of all scenarios. This points to this scenario having the most uniform variations in region market price. Similarly to the results for 2022 and 2027, adapting a 12 hour storage capacity solution yield a higher operation and higher profitability from sold electricity compared to that of the 6 hour capacity. Hence, this option would return the highest profit over the 40 year operational lifetime. Moreover, just like for 2022 and 2027, the 6 hour storage capacity unit is the preferable option if a shorter payback time or LCOS is favourable.

The impact on the electricity balance with the 6 hour phase 3 solution in the scenario beyond 2030 was also studied. In Figure 5.5 below, the simulated balance in SE4, with and without Texel's solution in the future scenario is shown.

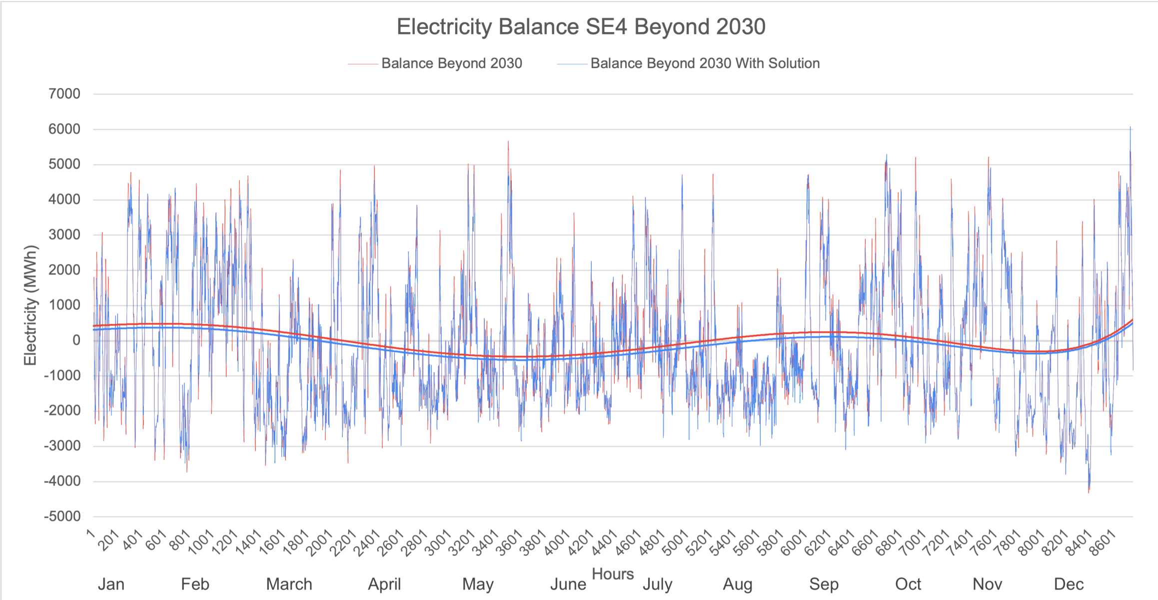

Figure 5.5: The hourly electricity balance in MWh in SE4 in the future scenario with and without Texel's phase 3 solution. The blue data shows the balance with the solution and the red data without. The colored trend lines corresponds to the data set in respective color.

The figure shows the hourly availability of electricity, seen on the y-axis, for each hour of the projected year in SE4. The solid red line is the trend line for the projected balance of electricity in the future scenario and the blue line is a trend line for what would be the balance in the future scenario with the phase 3 solution installed and operated to maximize profit. As seen, the solution would on average decrease the availability of electricity in the region.

Again, to more accurately illustrate how the electricity balance would be affected by the solution, a graph was made that shows the electricity balance of an arbitrary week with high operation of the phase 3 solution, see Figure 5.6.

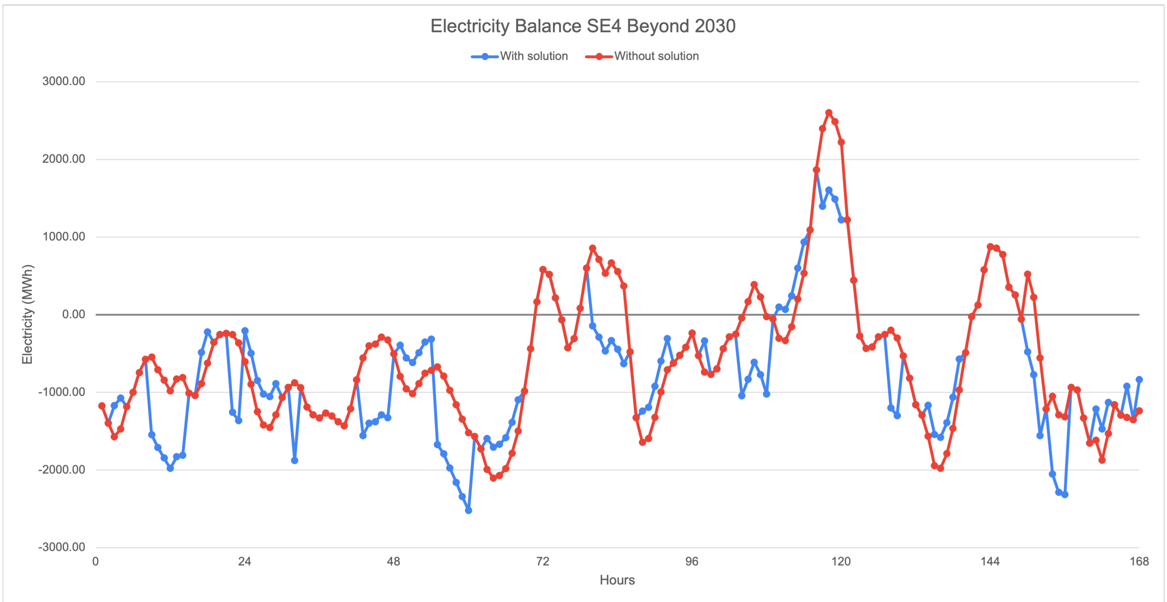

Figure 5.6: The hourly electricity balance for a summer week (29/7 - 5/8) in MWh in SE4 in the scenario beyond 2030 with and without Texel's phase 3 solution.

The graph shows that the storage solution acted according to the balance at some hours, and some hours it did not. As previously mentioned, this is a consequence of the price not being directly dependent on the electricity balance.

6 Discussion

This chapter provides a broad discussion covering the results of this report. The current energy situation in SE4 along with the potential economical gain through storage will be described. The potential introduction of capacity mechanisms will be discussed followed by a description and discussion of the interlinked and complex electricity system of SE4. The possibility of extracting heat from Texel's technology will be brought up and a discussion of how this could affect the results will be outlined. The future changes in the Swedish electricity system due to new establishments of energy intensive industries and its effects on the solution will also be brought up. Lastly, the implementation of the Texel solution outside of SE4 will be discussed.

6.1 The Energy Situation 2022

The world situation in 2022 made a clear mark on the energy year of 2022, and gave consumers and producers of energy a glimpse of a typical future energy year. With the electrification and expansion of renewable power sources together with ongoing and potential future energy conflicts, a more volatile energy and electricity market is to be expected. A future with increased price volatility is positive seen from an operational perspective and profitability for Texel's solution as it can operate more hours when there are vast fluctuations between high and low electricity prices. In addition, the technology has the potential to decrease consumers price of electricity as the storage solution could mitigate price peaks in a volatile system.

The factors that affected the energy year (brought up in Chapter 2) have strongly influenced the results of this report. Not only the results for 2022, but for 2027 and the scenario beyond 2030 as well as they build upon the 2022 data. If 2022 would have been a more stable year, less price variations would most likely have been seen, and potentially less profit would be gained.

6.2 Potential Economic Gain Through Storage

Before analyzing the results it is important to remember that these are based on life-time costs provided by Texel, which are simplified, and does not account for the time value of money as explained in 3.4. Furthermore, the results are based on optimal operation to maximize profit, and since market price data for a whole year was available, the economical results found are higher than what would be seen in a real situation, as the simulation could be performed with known price data for every hour. This does not mean that the results are incorrect, but that there is a low chance that optimal operation can be achieved when acting on the actual day ahead market. In addition, the results assume that the solution will have no effect on the market price within the region. This is based on the fact that the data did not show a direct correlation between changes in the electricity balance (due to changes in production and consumption), and changes in the price. The reason for this is that the price is being affected by much more than the balance within the price region, as previously discussed. With the phase 1 solution it is more reasonable to assume that the solution does not have any effect on the price, since the input and withdrawal of electricity to and from the region is negligibly small in comparison to what is traded. However, when it comes to the larger phases, a price impact could be seen. As a result of this, the economical results for the larger phases would in reality decrease compared to what is seen in this report, meaning that the average profit per sold MWh for the 50 MW phase would be slightly lower, and the decrease would be more pronounced for the 400 MW phase.

The results show a high economical profitability using the Texel storage solution, with an average profit per MWh of electricity ranging between 130.4 EUR and 194.4 EUR. The reason for the high economical potential is due to the instability of the electricity system which cause large fluctuations in price. The average profit per MWh of electricity in the 2022 scenario is roughly equal to the average price of electricity in 2022, which is reasonable since the solution acts on the peaks and bottoms of price and due to the large variability in the price. The same is seen in the average profit per sold electricity in 2027 and beyond 2030, albeit slightly higher than the average spot price due to the projected increase in price volatility.

The levelized cost of storage was found to be between 31 and 47 EUR/MWh (excluding charging costs) depending on the storage capacity unit used and the year analyzed. The analysis performed at Savannah River National Laboratory by McWhorter (2020) found the Texel solution to have an LCOS of 18 EUR/MWh. Lazard (2023) has performed an LCOS analysis including battery storage with a capacity of 100 MW and a storage capacity of 8 hours. In Lazard's analysis LCOS is calculated based on an assumed lifetime of 20 years and values range from 58 to 144 EUR/MWh excluding charging costs. Both Lazard (2023) and McWhorter (2020) base their LCOS calculations on a predicted 365 operational cycles per year. However, the results of this report are based on the actual operation that would be seen during a year, leading to a lower number of cycles compared to both Lazard (2023) and McWhorter (2020), which is one of the reasons why this report presents a higher LCOS than McWhorter (2020). It is important to note that LCOS is strongly affected by the methods used for calculation and the assumptions made concerning the market that is analyzed. This means that comparing LCOS from two different sources is difficult. However, the range of LCOS obtained in this report for Texel's solution is noticeably lower compared to what was seen in Lazard (2023) which points to the technology being cost-competitive with large-scale batteries for grid storage use. Even though this report's results for LCOS are not as low as the one presented by McWhorter (2020) for the Texel technology, the results still show that there is a large difference between the profit per each MWh and the cost to store it, which further points to the substantial potential for profit.

6.3 Capacity Mechanisms

The result and analysis display that operating to maximize profit while helping the regional electricity balance does not correlate too well. This could potentially be a problem in the future if a large volume of storage capacity is installed which could lead to problems with maintaining the balance within the regional grid. This is a problem that has been raised by SvK, whom has proposed the introduction of capacity mechanisms (Svenska Kraftnät, 2023a). A capacity mechanism is used to enable power plants and storage solutions to keep capacity available for times of need. In exchange, the mechanism provides payments to storage solutions which acts in addition to the arbitrage. This would shift the focus from operating a storage solution only based on the spot price, to instead also aid the electricity balance within a region. Thus, maximizing profit would not only be maximizing arbitrage, but instead a mix of arbitrage and saving capacity for hours of larger regional deficits.

6.4 The Interlinked Electricity System of SE4

The results show that there is a large discrepancy between the market price in SE4 and the regional electricity balance. This was stated earlier when looking at the data, but it became even more apparent due to the results obtained from the simulation. As has been discussed, the market price is not only determined by the regional supply and demand of electricity, but rather by the consumption and availability of electricity for transport to the region. This electricity could be imported from Denmark, Germany, Lithuania or Poland, but is most often determined by the availability for transport from SE3, which in turn often comes from SE2 and SE1. In addition, if a higher market price is seen in any of the countries or price regions that SE4 is connected to, the electricity will flow there until the market price is evened out, or the grid connection capacity is maxed out. When having a storage solution that operates on electricity price, the results show that the regional effect on electricity balance is not necessarily positive, as the price most often reflects the balance within the wider system. In other words, a solution operating on price will help the balance within a region that determines the price itself, but in reality it often includes many other regions and even countries. This means that the help the solution gives to the wider system of SE4 in terms of balancing becomes relatively small as it is acts on a market where the physical amount of electricity affecting the price is substantially higher than what is produced in SE4.

Connecting the grid of many regions and countries has many benefits. For example, it prevents regions from having substantially higher electricity prices than other regions connected to it. With a sufficiently connected grid, the need for storage solutions could be counterargued by the fact that electricity always will be excessively produced somewhere, which complicates the market for solutions such as grid storage and reserves. However, with renewable electricity production increasing, the production is becoming less predictable, which means storing electricity for periods of low wind, or periods of low temperatures will be more important, especially for industries relying on electricity for continuous production.

The results show that the solution does not necessarily help the actual balance of the local price region, but rather help the balance in other areas within the interconnected system. This can be seen in two ways. On one hand it shows that the solution has a large potential to help the broader system with balancing the price peaks, but on the other it shows that there is only a small help it can give to the electricity balance of SE4 specifically, rather affecting the balance negatively. This is, as previously mentioned, a consequence of the price being determined by many other factors than the local balance. For the grid operator in SE4 this is a problem since they, with the current policies, cannot rely on a storage solution operating to the regional benefit meanwhile operating to maximize profit. To counteract this, some sort of profit needs to be obtainable for a solution operating to help the regional balance instead of only acting on arbitrage. Capacity mechanisms, as previously discussed in Section 6.3, is one example. With such mechanisms introduced, there is potential for helping the SE4 deficit by ensuring stored energy is available to cover the deficit in the price region.

The impact on the electricity balance varies between the three scenarios studied. Operating in 2022 and 2027, where the electricity balance is at a constant deficit without transmission, the solution can not help decrease an excess of electricity in the local system, but can only help reduce at times of peak deficit. However, in the scenario beyond 2030, the local system is in balance on a yearly basis, which means that there will be hours where there is an excess of electricity as well. This leads to the solution both helping the local balance at times of deficits, and at times of excess, which differs from the other scenarios. Since the local deficit of electricity in the 2022 and 2027 scenario is assumed to always be compensated by transmission to the area, the actual affect of this extra help it gives to SE4 is hard to quantify. What can be said is that the number of hours when the solution is operating to help the balance in the local system is higher in the scenario beyond 2030 than what is seen in the 2022 and 2027 scenario.

6.5 Heat Utilization

This report has only been analyzing the potential electricity outtake from the Texel storage solution and its effects on the electricity system. However, as mentioned in Section 2.2.2, there is also a possibility to extract heat from the storage solution which can be used in district heating, industries or micro grid applications, which would increase the profitability and usefulness of the solution. The Texel solution utilize a Stirling engine with a 40% efficiency, meaning that 40% of the energy that is used gets converted to electricity. Of the remaining 60%, 10% is lost, and 50% is extractable as heat which originates from the cooling loop in the Stirling engine and has a temperature between 45 and 65°C. Coupled with a heat exchanger it is well suited for district heating. This possibility is an additional argument for implementing the Texel solution, especially if the solution is used in applications where there is a need for both heat and electricity. This could for example be industries using both for production, or larger residential areas using it for district heating.

The heat utilization was not analyzed because it would require a comprehensive investigation of the heat system in SE4, which was not possible with the time constraints of this project. It can be assumed that connecting the solution to the district heating system could increase the profitability by a substantial amount, especially since the amount of energy produced as heat is higher than the amount of energy produced as electricity. This would lead to higher profitability and shorter payback time. However, it should be noted that the heat production occurs at the same time as the electricity production, which could be a problem if the need for heat does not correlate with the need for electricity. If this is the case, the heat would not be as valuable, or it would need to be stored elsewhere. In future applications this heat might be used to refill the storage of the Texel battery, but as of today this not possible since the heat needed for recharging is of much higher temperatures. Instead, this heat could be stored through other means, for example through the emerging technology of pit storage, which then would ensure the availability of heat for colder seasons. If such a technology was implemented in tandem, the Texel solution would not only help mitigate the increasing problems with electricity intermittency, but also indirectly lower the need for electricity by supplying the system with production and storage of heat.

6.6 Establishment of Energy Intensive Industries in Sweden

The scenarios in SE4 that this report covers present a future in which transmission is assumed to cover the deficit of electricity for all hours of the year. However, the transmission between Sweden's electricity price regions will most likely look very different in the future. One of the things affecting this is the establishment and operation of energy intensive industries such as battery factories and SSAB's fossil-free steel technology HYBRIT.

Depending on the establishment location of energy intensive industries, electricity deficits might arise or worsen in a price area if the amplified demand cannot be met by the existing or planned supply. For example, in a situation where several electricity demanding establishments are introduced in the northern price region SE1, which today has an overproduction of electricity and therefore acts as an important supplier to the other Swedish regions, SE4 might instead have to import from other countries where electricity is substantially more expensive. If the production within Sweden would be sufficient, transmission patterns among the price regions would change. Another possible effect of a situation with the introduction of energy intensive establishments in the north is that the prices would increase in that region due to a decrease in available electricity. A possible consequence of this is that the transmission from the northern regions might become less reliable and the deficit in SE4 might need to be covered by an increased import from Europe. A potential increase in price fluctuations, induced by these potential transmission changes, would affect the economic viability of Texel's solution as it operates based on price variations.

There is a need to expand the transmission grid between the north and the south of Sweden to secure the ability of transport of more electricity. Expansion and establishment of new power lines is usually a very long process, and if the grid is not extended enough at the time needed, energy storage solutions are important. Additionally, as Texel's solution not only allows large scale grid storage but can be used as storage in direct connection to industries as well, the technology is promising in helping to supply industries with both electricity and necessary heat for them to maintain their operations in a less reliable electricity system.

It is important for many large-scale industry applications to have cheap electricity production in direct connection to their factories. The production that is installed is usually intermittent which enhance the need for connection of storage such as Texel's in order to ensure security of supply.

6.7 Texel's Solution Outside of SE4

High consumption, low production or a mismatch between them are two reasons why the system of a region becomes dependent on the electricity systems of other areas. Taking Europe as an example, there are many grid connections within the union which allow transport and share of electricity, and therefore it can be assumed that the case for SE4 presented in this report, regarding the region's price- and balance discrepancy, is not unique. As the electricity system situation is unique for each area, it is hard to say something about the application of the Texel solution outside of SE4 in terms of profitability and helping the electricity balance.

7 Conclusions

This work was performed with the aim to understand how the electricity balance in SE4 would be affected by the implementation of Texel's storage solution in Malmö, and what economic viability that potentially can be seen by operating the solution the year of 2022, 2027 and a year beyond 2030.

The analysis and results from the work conclude that there is a discrepancy between the electricity balance and electricity prices in SE4. This means that an implementation of the storage solution in Malmö does not necessary help the balance within the electricity area, but it helps the electricity balance on a larger scale. The impact on the local electricity balance is negligible for the 2 MW phase for all years studied due to the withdrawal and input of electricity being very small in comparison to the physical amount of electricity present in the region. The impact on the balance in SE4 is more pronounced for the 50 MW phase, and especially for the 400 MW phase. Due to the almost constant deficit in the region 2022 and the increase in deficit up to 2027, the solution always operate in a local deficit, and due to it being a net consumer of electricity its operation leads to an annual increase in the local deficit. For the scenario beyond 2030, the same trend was observed, but here it also acts to reduce hours of high excess in the local system due to the local system not always being in a deficit.

The results show a large potential for economic gain through storing and selling electricity in SE4. This was found to be due to the large fluctuations in market price. The profitability was found to linearly increase with the size of implementation, while the average profit per sold MWh, LCOS and payback time stayed the same for each phase. The 12 hour storage unit performed better in terms of annual profitability and average profit per sold MWh, but the 6 hour storage unit resulted in lower LCOS and payback time. Below, the main results for the phase 3 solution of 400 MW are presented.

- The net profit was highest for the 12 hour storage unit in the 2027 scenario with a value of 101 MEUR, followed by 78.4 MEUR in 2022 and 55.5 MEUR in the scenario beyond 2030.
- The average profit per sold MWh was highest for the 12 hour storage unit in the 2027 scenario with a value of 194.4 EUR/MWh followed by 163.7 EUR/MWh in 2022 and 140.2 EUR/MWh in the scenario beyond 2030.
- The LCOS was lowest for the 6 hour storage unit in the scenario beyond 2030 with a value of 31 EUR/MWh followed by 34 EUR/MWh in 2027 and 35 EUR/MWh in 2022.
- The payback time was lowest for the 6 hour storage unit in the 2027 scenario with a value of 5.67 years followed by 7.00 years in 2022 and 7.25 in the scenario beyond 2030.

As can be seen, the profit was highest when using the 2027 projected price data, but due to the higher operation in the scenario beyond 2030, the LCOS was lowest in this scenario. The reason for higher profit in 2027 is due to this scenario having the highest average market price, and the reason for the higher operation in the scenario beyond 2030 is due to the higher intermittency of production which resulted in more frequent oscillations in market price. The economic results given by the model assumes that the storage solution is operating knowing the spot price of every hour of the year, which means it can make operational decision considering the price of every consecutive hour. In addition, since no price impact is accounted for, the profit from sold electricity is higher than what would be observed when operating on the actual market, especially for the larger phases of implementation. In consideration of this, the economic results presented are higher than what would be practically attainable.

The generation of heat was not quantitatively analyzed, but it could provide further profitability and increase the applications of Texel's storage solution. As for example when integrated with a heat storage facility or in direct connection to industries or residential areas.

This work has shown that helping the local balance and maximizing profit simultaneously was unattainable. Therefore, it was found that a systematic change in the market is crucial in order for a storage solution to help the local balance in SE4 and still be economically viable. This change could be provided by the introduction of capacity mechanisms.

7.1 Proposed Further Research

To fully investigate the potential for storage in SE4, further research is needed. Since the local balance and the price within the region see a weak correlation, an analysis where the system of SE4 is expanded is needed to find the large-scale help the solution gives in terms of balancing. If research is conducted with the aim of finding a storage solution that could help the balance within a local region, we propose that the implementation of capacity mechanism and their structure is investigated first.

The model developed to find the results in this report does not include the impact a storage solution of this size would have on the market price in the region. With this in mind, we propose that a method to simulate price impact within a local system is developed to obtain a result that would be more in line with reality. In addition, instead of finding the maximum profit for a time period, an AI model could be developed that, given the physical constraints within the market, operates as a real actor on the day-ahead market of electricity.

Due to 2022 being a special year in terms of electricity prices and disturbances in the European energy market, developing and analyzing a scenario that is based on a more consistent year with less extremes would be of interest. We therefore propose that further research is conducted to analyze the electricity system of SE4 and the need for storage solutions based on another year, preferably where the intermittency of production is present but where the market is less affected by external perturbations.

Lastly, since the solution operates on differences in market price, it would be of interest to analyze a system where the production of electricity is of a fully intermittent nature. This would illustrate the impact and economic viability of a storage solution in a system that is likely to be found in the future.

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Appendix A

Python Code for Optimization and Simulation

```python
import sys
from RealTimeCurrencyConverter import RealTimeCurrencyConverter

url = 'https://api.exchangerate-api.com/v4/latest/USD' # API
converter = RealTimeCurrencyConverter(url) # Currency converter

MAX_STORAGE = # 6 or 12 depending on unit used
DISCHARGE_EFFECT = # 2, 50 or 400 depending on phase
CHARGE_EFFECT = DISCHARGE_EFFECT*2.5 # 40% efficiency


def main(argv):
    # Read the prices from file "filename.tex"
    price = []
    with open("filename.tex") as file: # Filename for price dataset
        for line in file:
            price.append(float(line.split(" ")[0]))

    hours = len(price)
    if MAX_STORAGE == 6 : # Cost for 6 hour storage
        CAPEX = converter.convert('USD', 'EUR', 44220)*(DISCHARGE_EFFECT*1000/30)/40 # Capital cost of all 6 hour units for a year
        OPEX = converter.convert('USD', 'EUR', 16800)*(DISCHARGE_EFFECT*1000/30)/40 # Operational cost of all 6 hour units for a year

    else : # Cost for 12 hour storage
        CAPEX = converter.convert('USD', 'EUR', 69730)*(DISCHARGE_EFFECT*1000/30)/40 # Capital cost of all 12 hour units for a year
        OPEX = converter.convert('USD', 'EUR', 34600)*(DISCHARGE_EFFECT*1000/30)/40 # Operational cost of all 12 hour units for a year

    # Initialize the profits for each state to 0
    profit = [[0] * (MAX_STORAGE + 1) for _ in range(hours+1)]

    # Update profit for each state
    for i in range(0, hours+1):
        for k in range(0, MAX_STORAGE + 1):
            update_profit(i, k, profit, price)

    grossProfit = profit[hours][0] # Arbitrage
    payback = ((CAPEX)*40)/(netProfit-OPEX) # Payback time
    yearCost = (OPEX+CAPEX) # Yearly cost
    netProfit = grossProfit-OPEX-CAPEX # Net profit
```

```
    print(f'Gross profit = {grossProfit} \nNet Profit = {netProfit} \nPayback time = {payback}')

    # Backtrack to find the path we took to find the maximum profit
    sys.setrecursionlimit(10000)
    storage = []
    backtrack(hours, 0, profit, price, storage)
    with open('storage.txt', 'w') as f:
        for d in storage :
            d = str (d)
            f.write(d)
            f.write('\n')

""" Find the maximum profit to the current state
:param h: hour
:param k: battery level
:param profit: profits
:param price: prices
"""
def update_profit(h, k, profit, price):
    # Battery level cannot be higher than hours
    if k > h:
        profit[h][k] = None

    # Starting hour will be 0
    elif h == 0:
        profit[h][k] = 0
    else:
        tmp = []

        # Charge
        if k != 0:
            tmp.append(profit[h-1][k-1] - CHARGE_EFFECT * price[h-1])

        # Wait
        if profit[h-1][k] is not None:
            tmp.append(profit[h-1][k])

        # Discharge
        if k != MAX_STORAGE and profit[h-1][k+1] is not None:
            tmp.append(profit[h-1][k+1] + DISCHARGE_EFFECT * price[h-1])

        # Set current profit to max of the cases
        profit[h][k] = max(tmp)

""" Find the path to the current state
:param h: hour
:param k: battery level
:param profit: profits
:param price: prices
:param price: storage
"""
def backtrack(h, k, profit, price, storage):
    # Save the battery level for the current hour
    storage.insert(0, k)

    # Check if we reached the starting hour
```

```
    if h == 0:
        return
    else:
        # Check if we charged to get current profit
        if k != 0 and profit[h-1][k-1] - CHARGE_EFFECT * price[h-1] == profit[h][k]:
            return backtrack(h-1, k-1, profit, price, storage)

        # Check if we waited to get current profit
        if profit[h-1][k] is not None and profit[h-1][k] == profit[h][k]:
            return backtrack(h-1, k, profit, price, storage)

        # Else we discharged to get current profit
        else:
            return backtrack(h-1, k+1, profit, price, storage)

if __name__ == "__main__":
    sys.exit(main(sys.argv))
```
Listing A.1: Python example