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An Analysis of the Swedish Intraday Market

Klara Haglund & Alicia Lööf

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Klara Haglund & Alicia Lööf

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Supervisor at the Division of Environmental and Energy Systems Studies was Lars J Nilsson and Hannes Sonnsjö. Supervisor at Flower was Catarina Almeida.

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Faculty of Engineering
Lund University

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Abstract

To fully decarbonise the energy system, electrification is needed as one of the most important strategies for reducing carbon dioxide emissions in Sweden and Europe. The deployment of renewable energy resources plays a central role in electrification and will continue to increase. In January 2024, Svenska Kraftnät published a long-term market analysis with four future scenarios regarding the development of the energy system. The scenarios include two with higher electrification; Plannable Electrification (PE) and Renewable Electrification (RE) and two with lower electrification; Small-scale Renewables (SR) and Mixed Roadmaps (MR). Due to changes in flexibility, the electricity market will be affected by electrification. It is further divided into four submarkets; the financial market, the day-ahead market, the intraday market and the balancing market. This study aims to analyse the development of the intraday market and to discuss its future trajectory along with the scenarios from Svenska Kraftnät. The study is limited to SE3 and includes the years 2021, 2022 and 2023. Since 1999, when the intraday market was introduced, trading has been ongoing on Nord Pool. The intraday market is a single cross-border European market where trades occur continuously during every hour of the day. The data analysis concluded that intraday prices showed a more volatile pattern during 2021 and 2022 and stabilised during 2023. The highest peaks of intraday prices and volatility are in 2022, a clear connection where identified with a power shutdown of the nuclear power plant Ringhals 4. The total volume of the trades has shown a stable pattern in 2021 and 2022, with around 50 GWh trades per month. At the end of 2023, the trading volume increased and reached up to 130 GWh. The increase in volume indicates an increased liquidity of the market. Day-ahead prices, renewable deployment, balance between demand and supply, grid connections and macroeconomic indicators are analysed in order to understand the deployment of the intraday market. Solar power production and intraday prices correlate to -8%. However, solar power accounts for a low share of the electricity mix. In the future with a larger share of solar production, it could be expected to have an increased influence on intraday prices. The wind production accounts for a larger share of the electricity production and is impacting the intraday prices to a greater extent. The correlation between the intraday prices and wind production shows seasonal differences. The highest correlations were reached -39% in December, followed by -32% in June 202. An increased wind production indicated an increased demand for flexibility in the supply. However, this can be adjusted by demand-side flexibility. Consequently, flexibility resources are expected to emerge on both the demand and supply sides in the future. Due to an integrated European market, the implementation of new grid connections between countries impacts electricity prices and the electricity market outcome in Sweden. The factors analysed impact the intraday market. However, it has been seen that other macroeconomic indicators have had a large impact on the intraday trading. The years 2021 and 2022 have shown a unique pattern in intraday trading due to the pandemic and the gas crises. To summarise, the factors studied within this report are all affecting the intraday prices. The prices have shown a volatile pattern during the three studied years, with notable peaks and valleys and it will probably show similar patterns within the future. With an increased amount of trades, the liquidity of the intraday market will most likely increase in the future. The range of electrification and the increase of RES will have an impact on the future intraday market.

Keywords

Intraday Market; Day-ahead Market; mFRR market; Wind Power; Solar Power; Price; Volatility; Liquidity

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Hej så länge!

Alicia & Klara

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List of Abbreviations

SIDC - Single Intraday Coupling

XBID - Cross Border Intraday

TSO - Transmission System Operator

BRP - Balance Responsible Party

PV - Photovoltaic

Ei - The Swedish Energy Markets Inspectorate

RES - Renewable Energy Sources

VRES - Variable Renewable Energy Sources

mFRR - Manual Frequency Restoration Reserve

SR - Small-Scale Renewable Scenario

MR - Mixed Roadmaps Scenario

PE - Plannable Electrification Scenario

RE - Renewable Electrification Scenario

Introduction

Climate change is a well-known problem, with the energy sector as a major contributor to global greenhouse gas emissions. As climate change intensifies, the transition to electrification offers a crucial pathway to reduce carbon emissions and mitigate environmental impact. Embracing flexible energy solutions and renewable energy sources is essential in addressing the challenges posed by climate change. To combat this issue, the European Union has set mandatory objectives to achieve net zero carbon dioxide emissions by 2050, as outlined in the European Climate Law within the European Green Deal (European Commission, n.d.). Sweden aims to achieve net-zero greenhouse gas emissions by 2045, with large-scale energy transition being a key component of this goal (Swedish Energy Agency, 2023). The EU's climate targets apply across the Union, and in addition to national goals, Sweden is responsible for contributing to the EU's climate objectives. To reduce the impact of climate change, society as a whole must transition to fossil-free energy sources, with large-scale electrification providing a significant opportunity.

Ensuring an affordable and carbon-free energy system in the future requires a well-functioning electricity market and a robust interconnected grid within Europe. At the same time, it is important to build up a secure energy market where political uncertainties or regulatory obstacles do not interfere with the market's functionality. Electricity is crucial for sustainable development, as it allows access to clean energy, improves economic productivity, and improves the quality of life of communities around the world. The increase of renewable energy resources (RES) plays an important role in electrification and the path towards a fossil-free energy system.

With an increase in RES, the need for market flexibility increases and hence, the electricity trading needs to occur closer to the delivery hour to maintain market flexibility. The intraday market operates on the same day as electricity delivery, allowing market participants to adjust their trades after the day-ahead market. The increased amount of renewable energy sources (RES), like wind and solar power places new demands on the electricity market, including the intraday market. Trades on the intraday market occur continually and contribute to a more flexible market. The question is, how important is the intraday market and how will it develop in the future?

1.1 Purpose, Aim and Research Questions

The primary objective of this study is to gain insight into the development of the intraday market and to discuss its future trajectory. This will be accomplished through an analysis of historical data. The thesis will examine the development of the intraday market in Sweden, focusing on electricity prices and market volatility. The aim is to extract valuable insights, identify patterns within the data, and formulate hypotheses about the future. This will be achieved by addressing the following research questions:

1. How has the trading on the intraday market developed in Sweden from 2021 to 2023?
2. What findings can be identified about the future trends of the intraday market based on the first research question?

When investigating the trading on the intraday market it includes price, price volatility and volume traded. Given the limited availability of literature on the subject, the topic has been selected to maintain a deeper understanding of the intraday market. The scarcity of research motivates the need for an in-depth investigation to fill the knowledge gap and contribute to a better understanding of the topic. By exploring the area where literature is sparse, the study aims to provide new insights and expand the knowledge base in this field.

1.2 Scope & Delimitations

The analysis is limited to Sweden and more specific to bidding zone SE3. Bidding zone SE3 is chosen based on Flower's interest and in order to limit the amount of data. All price data are based on SE3, while wind data are based on the total wind power production in Sweden. Our chosen methodological approach is based on the average values of the hourly and daily data on volume, price, and price volatility, which allowed us to investigate the development of the intraday market over time. At the same time, it did not enable one to visualise the full picture of all peaks and valleys, since those are mitigated when mean values are calculated. The same applies to negative values, which are not distinguished when hourly and daily averages are calculated. Another limitation of this study is the conscious decision to focus on studying the intraday market from a short-term perspective with data based on 2021, 2022 and 2023. The analysis is based on only three years due to a limited availability of data. The data analysis in this study is grounded in the concept of intraday continuous trading, reflecting the current market format. However, intraday auctions will be briefly mentioned and discussed in a limited manner. The consumer's electricity price is not taken into account in this report.

A Background of the Electricity System

This Section presents a background of the Swedish electricity system. It includes electricity production and consumption, the electricity network, the balance of the electricity system, and the electricity market, focusing on the intraday market. The last part of the Section contains the future scenarios from Svenska Kraftnät that will be used to conclude the future.

2.1 Electricity Production & Consumption

In Sweden, a total of 163 TWh of electricity was produced in 2023 (Statistikmyndigheten, 2024). The electricity production originating from fossil-free sources reached up to 98,3% where hydropower accounts for a majority followed by nuclear power, wind power, combined heat power (CHP), and solar power. (Ember, 2023) Figure1 shows the electricity production in Sweden from 1990 to 2023.

Electricity production by source, Sweden

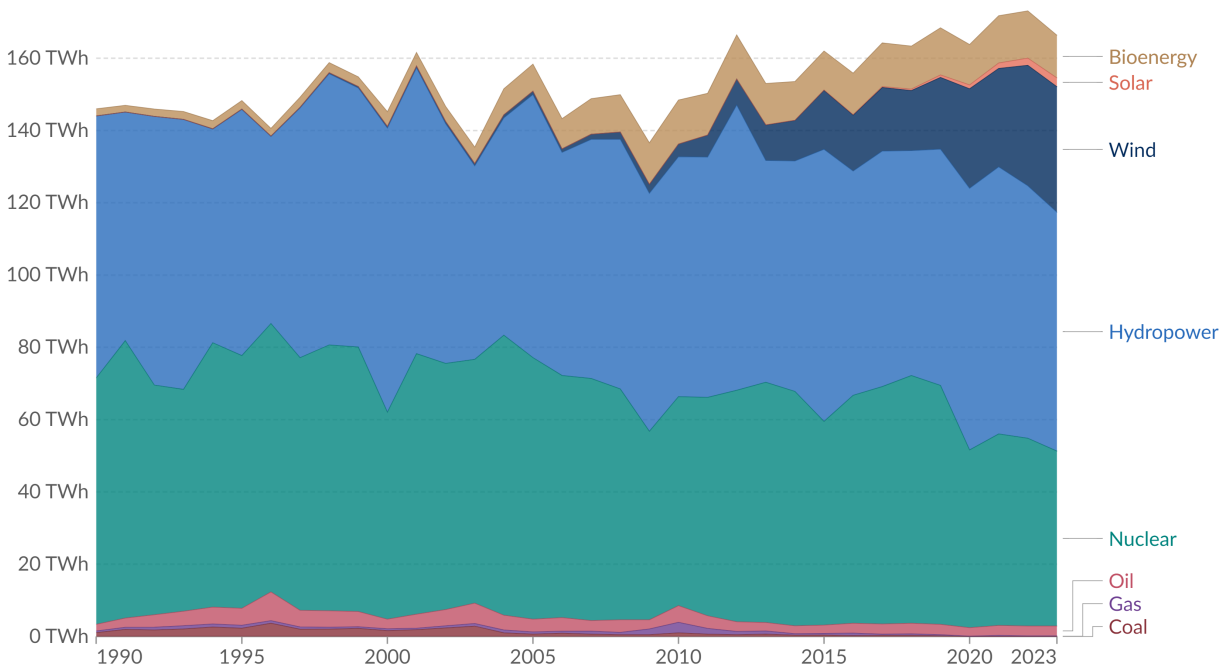


Figure 1: Electricity production in Sweden 1990 to 2023 (Ember, 2023)

Hydropower and nuclear power have been relatively stable since 1990 while wind power and bioenergy have shown the largest increase. The wind power supply has increased rapidly since the year 2000 (The Swedish Energy Agency, 2023). The capacity of wind power in Sweden was 16,441 MW in 2023. This accounted for 26% of the total energy production. (Costanzo et al., 2023) Today there are over 5000 wind turbines in Sweden distributed throughout all bidding zones in the country. Figure 2 shows the wind power deployment at the end of 2022 where 'vindkraftverk' is translated into a wind power plant and 'elområde' is translated into the bidding zone. The share of solar power on the other hand accounts for a small part of the electricity production. In 2006, the first grid-connected Swedish photovoltaic (PV) was installed. In 2022, there was approximately 800 MW installed PV. (IEA, 2022)

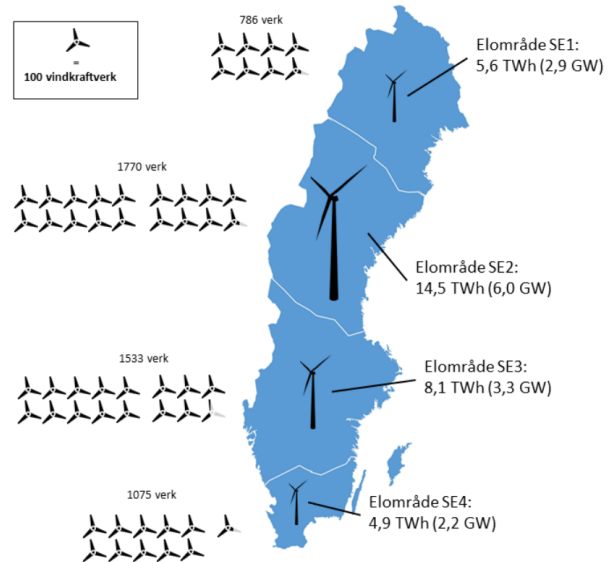


Figure 2: Wind power in Sweden at the end of 2022 (Sandberg, 2023)

Since 1990, the electricity consumption in Sweden has been stable at around 140 TWh, mainly due to a slow down of electric heating growth and a higher efficiency within the electricity consumption. How much electricity is consumed depends on different factors such as electricity prices, the type of industries in operation, what energy source is used in households or industry, and the temperature which affects the electricity needed for heating. By sector, households and services account for 58% followed by industries (37%), electricity-, gas-, heating and water utilities (3%), and railways and busses (2%). Industry, households, and services account for the majority where transport and electricity use from the public sector is included in services. (Statistikmyndigheten, 2023). With a major electrification of society and an increased demand for electricity in the long term, electricity consumption in Sweden is expected to increase. According to Svenska Kraftnät's long-term market analysis, a major expansion of the Swedish electricity system is expected to meet the future demand. (Nycander et al., 2023) The driving force of the electricity consumption increase is mainly large-scale electrification of the transport sector and parts of the industry, specifically the mining and steel industry. In contrast, the forecasts of future demand are uncertain, however, an increase is expected and the future will face challenges with the transmission capacity to phase out fossil fuels. (Bergman, 2022)

2.2 The Electricity Network

The aim of the electricity network is to transfer electrical energy from producers to consumers and at the same time remain balanced between supply and demand within the system. The electricity system can be divided into two parts: the physical transmission of electricity, which consists of the transmission, regional, and local grids, and the financial trade of electricity, which is comprised of the electricity market and trading companies. It is within the financial trade of electricity where the actual trading occurs. The electricity system is visualised in Figure 3. The physical transmission is described in this Section and the financial trade of electricity is described in Section 2.4.

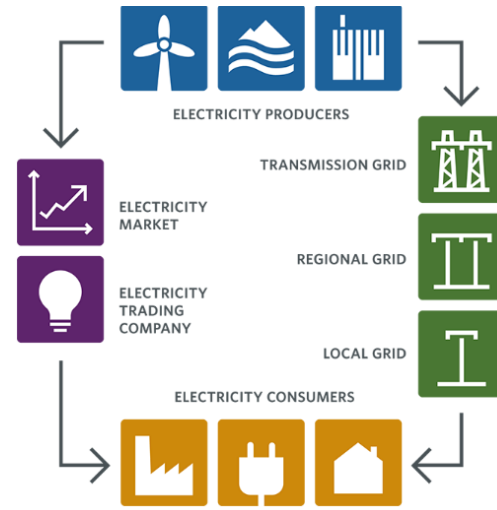


Figure 3: The electricity route from production to consumption (Svenska Kraftnät, 2021b)

The electricity network consists of three hierarchical levels, with the transmission grid at the top. The transmission grid transports electricity from major producers to regional and local grids. Running from north to south across the country, it operates at high voltages to minimize losses when transporting large amounts of power. The transmission grid is owned by Svenska Kraftnät, the transmission system operator (TSO) which is responsible for its operation and maintenance under the regulation of the Swedish Energy Markets Inspectorate. Through the transmission grid, electricity can also be transported across borders through international connections. Below the transmission grid are the regional grids, which connect to the transmission grid and distribute electricity to local grids. Medium-sized producers can connect directly to the regional grids. These regional grids are owned by distribution system operators (DSOs), which are electricity network companies responsible for electricity distribution at the regional level. The DSO has a system responsibility at a lower voltage level, operating as monopolies within their geographical areas. The local grid, in turn, distributes electricity to the primary users and industries. Voltage is reduced at the regional and local grid levels to meet the required standards. Very small electricity producers, such as those selling surplus electricity generated by solar panels, can also connect to the local grid. To maintain system balance within the electricity network, Svenska Kraftnät has the overall responsibility for ensuring a balance between production and consumption across the transmission, regional, and local grid. (Svenska Kraftnät, 2022)

Sweden is divided into four bidding zones; SE1 to SE4 shown in Figure 4. The purpose of the bidding zones is to manage physical constraints, so-called bottlenecks within the transmission network and to ensure that traders are treated equitably in addressing bottleneck situations, a stipulation mandated by European legislation. The bidding zones were introduced in 2011, prompted by the Swedish National Grid's limitations on cross-border electricity transmission, which were assessed as conflicting with EU competition rules. The electricity prices can differ in the different zones due to the difference in the capacity of energy, resulting in an abundance of electricity in zones SE1 and SE2 and a deficit of electricity in zones SE3 and SE4. (Svenska Kraftnät, 2021c)



Figure 4: Bidding zones in Sweden (Svenska Kraftnät, 2021c)

2.3 A System in Balance

For the electricity system to function properly, there must be a continuous balance between supply and demand. This equilibrium is essential to ensure a reliable power system that consistently delivers electricity whenever it is needed (Eicke et al., 2021). Any disturbances in the system risk damaging or completely knocking out technical equipment. Additionally, for the electricity transmission system to function properly, the frequency must be maintained at 50 Hz. The balancing process includes different actions. Svenska Kraftnät is ultimately responsible for ensuring the electricity system remains balanced. (Svenska Kraftnät, 2023a) When disturbances occur, the frequency can be disrupted, causing the system to become unbalanced. To counteract this, stabilizing resources and ancillary services are activated (Lokhande et al., 2023). Along with Svenska Kraftnät, certain actors can be designated as balance responsible parties (BRPs), meaning they are responsible for matching their electricity supply with the consumption of their consumers. In Sweden, Svenska Kraftnät decides who can be a BRP. (Svenska Kraftnät, 2021a). The BRP must continually plan and if necessary, engage in trading activities to maintain system balance. They are obligated to cover the costs associated with imbalances, which are determined in the imbalance settlement process. (Lokhande et al., 2023) The planning is done per bidding zone and extends until one hour before delivery hour. After that, the balance planning is submitted to Svenska Kraftnät, which ensures real-time balancing of the entire electricity system. (Svenska Kraftnät, 2021a)

Flexibility is defined as the capability of a power system to cope with the variability and uncertainty that variable renewable energy generation introduces into the electricity system. It can be described as the system's capacity to adjust to dynamic conditions, encompassing variations in both electricity demand and supply at different time scales. Short-term flexibility refers to quick changes in minutes and seconds while seasonal flexibility refers to flexibility over longer periods such as months. (Harit et al., 2022) Flexibility in the system can be derived from different sources both from the demand and supply side increasing with increased variable renewable energy generation and it moves from secondary to seasonal. Demand-side flexibility implies that society requires the capacity to adjust electricity consumption based on the availability of electricity. One way of implementing demand-side flexibility is through reducing load during peak hours. (Jaraité et al., 2019) It is important to note that increased demand flexibility becomes essential to harmonize with the variability in electricity production, ensuring stability and sustainability within the power system. Flexibility on the supply side currently consists of a large proportion of hydropower playing a major role in providing flexibility as they are able to quickly adjust production at a low cost and thereby act as seasonal storage. (Energimyndigheten, 2021) Other flexibility resources, such as transmission side flexibility and energy storage systems also provide the energy system with flexibility in order to keep being in balance. (Harit et al., 2022) The transmission grid plays a crucial role in the balance of power supply and demand through grid connections between countries and bidding zones. Grid connections provide an exchange of production resources and flexibility in order to handle seasonal variations and efficient use of the power grid. (Nordic Transmission System Operators, 2023)

2.4 The Electricity Market

To maintain the balance between electricity supply and demand, electricity is traded on the market. Within the EU, the electricity market is liberalised, meaning that electricity is traded under free competition. The goal is to ensure that resources are used efficiently so that supply meets demand. Sweden is part of the European electricity market, meaning the electricity used is produced both domestically and abroad. A common regulatory framework established by EU countries aims to create a single internal market for electricity. (Nycander et al., 2023) The national electricity supply is divided into the electricity market and electricity grid services. The electricity market is deregulated, allowing electricity to be bought and sold based on commercial contracts. The primary goal of the electricity market design is to balance the power system effectively and efficiently, both in the short and long term, through various wholesale markets. (Brännlund et al., 2022)

Economic flows within the electricity market occur on the electricity exchange. Electricity can thus be traded from years in advance until the physical hour of delivery. The electricity market and the physical electricity grid are interconnected. To maintain the balance between production and consumption, the electricity market must be designed in accordance with the conditions of the physical electricity grid. Trading takes place on different electricity exchanges where the actors are electricity producers, electricity trading companies, balance responsible parties, and major electricity users. (Svenska Kraftnät, 2023c) The same actor can assume multiple roles within the energy sector. For instance, large power producers may also operate an electricity trading department, while government agencies might simultaneously serve as transmission network owners and system operators. Physical electricity trading is conducted mainly through electricity exchanges on a centralized market, where producers and, in some cases, even consumers submit their sell bids to the central electricity exchange. For each trading period, an electricity price is set for the overall market, or a number of local electricity prices valid for a specific part of the market. Since it is hard for actors in the electricity market to forecast how much electricity that will be traded in a given trading period, the electricity market is divided into different sub-markets. (Söder et al., 2011)

In Sweden, the electricity market is divided into four sub-markets: the financial market, the day-ahead market, the intraday market and the balancing market. In the different markets, electricity trades are carried out at different time intervals. Figure 5 visualises the different markets. (Brolin et al., 2021)

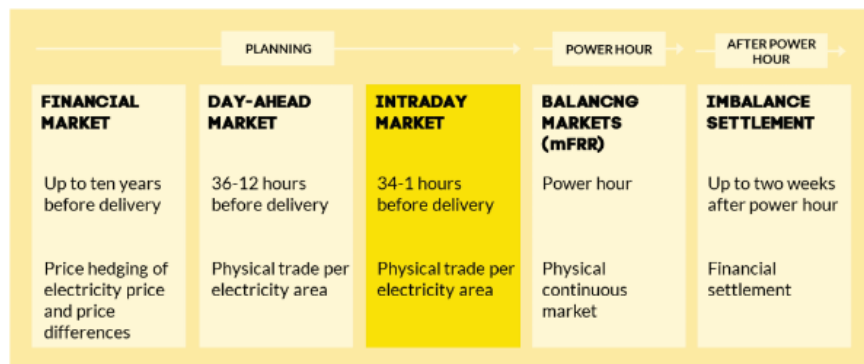


Figure 5: Electricity market design in Sweden (Brolin et al., 2021)

In the financial market, participants can mitigate their risk through various forms of price securing, primarily conducted on the long-term market (Nord Pool, n.d.[a]). Long-term contracts for trading are established for duration spanning days, weeks, months, quarters, and years (Ei, 2023a).

In the day-ahead market, the participants can sell or buy energy for the next 24 hours through a closed auction system. This market segment typically involves electricity producers, traders and major electricity consumers. The trading takes place on the electricity exchanges Nord Pool and EPEX where the market participants can submit bids for Swedish electricity zones. In Europe, all electricity exchanges are interconnected, including Nord Pool. The price of electricity in the day-ahead market is set in a common European auction where orders are matched with other orders in the pan-European market coupling process called the Single Day-Ahead Coupling (SDAC). This is called market coupling. (Nord Pool, n.d.[a]).

The day-ahead market along with the intraday market is called the wholesale market. Closer to the delivery hour the intraday market takes place, where day-ahead trading adjustment occurs. Together with the day-ahead market the intraday market helps to secure the balance between the supply and demand of produced and consumed electricity. The intraday market will be described in detail in Section 2.5 below.

On the balancing market, the TSO, Svenska Kraftnät, purchases regulation services to maintain grid stability. This process involves buying and activating ancillary services, some of which are automated, while others require manual control. Additionally, the imbalance between planned and metered production or consumption is addressed after the delivery hour during the imbalance settlement. The balancing market is crucial due to its impact on the imbalance settlement. There are different types of ancillary services in order to balance and manage disturbances in the power system. Mainly there are frequency containment reserves and frequency restoration reserves. The Manual Frequency Restoration Reserve (mFRR) is a manual ancillary service that relieves the automatic services and restores the frequency to 50 Hz. Further, it sets the price of the balancing settlement and aims to provide frequency regulation when disturbances occur in the electricity system. (Brolin et al., 2021)

2.5 Market Efficiency

When analyzing the electricity market, an important factor to consider is volatility, which refers to the degree of variation in the price of a stock or financial asset. High volatility suggests significant price fluctuations, while low volatility indicates more stable prices. Both high and low volatility can be favourable or non-favourable depending on the situation, as they represent both risks and opportunities for profit. High volatility signifies increased risk but also the potential for greater profits, whereas low volatility suggests reduced risk and price stability. In discussions concerning stock prices, volatility is typically expressed as a percentage, with higher values indicating greater volatility and lower values indicating lower volatility. Volatility can be calculated using different methods, such as standard deviation or variance among returns for a specific security or market index. There are different types of volatility: implied volatility and historical volatility. Implied volatility estimates how volatile the market will be in the future, while historical volatility refers to the observed movements in historical data for a security or market index, indicating how volatile the market has been over a certain period in the past. (Hayes, 2023)

For a market to operate effectively, it must be liquid. An electricity market is considered liquid if participants can trade large quantities quickly without significantly affecting market prices. One common measure of market liquidity is the churn factor, which indicates how frequently electricity is traded on the market. It describes the relative size of the electricity market compared to its physical size (ACER, 2021). High liquidity indicates a market with a substantial number of buyers and sellers, providing a sense of security and ease in trading. (Brolin et al., 2021)

2.6 The Intraday Market

The intraday market serves as a crucial market for optimising resources and balancing the system in the electricity market. It functions as a continuation of the day-ahead market where BRPs can trade to maintain balance, it becomes operational once the day-ahead market results are released and remains active from one hour to fifteen minutes before the scheduled delivery hour.

Trading on the intraday market occurs continuously during every hour of the day. It is called continuous trading. Every trade occurs between two parts for a certain volume of electricity for a certain second. The price is individual for each trade, determined by the pay-as-bid principle, where buy and sell orders are matched for every second. However, traders on the intraday market do not have the option to select specific sellers or buyers, nor can buyers choose the type of energy they wish to purchase. This is because the market operates based on the principle of real-time matching supply with demand, and the available energy may vary depending on factors such as generation capacity, transmission constraints, and prevailing market prices. Therefore, buyers must typically accept the energy that is offered at the prevailing market price, rather than being able to specify particular energy sources or characteristics. Instead, transactions are executed based on prevailing market conditions and available offers. (Svenska Kraftnät, 2023b)

In May 2023, a change from one hour to fifteen minutes trading period on the intraday market occurred and aimed to make trading more efficient. (Brolin et al., 2021) The change impacted all actors in the intraday market by enabling more accurate management of variations in the power system, which is crucial as the amount of variable electricity production increases. The 15-minute trading makes it possible for actors on the intraday market to keep the market financially balanced to a larger extent. Once all European countries have harmonised the imbalance settlement period to 15-minute it will be possible to trade balancing energy between countries to a greater extent. This change is favorable for unplanned generation such as wind and solar power which will be handled with higher efficiency as it generates flexibility and more accurate price signals. (Svenska Kraftnät, 2024)

In 2019, the European Union Agency for the Cooperation of Energy Regulations, (ACER) approved the algorithm methodology of intraday auctions in accordance with CACM Article 55. (ACER, 2019) The Methodology for pricing intraday cross-zonal capacity is planned to take place in June 2024 and aims to improve trading opportunities on the intraday market by a so-called, pay-as-clear principle. It is a collaboration between the European TSOs and the electricity exchange NEMO. The method will consist of three daily auctions on the intraday market which will make the intraday market too a pay-as-clear market, instead of a pay-as-bid market as it is today. The auctions are implemented to improve trading opportunities on the intraday market and will create a fair allocation of transmission capacity. The liquidity will accumulate and create a better formation, an easier trading situation and a greater likelihood of bids being matched. (OTE, 2024) However, the data analysis in this study will, as mentioned in the methodology, focus on the intraday continuous.

The traders on the intraday market can be divided into demand-side participants and resource-side participants. Actors can act as both sides depending on the situation. The demand-side participants are actors that need to trade after the closing of the day-ahead market due to, for example, changes in the weather forecasts, unbalance between planned production and available capacity, or changes in electricity demand. The resource-side participants are actors who possess resources that were not allocated in the day-ahead market, indicating that they have available capacity to sell. This could depend on different factors, for example, trades being too expensive, changing cross-border trading capacities, or newly added units that were available after the closing of the day-ahead market. When the day-ahead market closes, the demand-side participants can either trade on the intraday market or close their positions in the imbalance settlement and the resource-side participants can either, like the demand-side participants, trade on the intraday market or offer their resources on the balancing market. The participants in the intraday market include a diverse number of stakeholders within the energy sector. This includes individual or organisational traders, electricity producers, distributors, as well as system operators responsible for managing the real-time balance between electricity supply and demand. Electricity market operators play a crucial role in facilitating transactions and ensuring the efficient functioning of the market. Regulatory agencies and market oversight organisations are also key participants due to their work on maintaining market integrity and enforcing established rules. In essence, the intraday market involves a dynamic interplay among various actors, each contributing to an effective and real-time trading of electricity. (Brolin et al., 2021)

2.7 Future Scenarios

Svenska Kraftnät published in January 2024, a long-term market analysis where four scenarios representing the future development of the energy system during the years 2025-2050 in Sweden are presented. The growing need for increased electrification is representative in all scenarios as a part of the transition towards a fossil-free society. The four scenarios of the report are listed below:

1. Small-scale Renewables (SR)
2. Mixed Roadmaps (MR)
3. Plannable Electrification (PE)
4. Renewable Electrification (RE)

Figure 6 on the next side, shows the analysis results for 2035 and 2045. Wind power production is planned to increase in all the scenarios. Scenario Renewable electrification has the highest planned wind power production, 170 TWh in 2045. The renewable electrification scenario and the small-scale renewable scenario both include a phase-out of all nuclear power plants in Sweden. In these two scenarios, renewable energy sources will play a major role, especially in the expansion of land-based wind power. To enable the required investment in RES and an expansion of wind power, the authorization processes for wind power need to be rewired and updated. In the scenario of Plannable electrification, nuclear power is on the other hand planned to expand to 110 TWh. (Nycander et al., 2023)

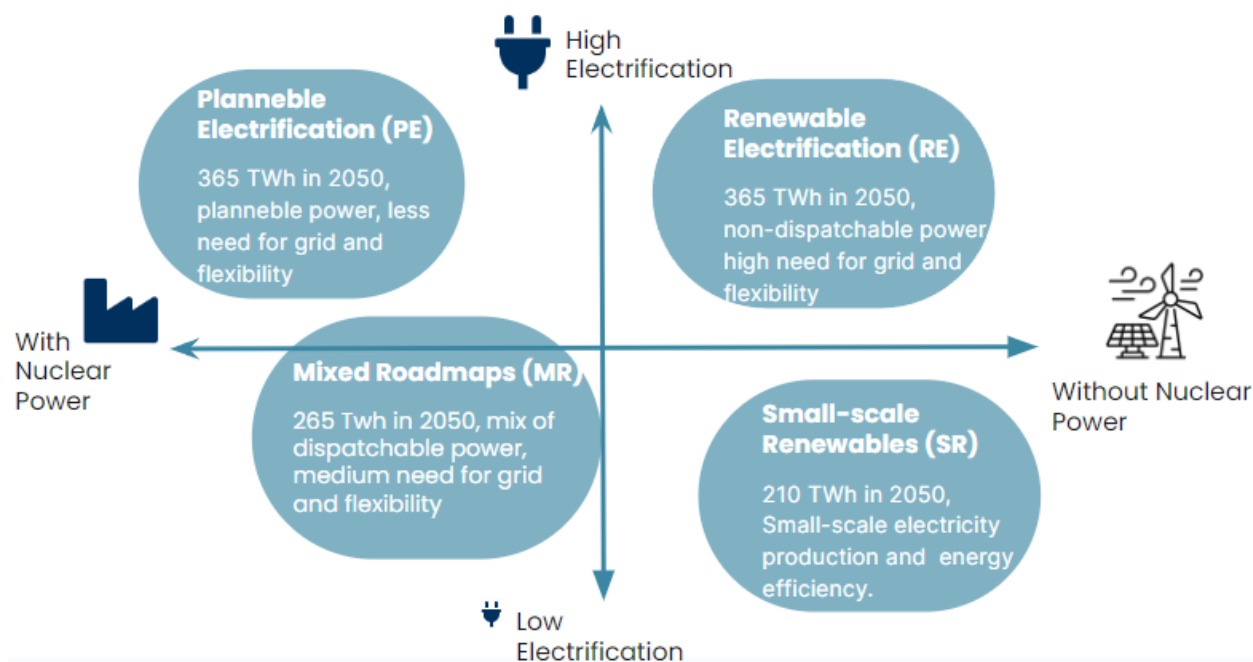


Figure 6: Illustration of scenarios of Svenska Kraftnät's long-term market analysis. The scenarios are mainly differentiated by the share of nuclear power versus renewable production (x-axis) and electricity usage (y-axis). Derived from (Nycander et al., 2023)

Methodology

This section outlines the study’s methodology, aiming to explore the historical development and the future trajectory of the intraday market. The first research question seeks to understand the intraday market’s historical evolution using qualitative and quantitative methods. The second research question aims to draw conclusions about the future intraday market, based on the findings from the first research question. Developed by Flower, these researched questions enhance understanding of the intraday market and provide a foundation for further research. Driven by Flower’s interest, relevant correlation factors are analysed. These factors are identified based on Flower’s knowledge of what influences the intraday market. To ensure reliability, the chosen correlation factors are supported by an analysis from the Swedish Energy Markets Inspectorate, which has summarized factors affecting electricity prices that align with those examined in this study regarding intraday prices. An illustration of Ei factors impacting electricity prices is presented in Figure 11. Flower identified the following five correlation factors for this study:

- Day-ahead Trades
- Renewable Deployment
- Balance between Demand and Supply
- Grid Connections
- Macroeconomic Indicators

The day-ahead trades, including price and volatility, will be analysed in Section 4.4. Renewable deployment, focusing on wind power production, is studied in Section 4.5. Section 4.6 examines the balance between demand and supply, emphasizing the importance of a balanced system involving production and consumption. Section 4.7 explores the correlation between physical grid connections and electricity trades. Lastly, macroeconomic indicators, which include events that impact the intraday market, are analysed in Section 4.8. The main purpose of the correlation factors is to understand the historical development of the intraday market. Similarly, data analysis aims to provide insight into the observed changes in the intraday market. Specifically, the data analysis on intraday trades focuses on comparing these changes with selected correlation factors to understand their impact. Among the five identified correlation factors, wind deployment and day-ahead prices are further analysed due to the availability of relevant data. A detailed description of the data analysis process is provided in Section 3.1. In order to forecast the future of the intraday market, scenarios derived from Svenska Kraftnät’s long-term market analysis are used. The discussion integrates the five correlation factors, results from the data analysis, and future scenarios to comprehensively address the research questions. Figure 7 illustrates the methodology in a diagram.

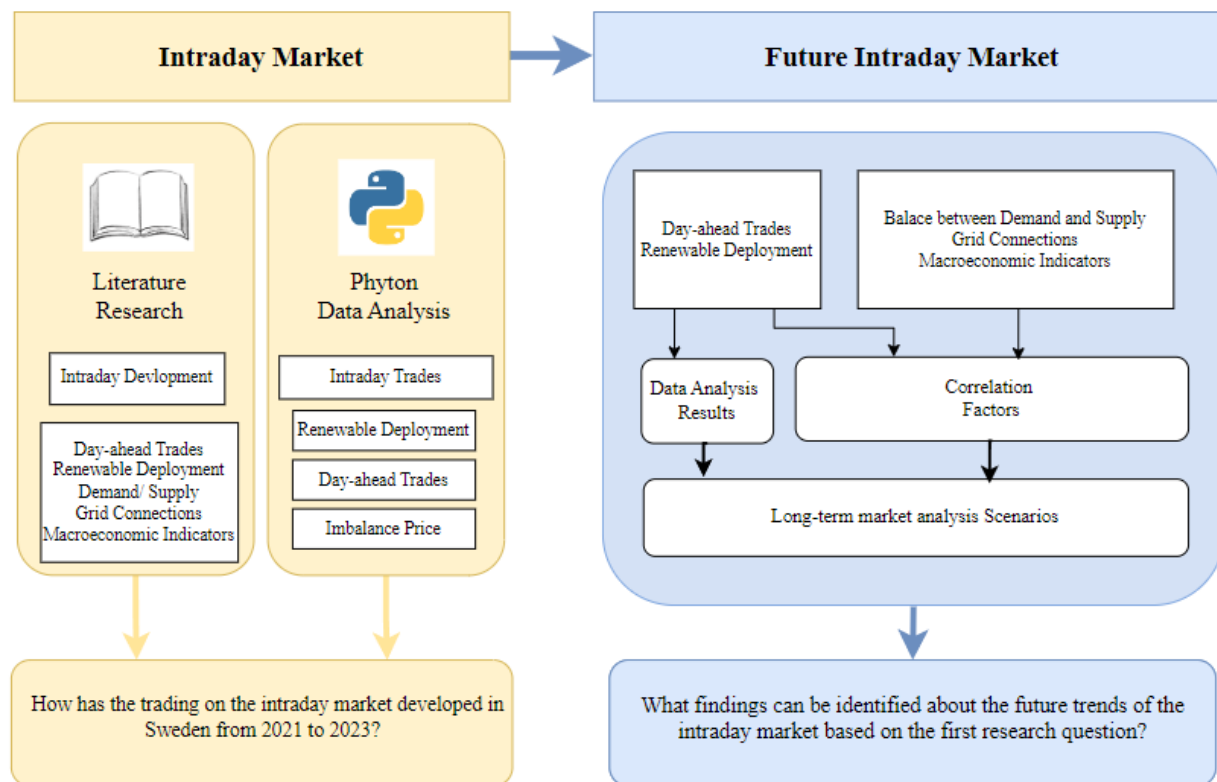


Figure 7: Schematic illustration of the methodology of the study

3.1 Data Analysis

The data analysis is conducted by mapping data provided by Flower and collected from Nord Pool. The analysis is performed in Jupyter Notebook using Python. Due to restrictions on sharing energy market trading data, the code from the data analysis will not be included in the report. The analyzed data spans the years 2021 to 2023, with price data based on bidding zone SE3. Wind power production and wind forecasts refer to the total wind power production in Sweden, encompassing all bidding zones. The data used in the analysis include intraday trades, day-ahead trades, mFRR regulation prices, wind power production, wind forecasts, and solar production. The intraday data, day-ahead data, the mFRR data and the wind data are provided by Flower, collected from Nord Pool, and the solar data are collected from the Svenska Kraftnäts statistical database Mimer (Svenska Kraftnät, n.d.). The data analysis is conducted in five steps, from collecting the data to obtaining the results. The first step is to collect and sort the data. Depending on the data format, different methods are used to process the data and simplify the calculations. This step is described in Section 3.1.1. Once all the data is ready, it is plotted, and the correlations between the plots are measured. The imbalance calculation is performed to analyze the correlation between mFRR pricing and intraday prices. The plotting method is detailed in Section 3.1.2, the imbalance calculation is described in Section 3.1.3, and the correlation measurement method is explained in Section 3.1.4. The final step is to compile the results of the plots and correlations and analyze these results to form a discussion. The steps are described in detail below.

3.1.1 Collecting and sorting the data

The data of the intraday trades is originally showing each bought and sold trade that has been done every second. In order to analyse the data, some sorting has to be done. Firstly, the time format of the dates is changed to a more compatible format where the time is set, in Python called a *datetime-object*. In order to create an average over both bought and sold trades, a mean value for each second is determined by taking the mean of buy and sell for every trade according to Equation 1.

$$\text{IntradayTrade} = \frac{\text{BoughTrade} + \text{SoldTrade}}{2} \quad (1)$$

This means that the intraday data are based on an average value of buy and sell trades. After this, the data are cleaned to match the calculations. For example, duplicates and non-values are removed. An average value for every hour is calculated based on trade-specific data. This is done by collecting every trade within the same hour and then calculating a mean value for that hour, based on the trades for each second. Equation 2 visualises this calculation where *Hourly Trade* represents the average value of trades within a single hour, Trade_i denotes the value of each individual trade and n is the total number of trades that occur within that hour.

$$\text{HourlyTrade} = \frac{\sum_{i=1}^n \text{Trade}_i}{n} \quad (2)$$

The calculations are done in the same way to receive a mean value for each day and for each month. For the day-ahead, mFRR and wind data, the datasets already is in hour format meaning that less sorting is needed. The sorting was rather regarding changing the format of the dates, as with the intraday data. The wind forecast error is calculated as the produced wind minus the forecast wind for each hour according to Equation 3.

$$\text{Wind Error} = \text{Produced Wind} - \text{Forecast Wind} \quad (3)$$

After sorting the data, it is listed and compiled in order to plot it. One dataframe including all data is created to summarise all the collected information.

3.1.2 Estimating Price, Volume, Volatility and wind power production

The produced data plots of the three markets; intraday, day-ahead and mFRR consist of volume and price plots where the volume is measured in megawatt hours and the price plots are measured in Euro per megawatt hours. These plots are presented in Section 3.1.5 and 4.8. The prices are volume-based since a trade with a very high price may represent a low volume. It is therefore important to consider the volumes when calculating the prices. Prices are based on hourly average data. The volume plots show the total volume of intraday trades in SE3. The price and the volume are plotted based on hourly, daily and monthly values in order to have a high range of results. The plots in the report are however chosen to be on daily values. This is because the hourly data includes too many data points to have in a plot and the monthly data excludes important information. Volatility is determined by calculating the standard deviation of the hourly intraday and day-ahead prices. This means that the volatility values are received on daily values since they are based on hourly values. The price difference is calculated as the day-ahead price minus the intraday price and the wind forecast error was calculated as the actual produced wind minus the forecast wind.

3.1.3 Imbalance Calculation

The mFRR market starts after the intraday market and is relevant since it sets the imbalance price. Imbalances are created when traders on the intraday market do not produce or consume what they promised. The connection between the mFRR and intraday market is investigated due to Flowers' interest in understanding the correlation between the difference of imbalance minus intraday price and the difference between day-ahead price minus intraday price. Since the mFRR and imbalance settlement occur after the intraday market, the mFRR market is not determined as a correlation factor impacting intraday prices.

To determine the correlation between the imbalance and intraday prices, an imbalance calculation is done. The imbalance is equal to a certain price depending on the state of the system. For each hour, if the day-ahead price is lower than the mFRR up-regulating price for that hour, the imbalance price is set to the up-regulating price. If the day-ahead price is higher than mFRR-down regulating price, the imbalance price is set to the down-regulating price. Else, the imbalance price is set to the day-ahead price. (eSett, 2024)

3.1.4 Correlation Measure

The correlation measure is done with a function in Pandas in Python called *dataframe.corr()* which calculated the Pearson correlation coefficient. It gives a value between -1 and 1. A correlation of zero means that there is no correlation. A negative correlation means that the two factors move in opposite directions: when one increases, the other decreases. The function locates the pairwise correlation in a given dataframe (Pandas Documentation, 2024). The correlation values, except for volatility, are based on hourly data. The volatility is based on daily averages as it is only available in the format of daily data. The correlation calculation is done on the three years but also for each month separately to examine if there are seasonal differences between correlations of different months. This is of interest since wind power production varies within a year depending on the season and thereby might influence the correlation between price/volatility and wind power production. The data is hence divided per month and the same correlation calculation is done for each month. Equation 4 describes the correlation function *dataframe.corr()* where r is the correlation coefficient, x_i and y_i are the individual data points in the two data sets x and y , \bar{x} and \bar{y} are the means of the data sets x and y , respectively, and n is the number of data points.

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (4)$$

3.1.5 Peak Analysis

To interpret the data, a peak analysis is performed based on the intraday price plot. The highest peak within the data is chosen to identify the factors influencing prices during periods of very high and low intraday prices. Since the correlations are calculated on a monthly basis, the peak period is selected for the months with the highest intraday price values. First, the impact of wind power production and day-ahead prices on the peak price is studied, followed by the impact of other events. Nord Pool's REMIT UMM platform (Nord Pool, 2024) is used to identify unexpected changes in electricity generation and consumption and to inform market participants. By searching for specific dates on the REMIT UMM platform, unexpected changes in production and consumption were identified.

Historical Development

This Section describes the historical development of the intraday market and its influencing factors. It includes results from the data analysis regarding the development of intraday prices, day-ahead prices and a mapping of the wind power production from 2021 to 2023. The Section begins with a historical overview of the intraday market and continues with an analysis of the impacts of the market electricity price by analysing chosen factors and events that historically have affected the intraday market. The following factors are analysed in the Section: day-ahead prices, renewable deployment, grid connections, macroeconomic indicators, and demand and supply patterns.

4.1 Development of Intraday Market

In 1996, the Swedish electricity market was deregulated, transforming from a system in which the government held a monopoly on the Swedish energy market (Brolin et al., 2021). At the same time, the Norwegian-Swedish electricity exchange named Nord Pool ASA was established to facilitate efficient electricity trading. Finland joined Nord Pool ASA in 1998, followed by Denmark by the year 2000. By the turn of the millennium, all Nordic countries were part of the unified Nordic day-ahead spot market. Today it is known as Nord Pool and is defined as the world's first international power exchange. The establishment of Nord Pool led to the creation of the first international intraday market Elbas by the year 1999. The intraday market was first used by Sweden and Finland, but expanded 2004 by eastern Denmark, 2006 by Germany, and 2007 by western Denmark. By the year 2013, Norway, Belgium, the Netherlands and Balticum had entered the intraday market. (Nord Pool, n.d.[b]) In 2015, the European Union regulation established a guideline on capacity allocation and congestion management in order to promote competition in electricity production, trade, and supply while ensuring optimal use of transmission infrastructure and operational reliability. A significant change took place in the year 2018, when SIDC, Single Intraday Coupling, a cross-border European intraday market was introduced. SIDC is based on the XBID IT system, which enables bids to be matched from one bidding zone to another, provided that there is enough available transmission capacity. (Brolin et al., 2021)

4.2 Development of Intraday Prices

ACER stated in their 2023 Market Monitoring Report that market prices on the day-ahead and intraday market share the same main drivers regarding price development; economic efficiency and security of supply. Over the past few years, both the day-ahead market and the intraday market have improved their progress in terms of market integration. Today, all member states in the EU are coupled through continuous intraday trading in a functioning electricity market. The market integration has impacted the development of price, volume and volatility on the intraday market as well as on the day-ahead market. (ACER, 2023)

Since 2020, the overall volumes traded across the European network on the intraday market based on all bidding zones has increased. However, the volumes stabilised by 2021 to 2022 which is when the prices on all markets were spiking as a consequence of the energy crisis. The Nordic market, which is reflected by the outcome of the European market, followed this trend showing record high levels of volumes traded on the intraday market in 2023. According to EPEX spot annual market review, prices on the common European intraday market EPEX stabilised meaning that prices went back to normal levels by 2023, compared with the record price levels that appeared during 2022. The same was applied to volatility which spiked in 2022 and then went lower during 2023. (EPEX SPOT, 2023) The phenomena of negative electricity wholesale prices, meaning that power suppliers have to pay their consumers in order to sell electricity on the day-ahead and the intraday market, saw a rapid expansion in most of the Nordic bidding zones in 2023, stated in the *2024 Market Monitoring Report*. It can be explained as an expansion of RES, continued market integration and increased access to flexibility. Even other factors specific to 2023 might have impacted the negative prices and have yet to be further investigated by ACER. (ACER, 2024)

The implementation of SIDC, the single intraday market coupling taking place in 2017, has resulted in an increased share of cross-zonal intraday trading. Higher amounts of bids were available for market participants which has helped market participants to reduce imbalance costs and at the same time support the balance of the electricity system. (ACER, 2023)

Based on data from Nord Pool, a graph over the SE3 intraday price during the recent three years has been created. Figure 8 shows the intraday price from the year 2021 to 2023. Compared with EPEX annual market review, these are the prices only for SE3, however, there are similarities. According to EPEX annual market review, prices stabilised during 2023 which corresponds with Figure 8 where fewer peaks are visualised during 2023 compared to 2021 and 2022. Over the span of these three years, it is evident that the intraday prices peaked in 2022, notably with two significant spikes occurring in September and December. Additionally, there's a distinct period from November 2021 to March 2022 where prices remained consistently elevated compared to typical levels. Given that the graph displays average daily prices, it does not include any instances of negative prices even though it might occur. Further examination of the peaks visualised in the Figure will be undertaken in Section 4.8.

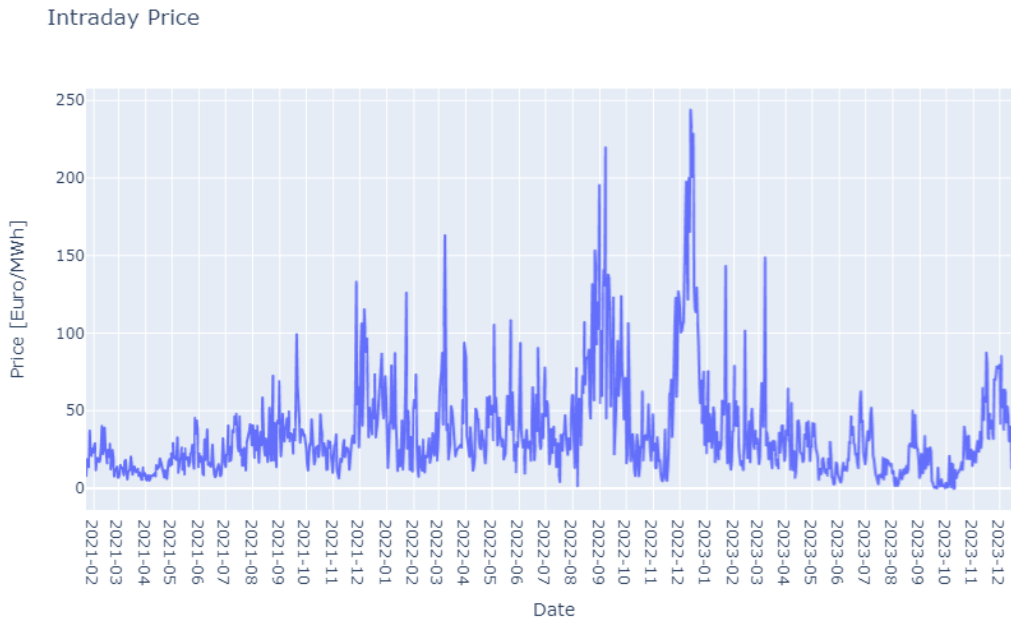


Figure 8: Intraday prices in SE3 for 2021 to 2023 based on daily values.

Figure 9 visualises the total volume traded each month on the intraday market in megawatt hours from 2021 to 2023. According to the EPEX annual market review, the overall volumes traded on the European intraday market have increased across all bidding zones. The Nordic market, in particular, reached new all-time highs in 2023. As shown in Figure 9, the trading volume remained stable throughout 2021 and 2022, with a significant increase observed towards the end of 2023. This pattern reflects the increase in trading volumes in the Nordic market and follows the trend of increased trading in the intraday market across Europe.

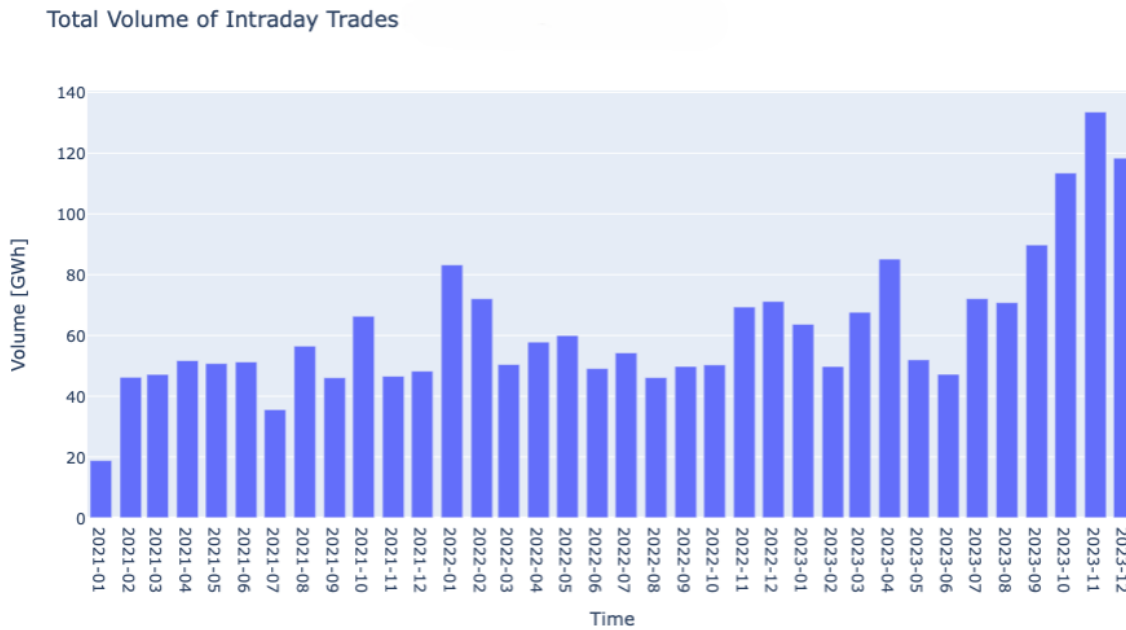


Figure 9: Intraday volume in SE3 for 2021 to 2023 based on daily values.

In order to analyse the spread of the trades, the volatility of the trades has been examined. Figure 10 illustrates the intraday volatility in SE3 spanning from 2021 to 2023. Notably, volatility reaches its peak in 2022, while experiencing a dip in both 2021 and 2023. The highest volatility peak manifests in September 2022, correlating with the day of the highest intraday price peak. The spikes of the volatility graph follow the peaks visualised in the graph over intraday prices. During periods of peak volatility, the degree of fluctuation in trading prices reaches its maximum, indicating a high level of intraday price volatility. As for intraday prices, a further examination of these peaks will be undertaken in Section 4.8.

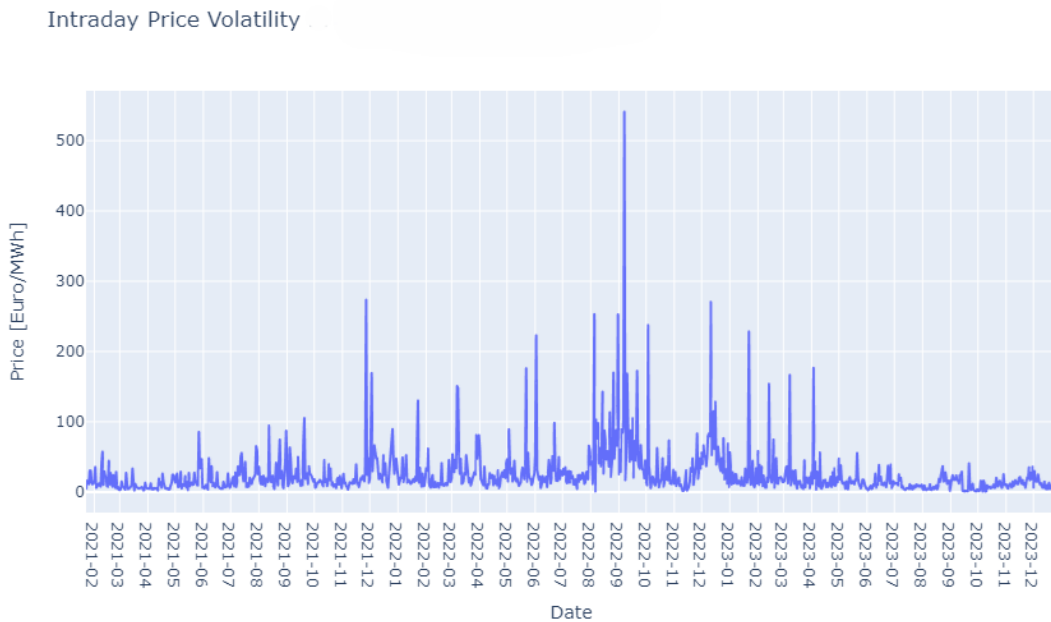


Figure 10: Intraday price volatility in SE3 from 2021 to 2023 based on daily values

4.3 Influencing Factors on the Intraday Market

There are different factors affecting the market price of electricity which further impact intraday price, volume and volatility. The market price of electricity on the electricity exchange sets the electricity prices reaching the consumer. Electricity prices partly depend on the current supply and demand of produced and consumed electricity and how well available generated electricity can be matched with consumer demand. Since the Swedish electricity market is integrated with the European market where trading occurs cross-boarder, the situation on the European market also has an impact on Swedish electricity prices. An illustration of the factors affecting electricity prices set on the day-ahead market is presented in Figure 11 on the next page. (Ei, 2023b)

Firstly, the electricity supply will impact electricity prices depending on the production source. The produced electricity in Sweden mainly consists of hydropower, nuclear power, wind power and heating power. Current weather conditions have an impact on the amount of electricity produced due to the great amount of variable and renewable electricity production, (VRES) in the Swedish electricity mix. The situation in Europe is different since fossil fuels are used to a higher extent which causes fuel prices to impact electricity prices on the integrated market, including Sweden. Since Sweden is integrated into the European market where electricity is traded across cross-boarders the price set in the neighbouring countries will impact prices in Sweden together with European regulatory frameworks and guidelines. The Swedish electricity network is especially well interconnected with Norway, Denmark and Finland which causes electricity prices in these countries to consequently affect prices due to electricity flows from low-high price bidding zones. The electricity demand affects electricity prices in mainly two ways; to which extent electrification of the industry and transport sector takes place together with the consumer capability to use electricity flexibly. (Ei, 2023b)

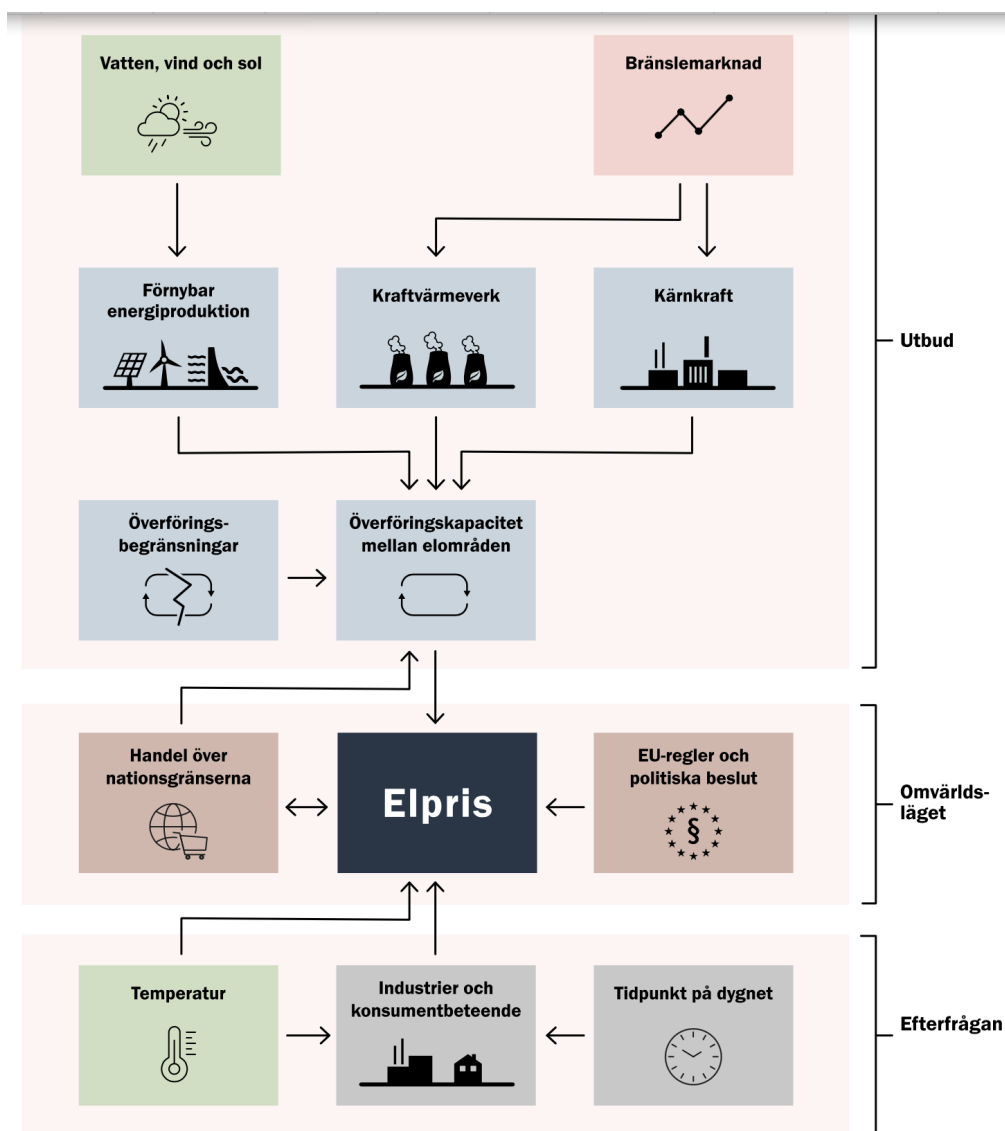


Figure 11: Factors impacting electricity prices (Ei, 2023b)

4.4 Day-ahead Trades

The day-ahead market influences the intraday market. What happens on the day-ahead market will have an impact on the following intraday market. (Brolin et al., 2021) Stated in a report by Cramer et al. (2023) where the correlation between intraday and day-ahead prices are studied, it is concluded that intraday prices fluctuate around the day-ahead prices. Both higher and lower peaks occur on the intraday market compared to the day-ahead market. Since the intraday market is used to adjust bids traded on the day-ahead market, the intraday trades compensate for forecast errors of demand and renewable electricity supply. (ibid.) Therefore, analysing the impact of day-ahead prices on intraday price development is of particular interest, given that the intraday market is an extension of the day-ahead market. Figure 12 presents the day-ahead prices in SE3 spanning from 2021 to 2023. Over the span from 2021 to 2023, it is visualised in Figure 12 that prices spiked in 2022, especially notable with two significant peaks similar to the intraday price peaks. According to ACER's *2024 Market Monitoring Report* regarding electricity prices in the EU, on average day-head electricity prices dive in 2023 even though variability persists compared with pre-crisis values in 2019. It is stated that within EU member states average day-ahead prices are still more than double the average day-ahead price in 2019. Similarly accounts for the volatility which also shows higher values in 2023 than pre-crisis. (ACER, 2024) The day-ahead prices in SE3 display similar patterns, however, comparing them with pre-crisis levels is not feasible.

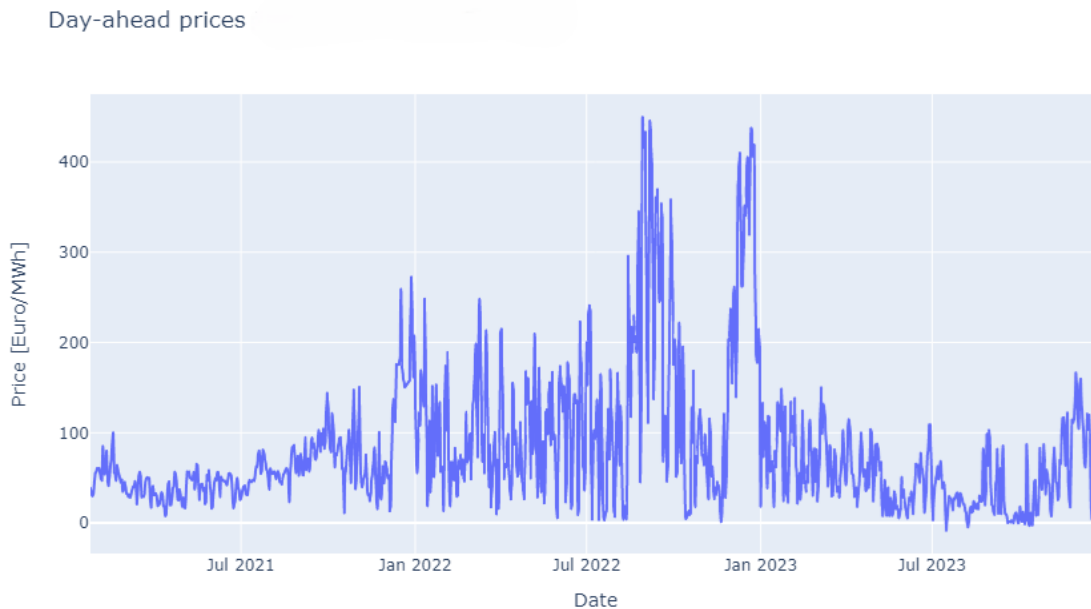


Figure 12: Day-ahead prices in SE3 from 2021 to 2023 based on daily values

4.5 Renewable Deployment

RES has a long history in Sweden. Hydropower has dominated Swedish energy access since the beginning of the 1900th century and was built to provide the mining industry in the north with electricity. Today, hydropower is well-developed and an important energy resource for the whole country. (Vattenfall, n.d.) Alongside the energy transition, wind power has become increasingly important as RES, especially in Sweden where the conditions for wind power are favourable. There has been a significant expansion of wind power deployment due to an increased demand for RES. (Brolin et al., 2021) The European Commission stated in 2018, in *A clear planet for all*, the importance of RES, including wind power and how it would play a major role in the energy transition. (European Commission, 2018)

Figure 13 shows the wind power production in Sweden from 2021 to 2023. The wind patterns indicate higher production during the winter months and lower production during the summer months. However, the wind power production pattern is not further investigated in this report.

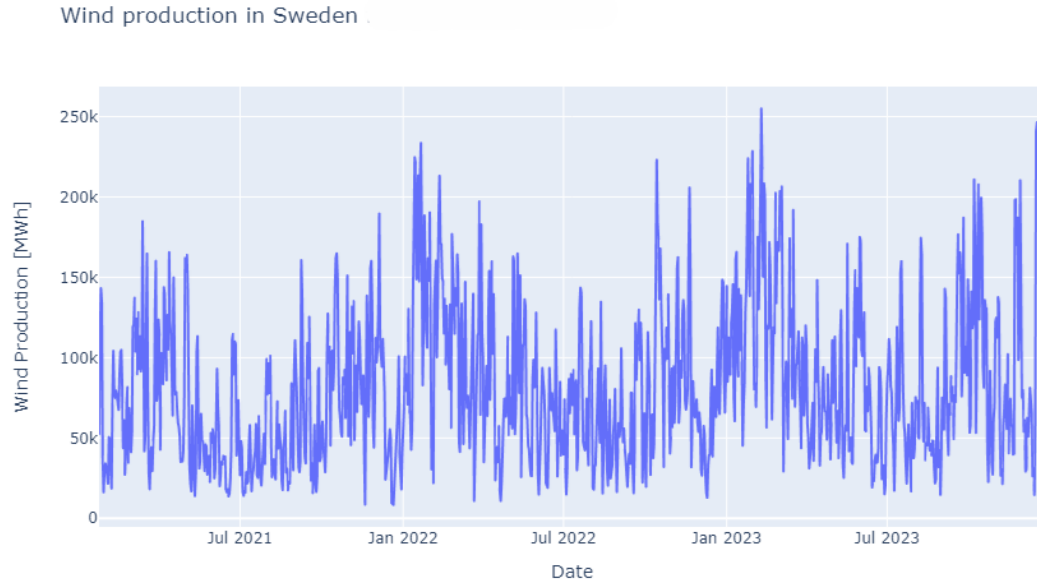


Figure 13: wind power production from 2021 to 2023 based on daily values

Wind power is an intermittent energy resource, meaning that its output cannot be controlled since the wind is not controllable. Its generation fluctuates based on wind availability, resulting in periods of both high and low output. (Spodniak et al., 2021) Due to the intermittent nature and the expanding deployment of wind power, it is becoming more accurate to predict actual RES closer to the delivery hour. The markets are consequently shifting towards intraday and balancing markets to avoid imbalances in the system and hence, trading on the intraday market becomes more important. (ibid.) Brolin et al. (2021) states in the report *En generell beskrivning av intradagmarknadens funktion* that there is a clear correlation between trading volumes on the intraday market and the development of wind power. (ibid.) If the expansion of wind power is rapidly growing, after reaching a certain threshold, the relevance of different electricity markets will change which will have an impact on the future market design. The near real-time markets, such as the intraday market, will become more relevant in a future scenario by serving as price references for capacity markets, hedging, investments and other decision-making purposes as the expansion of VRES. This is especially the case in areas with a large share of wind power generation such as SE4 and the southern part of Sweden. When the share of wind power generation is high wind-forecast errors affect the price spread at a higher rate. In SE3 where the share of wind power is lower, however still constitutes an important role, the wind forecast errors in contrast affected only the price spread between the intraday and regulated power markets. This is stated in an article by (Spodniak et al., 2021) where price spread between different marketplaces (day-ahead, intraday and regulating power markets) was investigated.

4.6 Demand and Supply Balance

Along with the development of the electricity system, it is important to keep a balance between consumption and production at every time frame. The Nordic TSOs explain this as an ongoing difficulty with elevated importance which demands more flexibility in the system. They claim that the high growth of production and consumption might generate imbalances in the system. (Nordic Transmission System Operators, 2023) These imbalances create incentives for owners of flexible resources to provide flexibility in the wholesale and balancing market, receiving income from selling flexibility services. The system is designed so that flexibility provided closer to the delivery hour is needed to maintain the frequency regulated at 50 Hz. Operating an electricity system with high levels of VRES will require increased flexibility on both the demand and supply sides to mitigate potential mismatches in supply and demand.

In the Swedish power system, the presence of substantial hydropower has ensured grid stability and has historically created a competitive wholesale and balancing market, thus it has been preventing flexibility issues. However, the need for flexibility services has changed and additional flexibility resources have been entered. (Harit et al., 2022)

In an electricity system with a growing share of wind power, electricity prices fluctuate: they are low when the wind power supply is abundant and high when it is scarce. These fluctuations incentivise investments in flexibility to complement wind power supply. This trend explains the recent increase in demand for flexibility services and may lead to an even greater demand in the future. (Göransson et al., 2023) A way of discussing the future of flexibility in the Swedish power system is the concept of (in)flexibility of the current power system. This is because indicators of inflexibility may be more readily apparent than those of flexibility. Firstly, a potential sign of inflexibility in the Swedish power system is an expected increase in power ramping meaning that the power, in terms of power flow per time unit, is expected to increase. Difficulties regarding balancing demand and supply might result in frequency fluctuations in the power system that has to be balanced, defined as the second sign of inflexibility. The third sign of inflexibility is the price volatility that might increase the occurrence of negative market prices which further might indicate limited system flexibility in terms of availability of ramping and limited demand flexibility. (**Flexibility**) Grid-scale flexibility is integrated into the power system through batteries, heat pumps and other production units. Apart from the flexibility provided by the supply side, there is demand-side flexibility. (gridX, 2024)

Flexibility on the supply side means adapting energy production based on the need of the energy system while flexibility on the demand side means adapting the consumption of electricity. Such demand-side flexibility can be increased, reduced or shifted at a certain time to facilitate the integration of VRES. In this way, demand-side flexibility will help the electricity system to adapt to the load on the electricity network based on renewable electricity production such as reduced peak loads and seasonality. At the same time, it can reduce electricity generation costs by shifting consumption from high-cost periods to low-cost periods. (International Renewable Energy Agency, 2019)

4.7 Grid connections

As previously mentioned, the physical flow of electricity must be balanced between demand and supply for the system to function. Due to the uneven spread of electricity production in Sweden, the supply and the demand in each bidding zone could be uneven and it is thereby of high importance to balance up the system. There is an excess of electricity in the north of Sweden, where there is a high electricity production while there often is a deficit in the south of Sweden, where the demand is higher and the supply is lower. This is the reason why the electricity price can differ in each bidding zone. In order to maintain a well-functioning electricity system, the bottlenecks need to be addressed. The flow of electricity needs to be balanced throughout the whole country for the system to match the demand and supply. Due to the uneven supply and demand of electricity, it is of high importance to have an efficient physical grid. (Svenska Kraftnät, 2021c)

European market coupling allows electricity to flow freely across borders. According to patterns of demand and supply and as a response of price signals, electricity flows between domestic and cross-zonal bidding zones. The Single intraday coupling (SIDC) allows participants to access a larger share of bids and offers allowing them to reduce their imbalances or efficiently support the overall system balance. Since 2017, when SIDC was implemented, the volume of electricity that has been traded cross-zonal within the EU has been increasing. Between 2017 and 2022 the continuous intraday-traded volumes within the EU have shown an increase of 70%. By having a well-functioning integrated electricity market resources can be used more efficiently enabling a better utilization of the electricity generation across the EU. A large part of the intraday trading that occurs through Nord Pool is part of the Single Intraday Coupling where XBID serves as the technical solution where the coupled cross-border intraday trading takes place. (ACER, 2023) Grid connections between countries open up for increased cross-zonal trading on the intraday market as well as on the day-ahead market and the balancing markets. At the beginning of 2016, a grid connection between Sweden and the Baltic region where implemented as one of the first grid connections strengthening the the connection between the Nordic and Baltic electricity markets. (Svenska Kraftnät, 2021d)

During 2021, two new interconnections between Norway and international markets became operational: North Sea Link and Nord Link. A new market integration was implemented between Norway and the United Kingdom and Norway and Germany commissioned in the autumn of 2021. Cross-border power flows have been in operation between the Nordic countries for decades however the connection to the UK and Germany opens up a large increase in transmission capacity to both the UK and to Central Europe. The North Sea link resulted in upward pressure on the Nordic power prices when implemented. Due to higher electricity prices in the UK compared to the Norwegian system, electricity prices in both markets were affected. The North Sea Link resulted in lower electricity prices in the UK and higher prices in the Norwegian bidding zone NO2, with higher flows occurring from north to south than the opposite. Neighboring bidding zones in Sweden, Norway and Finland have shown price fluctuations as a result of the implementation, since trading occurs on an integrated market. (Simonsen et al., 2022) Overall since 2021, the increased market coupling followed by the implementation of the Nord Link cable has affected the price levels upwards in the bidding zones covered by NordPool. This, is a result of the high continental electricity prices driven up due to increased fuel prices which has caused electricity exports from the Nordics to Germany to increase. This in term has affected the prices on the Nordic market. (Energimyndigheten, 2022)

4.8 Macroeconomic Indicators

The electricity market in Sweden has been facing multiple short-term challenges, one particular is the energy crisis causing unmanageable high electricity prices and an increased risk of electricity shortages as it started in 2021. Energy prices started to rise substantially in 2021 when the demand for liquefied gas started to increase as a result of the pandemic (International Energy Agency, 2023). Another influencing factor of the changes in the world economy is the COVID-19 pandemic that broke out at the end of 2019 and was ongoing until 2023 (European Centre for Disease Prevention and Control, n.d.). The pandemic caused changes in the energy consumption behaviour due to the restrictions. A study from Van Zoest et al. (2023) states that the restrictions caused changes of consumption patterns and an increase in electricity use. The use of electricity increased within the consumption sector due to people working from home. (ibid.) Berezvai et al. (2022) states that the changes in consumption behaviour have caused changes in the electricity peaks and valleys within an hour of the day and on weekdays or weekends. The same study stated that there was a 9% decrease in the total electricity consumption. (ibid.)

An unprecedented increase in gas and electricity prices in the energy market was recorded during the second half of 2021, with an impact on the electricity market in Sweden as well as in the rest of the EU. Apart from the consequences of the pandemic affecting electricity prices, the energy crises can be explained as a combination of three different independent crises that have hit the EU around the same period. Firstly, Russia's invasion of Ukraine has choked off exports of electricity, coal and gas causing fossil-fuels-based electricity production to increase in price within the EU. Although fossil fuels generate less than 40% of the electricity at an EU level, electricity prices are often set by the gas price due to the merit order principle meaning that it is the most expensive source of supply that sets the market price of electricity (Christensen, 2023). Secondly, technical problems and shut down of nuclear power plants in the EU occurred during the same period, affecting in particular the French nuclear power plants. On top of this, the overall hydropower production decreased by 21% in the EU due to a very dry season in southern Norway as well as in other parts of the EU (Holmberg et al., 2023). The energy crisis has driven electricity prices up to a level never experienced before. Prices in Europe reached a peak at an unprecedented 600 EUR/MWh in the summer of 2022. High electricity prices have caused large price differences between the bidding zones. (Christensen, 2023) Despite the high record of electricity prices, Sweden was one of the largest electricity exporters in 2022. Due to increased transmission capacity to other countries, the electricity markets in Sweden have been perceived as more vulnerable to high energy prices but at the same time improved the security of electricity supply through improved interconnections within Europe. (Naturskyddsforeningen, 2022)

The energy crisis has prompted questioning of the reliability of natural gas which could be a factor causing further acceleration of the renewable energy development around Europe. The importance of investing in infrastructure to better integrate regional markets and connect grid networks between countries has shown an increase as a consequence of the crisis. (International Energy Agency, 2023) For example the electricity generation in the EU reached record high levels during 2023 when the wind for the first time surpassed gas and coal in the electricity generation mix. The installed capacity of renewables increased sharply from 2022 to 2023 with an increase of the wind power of 8% in the EU. Apart from the crisis affecting the supply side, the demand side also appeared to be affected by the crisis. For example, in 2022 the crisis led to a decrease in electricity consumption which turned out to be a trend in 2023 when demand continued to fall across the EU, influenced by delayed economic effects. Due to the market integration within the EU, these effects most

likely have an impact on the intraday and day-ahead market in Sweden and might be an explanation for the spiking values of price and volatility visualised in the Figures presented above. (ACER, 2024)

Data Analysis

In this Section, the results of the data analysis will be presented and analysed. First, intraday trades will be analysed by comparing intraday patterns with influencing factors, allowing conclusions about intraday market trends. The correlation of the intraday price and volatility will be compared to wind and solar power production and day-ahead prices. This will be done to investigate the correlation between these influencing factors and the intraday price and volatility. To obtain further knowledge of intraday price and volatility, the highest peak has been selected for further investigation. The peak analysis will be presented in Section 5.5.

5.1 Solar Power

This Section will present the results of how solar power production influences intraday prices. Figure 14 shows the correlation between intraday prices in SE3 and solar power production in Sweden from 2021 to 2023. Solar power production peaks during the summer months, while there is almost no production during the winter months. The correlation between intraday prices and solar power production is -8%. In general, prices increase during the winter and decrease during the summer, which might explain the identified negative correlation, despite the low share of solar power in the Swedish electricity production mix.

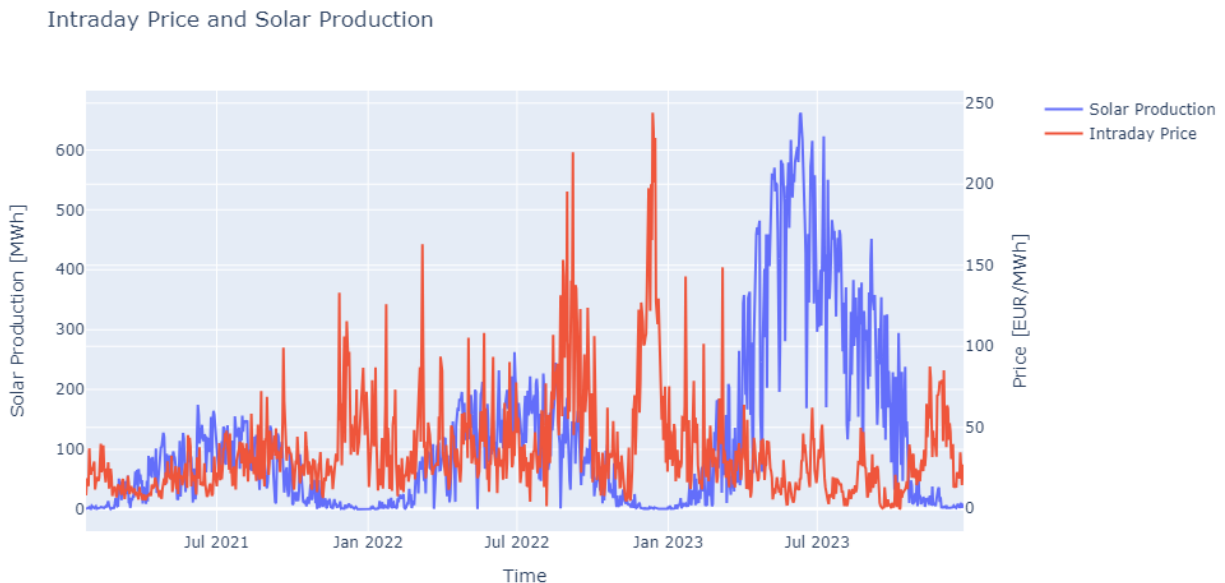


Figure 14: Intraday prices in SE3 and total solar power production in Sweden for 2021 to 2023, based on daily values

Figure 15 illustrates the correlation between intraday volatility and solar power production, calculated to be -9% . The peaks in intraday price volatility correspond with the peaks in intraday prices. Similar to intraday prices, volatility spikes during the winter when solar power production is nearly nonexistent. Due to the low share of solar power in the electricity mix, further examination of monthly correlations was not conducted. Since electricity prices are generally higher in winter and lower in the summer regardless of solar power production, the calculated correlations may appear to be higher due to other factors than the impact of solar power production, such as changes in electricity consumption.

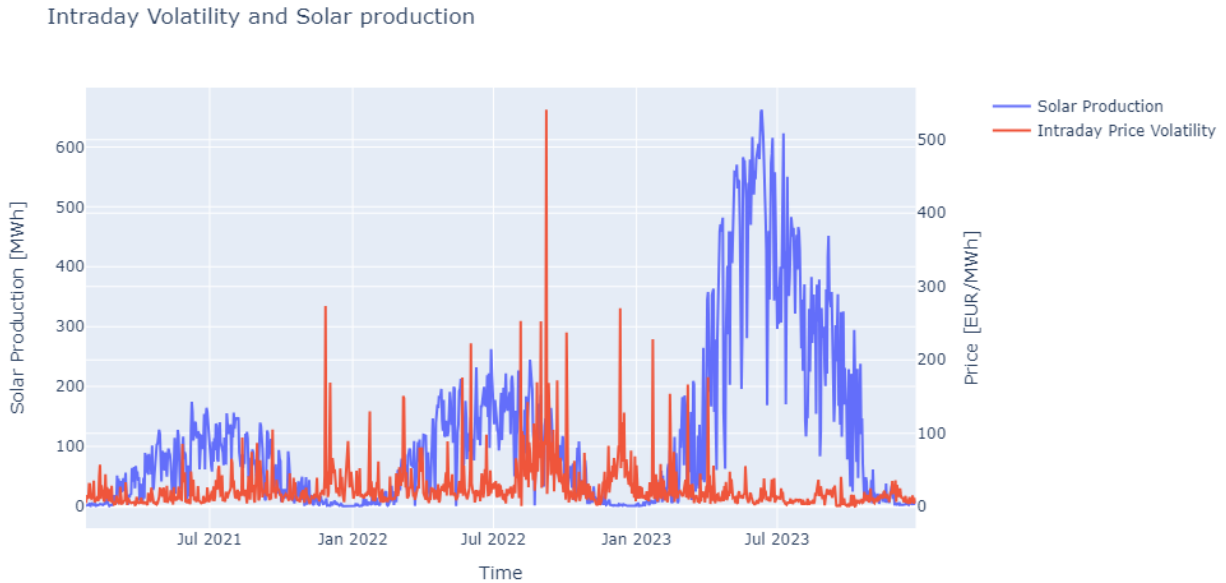


Figure 15: Intraday price volatility in SE3 and solar power production from 2021 to 2023 based on daily values

5.2 Wind Power

This Section presents how wind power production correlates with intraday and day-ahead price and volatility. Wind power production is presented as the total wind produced in Sweden in megawatt hours.

5.2.1 Wind power and prices

This Section will present the results of how wind power production correlates to intraday prices. It will also present how the day-ahead correlates with wind power production to compare it to the results regarding the intraday. Figure 16 shows how the intraday prices in SE3 correlate with the total wind power production in 2023. The blue line represents wind power production and the red line represents intraday prices. However, the wind power production follows a consequent pattern in 2021 to 2023. It is apparent that when wind power production increases, the intraday prices decrease and the other way around. However, the correlation between the intraday price and wind power production is -5%, which means that the intraday prices do not correspond much to wind power production.

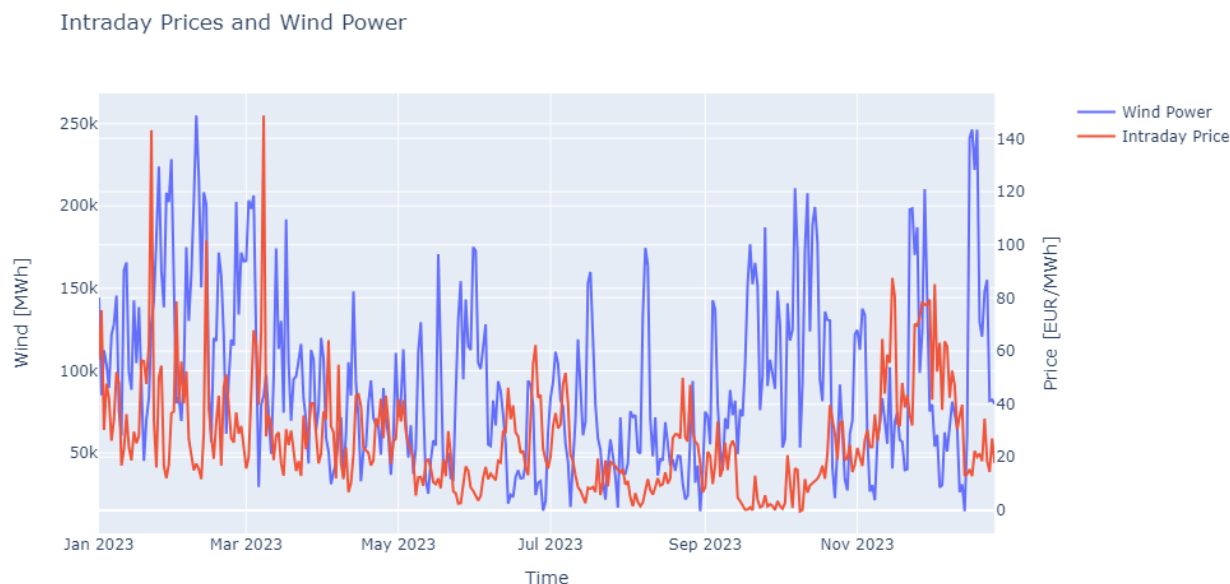


Figure 16: Intraday prices and wind power production in SE3 for 2023 based on daily values

An explanation of the low correlation between wind power production and intraday prices might be that the intraday price peaks do not correspond to the wind peaks even if the overall trend follows to some extent. The correlations calculated separately for each month show higher correlations. Between intraday price and wind power production, the monthly correlations are presented in Figure 17. The months with the highest negative correlations were December and June for 2023, December and January for 2022 and January and June for 2021. The identified months with high correlations have correlation values between -9% and -38%. Overall, the negative correlation is higher in 2023 compared to 2021 and 2022. Looking at monthly correlations, much higher values are identified compared to the overall value of -5%.

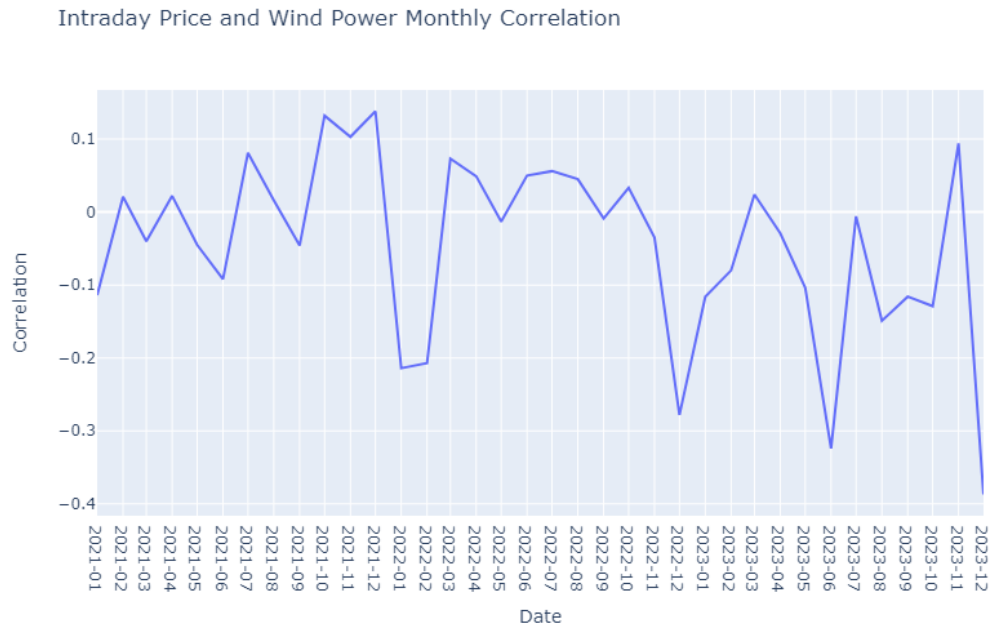


Figure 17: Monthly correlation of intraday prices in SE3 and wind power production in Sweden for 2021, 2022 and 2023 based on hourly values

The day-ahead prices in SE3 correlate to -28% with total wind power production. This is visualised in Figure 18 where the blue line represents the total wind power production in megawatt hours and the red line represents the day-ahead price in euros per megawatt hour.

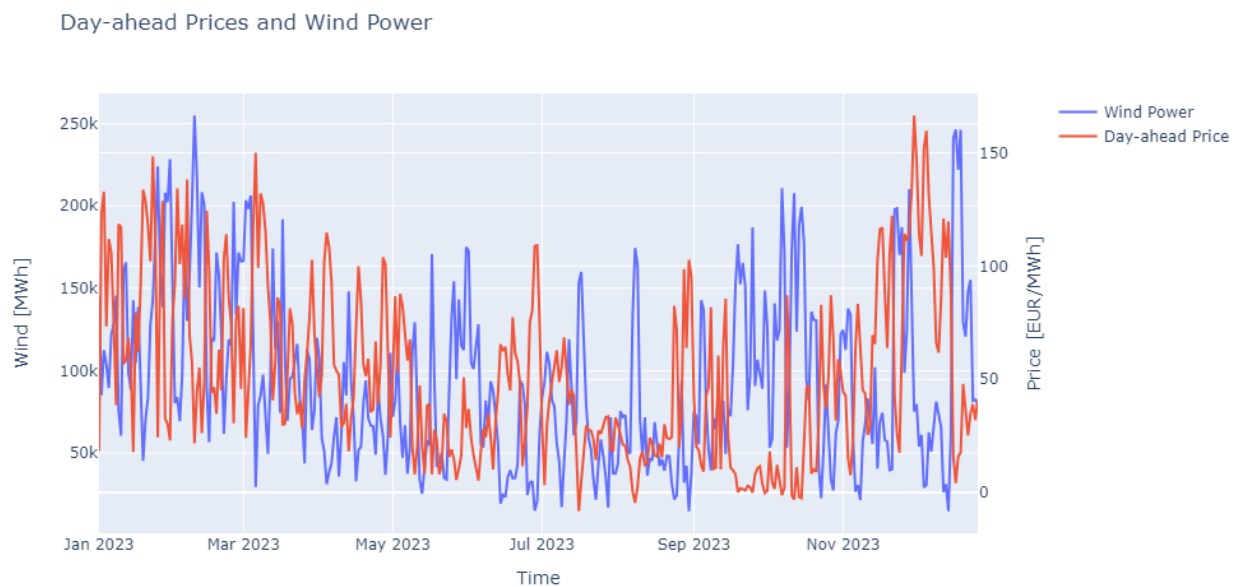


Figure 18: Day-ahead prices and Wind power production in SE3 for 2023 based on daily values

Wind power production correlates differently with intraday and day-ahead prices. A main difference between day-ahead and intraday prices is that the higher peaks distinguished for the intraday do not follow the wind power production which might have caused the lower correlation with the wind power production. These peaks will be further investigated. The day-ahead prices, on the other hand, follow the wind more consequent and thereby the higher correlation. Figure 19 shows the correlation between wind and prices per month for 2021, 2022 and 2023. The monthly-based correlations prove to be high throughout the years. Most of the correlations are between 40%-71%, which is considered to be much higher than the intraday and wind monthly-based correlations.

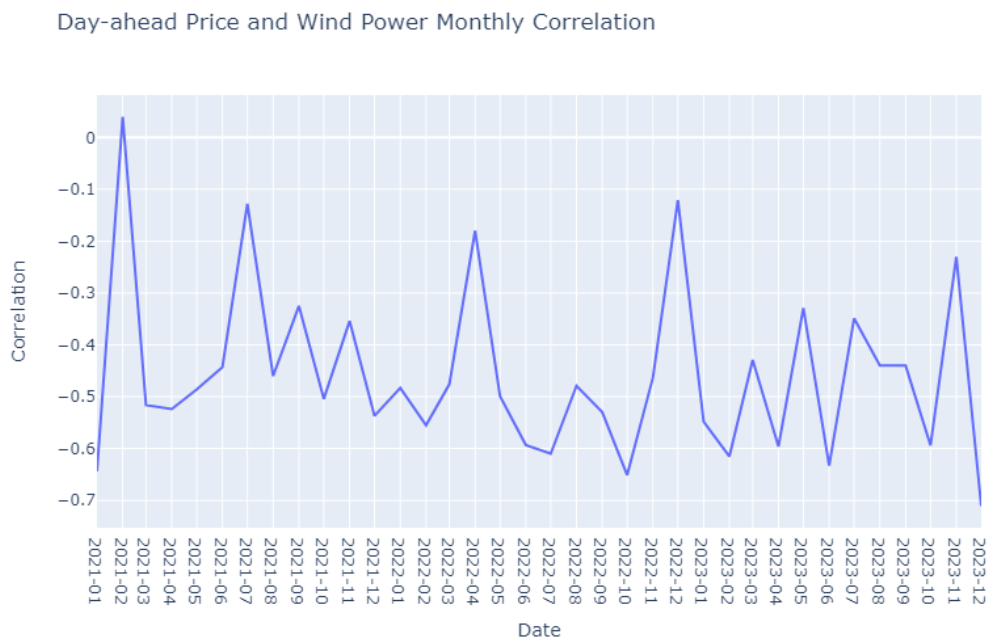


Figure 19: Monthly correlation of day-ahead prices in SE3 and wind power production in Sweden for 2021, 2022 and 2023 based on hourly values

Along with the intraday and day-ahead prices, investigations have been done into the price differences of these two markets. This has been analysed by calculating the price difference between the day-ahead price and the intraday price as the day-ahead price minus the intraday price. This price difference has then been compared to wind power production to examine if there is a correlation between the difference and also to investigate if this correlation differs from the day-ahead and the intraday prices separately. The correlation between the price difference and the wind power production is calculated to be -26%, which is lower than the correlation between day-ahead prices but higher than the correlation between the intraday price and wind power production. One potential explanation of the result could be that the correlation between the price difference and the wind becomes an intermediate value between the day ahead and the intraday. Since the day-ahead has a high correlation with the wind, and the intraday prices are low, the correlation of the price difference becomes close to the day-ahead. However, this must not always be the case due to significant high and low peaks in the intraday market.

To examine how miss-prediction in wind forecasting affects intraday prices, a correlation analysis was conducted between the disparity in wind power production and forecasts and intraday prices. This calculation measures the correlation between the wind forecast error and intraday prices. The difference between wind power production and wind forecast is named as wind error. The correlation of the wind error and the intraday price is calculated to be 0.4% and the correlation of the wind error and the day-ahead price is calculated to be 3%. The correlation of the wind error and the price difference for the day and the intraday was calculated to be 3%. Due to the low correlation, no further investigation has been done on the correlation of the wind error and the prices.

The highest correlation of the three years is detected to be between the wind power production and the day-ahead price. The correlation between wind power production and the price difference between the day-ahead and intraday prices is also high, but the correlation between the wind power production and the intraday price is low. This means that the day-ahead prices correspond to the wind power production while the intraday does not to the same extent. The correlations between the wind forecast error and the prices are all low which means that the prices follow the produced wind rather than the error in forecasting. The correlation between wind power production and the difference between day-ahead and intraday prices is negative but almost as high as the wind and day-ahead correlation. This correlation is further investigated based on the seasonality variations. The seasonal correlation of wind power production and the difference between day-ahead and intraday prices has been studied and can be seen in Figure 20. There are differences between the months, however, it is not further investigated due to the lack of correlation identified between the years.

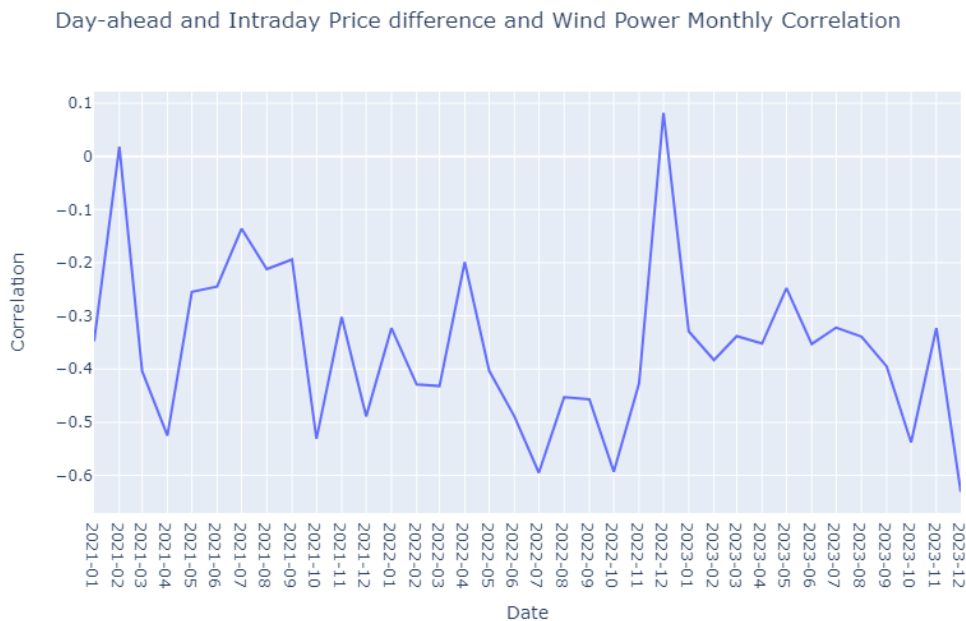


Figure 20: Correlation between wind power production and the difference between day-ahead and intraday prices for 2021, 2022 and 2023 based on hourly values

5.2.2 Wind Power and Volatility

This Section will present the results of how wind power production correlates to intraday price volatility and how the seasonal correlations differ. The wind power production is presented as the total wind produced in Sweden in megawatt hours. Figure 21 shows how intraday volatility in SE3 correlates with total wind power production in 2023. The correlation between the volatility of intraday prices and wind power production is -7%. As mentioned for intraday prices and wind power production, the correlation calculated based on all years from 2021 to 2023 does not correspond much to the wind power production even though it is higher for volatility than intraday prices.

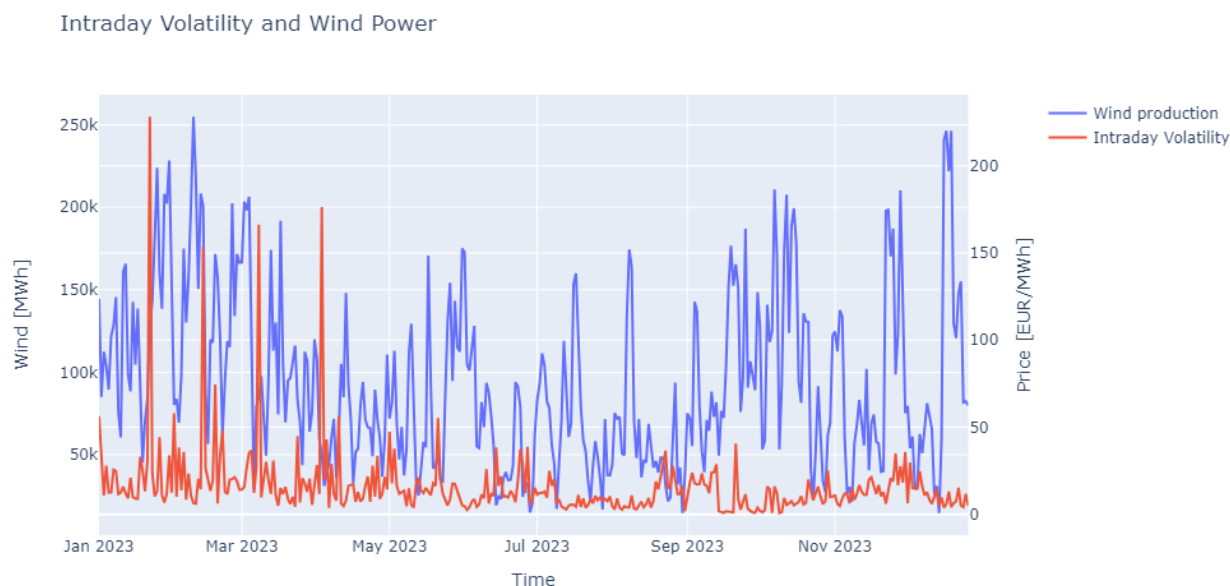


Figure 21: Intraday Volatility in SE3 and Wind power production for 2023

When examining the correlations based on each month, the higher correlations were identified and are presented in Figure 22. Between intraday volatility and wind power production, the months with the highest negative correlation were December and May for 2023, December and February for 2022 and September and January for 2021. These high correlations are between -25% to -46% which is much higher than the yearly based correlation of -7%. This indicates that there is a high variation in correlations between the months of the year.

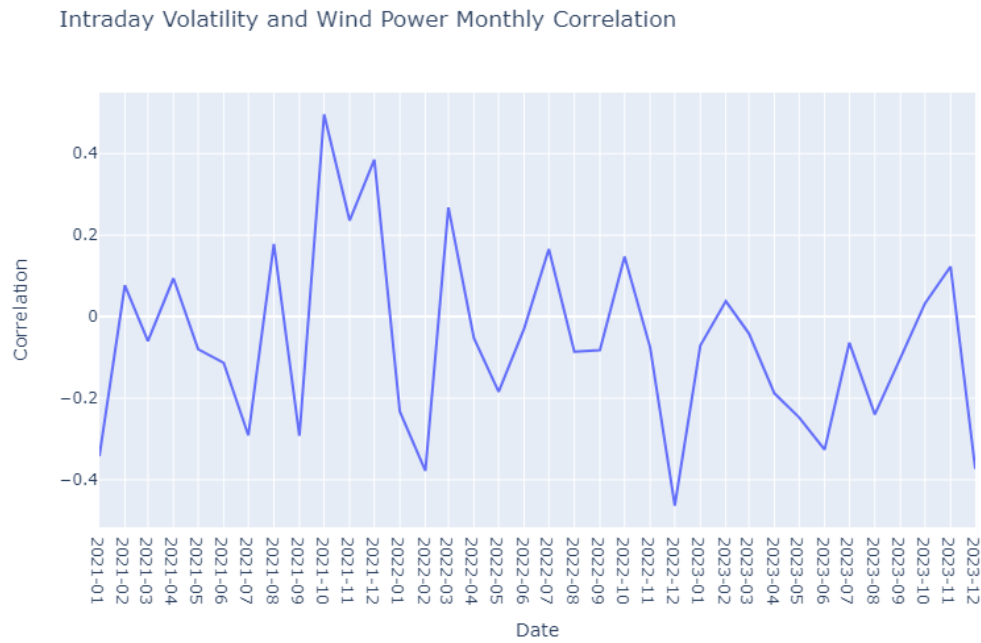


Figure 22: Monthly correlation of intraday volatility in SE3 and wind power production in Sweden for 2021, 2022 and 2023 based on hourly values

5.3 Day-ahead Price and Volatility

This Section will present the results on how intraday and day-ahead prices and volatility correlates. Figure 23 shows the intraday price and the day-ahead price in SE3 from 2021 to 2023. The graph is based on daily average values where the red line represents the day-ahead prices and the blue line represents the intraday prices.

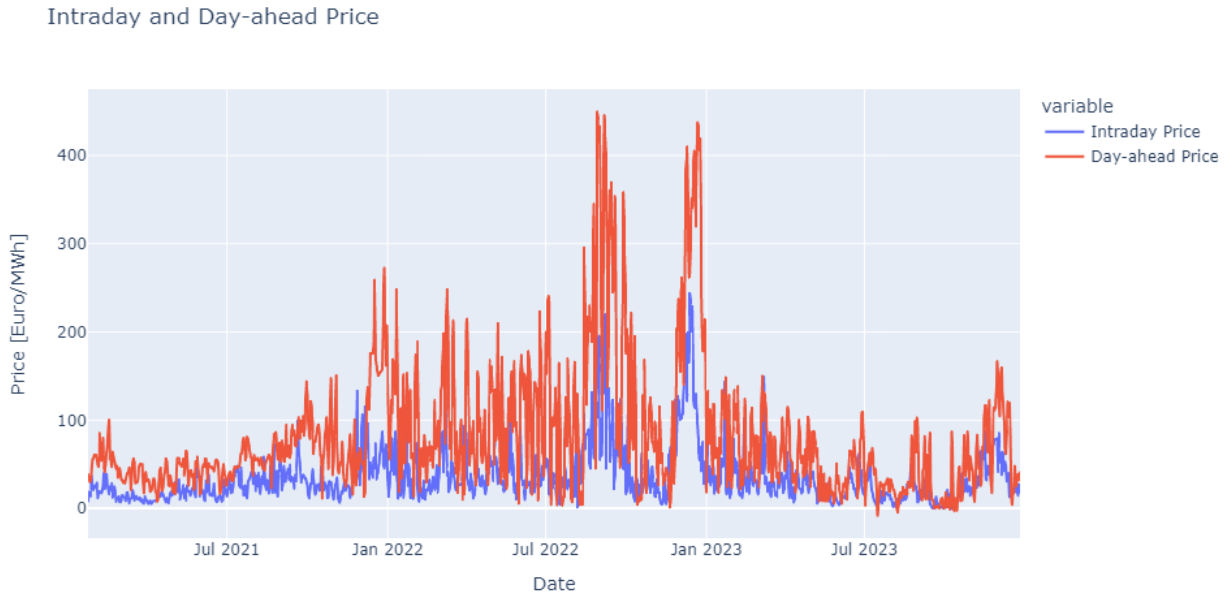


Figure 23: Intraday and day-ahead prices in SE3 from 2021 to 2023 based on daily values

It can be seen that the day-ahead prices are higher than the intraday prices. There are some notable peaks for both the intraday and day-ahead price plots. However, there are some intraday price peaks higher than the day-ahead price when looking at the hourly averages which are not visualised in Figure 23. These higher peaks occurred during a certain hour and are therefore not apparent when investigating daily averages. The correlation between intraday and day-ahead prices is 30%, based on hourly values. Figure 24 shows the intraday and day-ahead volatility in SE3 from 2021 to 2023. The graph is based on daily average values where the red line represents the day-ahead prices and the blue line represents the intraday prices.

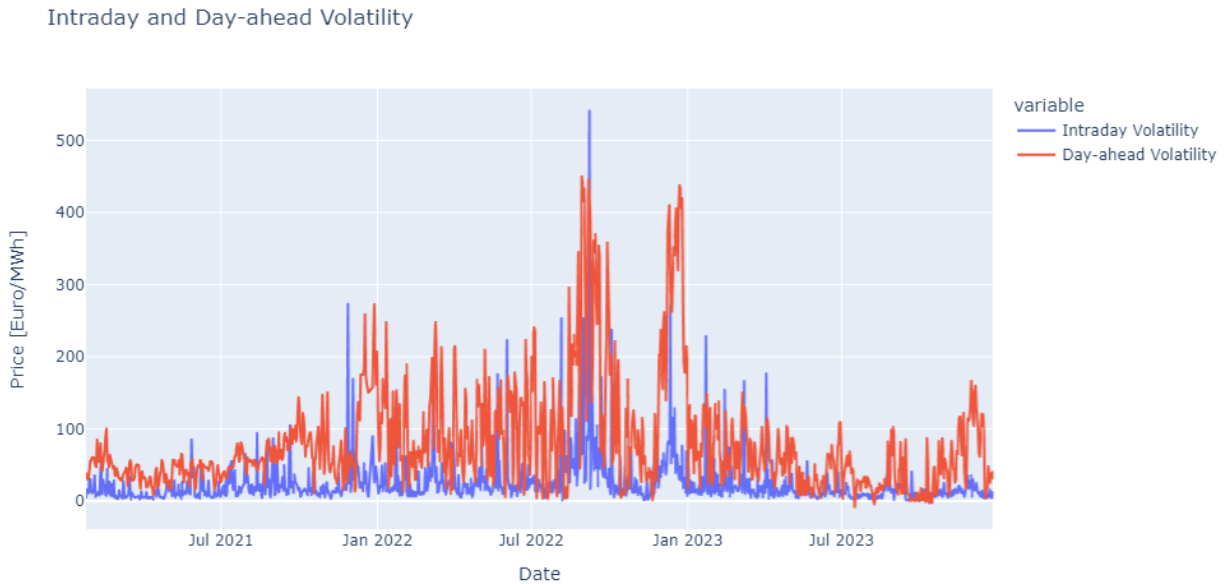


Figure 24: Intraday and day-ahead volatility in SE3 for the years 2021 to 2023 based on daily values

The intraday and day-ahead volatility correlates 38%. When the volatility of the price for the day increases, so does the volatility of the price on the intraday and vice versa. However, there are more frequent peaks of intraday volatility compared to day-ahead volatility. This can be visualised in the Figure. Due to more frequent and higher peaks for intraday volatility, the intraday price can be considered more volatile compared to the day-ahead price. The higher volatility also corresponds to the high peaks of the hourly intraday price. Due to the high correlation of the intraday and day-ahead prices, a monthly correlation has been studied to analyse if there are significant seasonality differences. Regarding the prices, the monthly correlation showed almost no seasonality. During summer and at the end of 2023, the correlations were higher and at their highest 50 %, however, this was not the case for 2022 and 2021. The same goes for the volatility, no seasonality of the monthly correlations were identified. For some months the volatility correlation was positive, as its maximum was 35%, but for other months a negative correlation of -27 % where identified. Tables over the monthly price and volatility correlations are presented in Figure 25

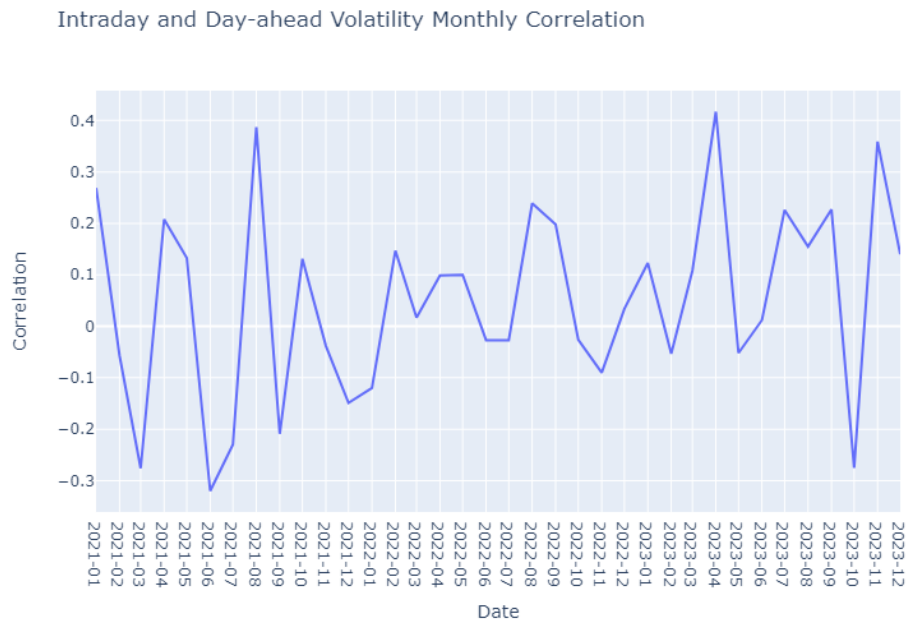


Figure 25: Correlation of intraday and day-ahead price volatility in SE3 for 2021, 2022 and 2023 based on daily values

5.4 mFRR Balancing Market

This Section presents the results regarding the mFRR balancing market and how it correlates to the intraday market. The imbalance aims to adjust the price according to the condition of the system. Each hour, if the day-ahead price is lower than the up-regulating price for that hour, the imbalance price is set to the up-regulating price. Conversely, if the day-ahead price is higher than the down-regulating price, the imbalance price is set to the down-regulating price. Otherwise, the imbalance price remains equal to the day-ahead price and the system is unregulated. The imbalance price is visualised in Figure 26.

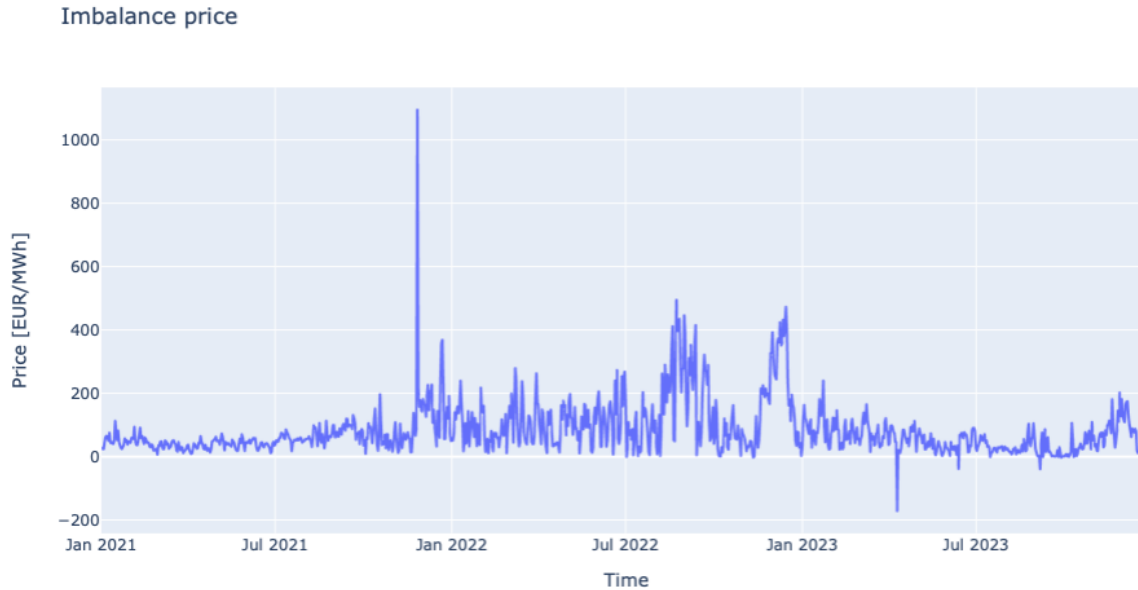


Figure 26: Imbalance pricing in SE3 from 2021 to 2023 based on daily values

The Figure shows the imbalance price for each hour but not anything about the state of the system. It is evident that imbalance prices spikes in 2022 as was also the case for intraday and day-ahead prices. In 2022, ACER stated in their *Wholesale Electricity Market Monitoring 2022* that imbalance and intraday prices followed similar upward trends in 2022 as day-ahead prices did in the Nordics. The following trend corresponds to the Figure above where Swedish imbalance prices for SE3 are visualised. To analyse the correlation between intraday and mFRR prices, the following correlation was calculated: day-ahead minus intraday and day-ahead minus imbalances. Figure 27 shows the difference between the day-ahead price and the imbalance price.

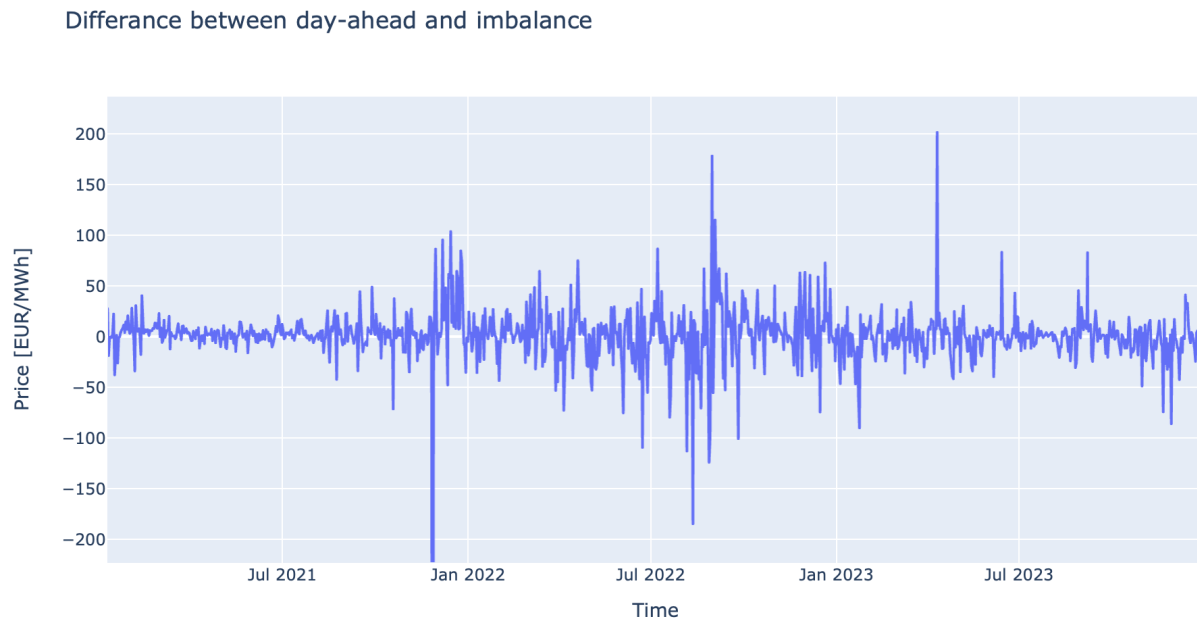


Figure 27: Difference between day-ahead and imbalance for 2021 to 2023

The results show a correlation of 4% between day-ahead minus intraday and day-ahead minus imbalances. When calculating the correlation for the same factors but without the values when the system is unregulated, the results showed a correlation of 5%. This is a low correlation, meaning that the mFRR prices do not follow the day-ahead and intraday prices higher than four, respectively five percent. Due to the low correlation, no further investment has been made in this study.

5.5 Understanding the two highest peaks of intraday data

In this Section, the data will be analysed to understand the peaks of the intraday price and what causes the correlations. The two highest peaks will be investigated to understand the data. Based on the intraday prices presented in Figure 8, the two highest peaks during the presented years occur from August 2022 to October 2022 and from December 2022 to February 2023. Between those two peaks, in November 2022, the prices are very low, close to zero.

When analysing the wind during this period, it can be seen that the wind has a negative correlation with the intraday price, meaning that when the wind power production increases, the intraday prices decrease and vice versa. The wind correlation between intraday prices and wind power production is visualised in Figure 28. The wind power production and the intraday prices from August 2022 to February 2023 have a negative correlation of -19% which is higher than the correlation of wind power production and intraday prices when measuring the years 2021 to 2023. This means that the intraday prices correlate more to the wind power production during this time, compared to the three measured years. When analysing the three extreme events apart, it can be seen that the correlation in August to October 2022 is -7% and in December 2022 to February 2023 is -37%. In November 2022, the correlation is -3%. This means that the peak in December 2022 to February 2023 has a significantly high correlation with the wind while the correlation is lower in August to November 2022. The prices in this period probably depend on something else than the wind.

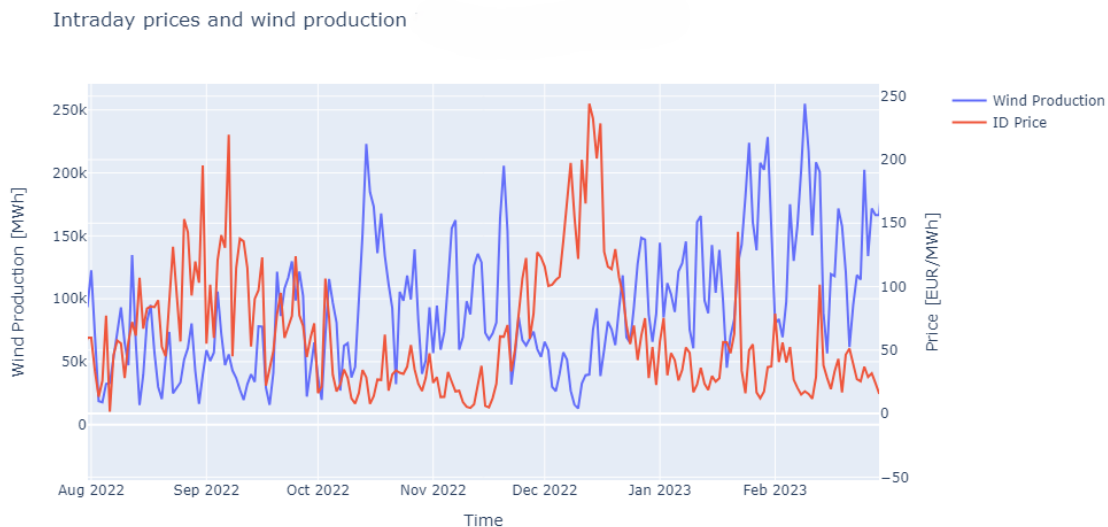


Figure 28: Intraday prices and wind power production in SE3 from August 2022 to Mars 2023 based on daily values.

The intraday and day-ahead prices during this time are visualised in Figure 29. The correlation between intraday and day-ahead prices during this period, August 2022 to February 2022 is 27%. When analysing the months further, the correlation during the first peak, August to October 2022 is 15% and December 2022 to February 2023 is 42%. In November 2022, the correlation between intraday and day-ahead prices is 30%.

It means that the intraday has a high correlation with the day ahead during the second peak and a lower one in the first one. During the dip in November 2022, the correlation between the day-ahead and intraday is 30%.

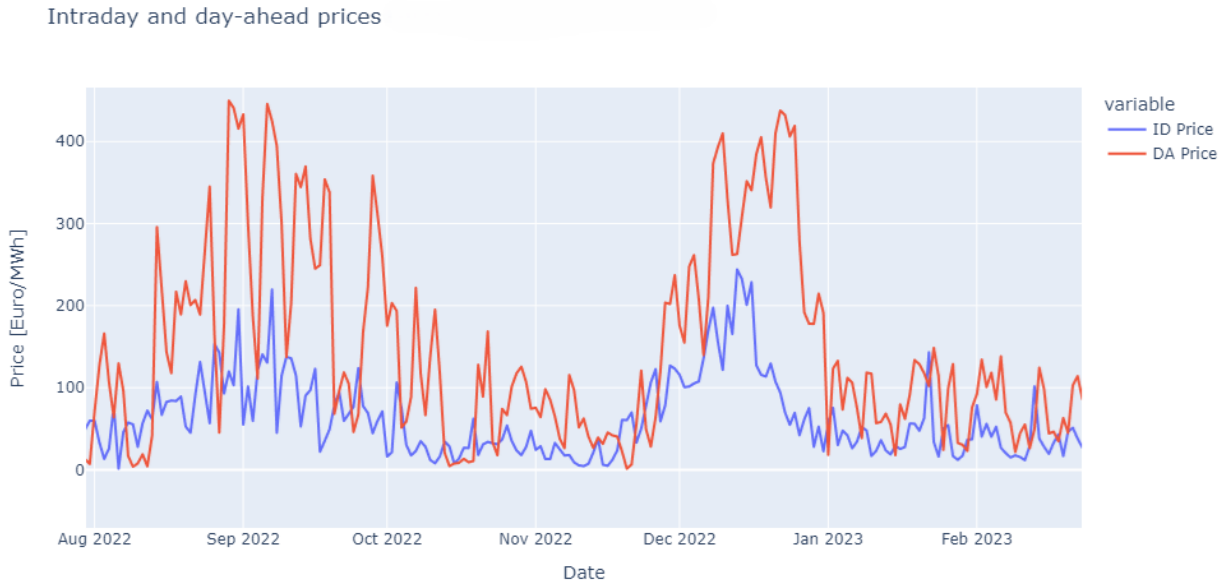


Figure 29: Intraday and day-ahead prices in SE3 from August 2022 to Mars 2023 based on daily values.

According to Nord Pool’s platform REMIT UMM where publications of production, consumption, transmission outages and other market-relevant information are available, some extreme events with high unavailable capacity were discovered. One such event is the Ringhals 4 nuclear power plant, located in SE4 that was out of operation for four months in September 2022 and March 2023. A planned maintenance work of Ringhals 4 followed by further delay of the restart of the reactor resulted in a remarkably large amount of unavailable capacity. The flow distribution in the grid is expected to change as a result of the maintenance of Ringhals 4 thus affecting possible transfer capacities between SE3 and SE4 during this period. The planned changes in the nuclear power plant impact the available capacity and thereby it might be an explanation of the extreme peaks during this period. (Nord Pool, 2024)

To summarise the study of the intraday prices during the time August 2022 to February 2023 it can be said that there are differences during this period in how the intraday prices correlate to the wind power production and the day-ahead prices. During the first peak, the correlation with both day-ahead prices and wind power production is low but during the second peak, the correlation is high. During the price dip, the correlation with the wind power production is low but the correlation with the day-ahead prices is high. The observed -37% impact of wind power production on intraday prices during the second peak indicates that wind power production influences prices more significantly during specific periods than the overall correlation suggests. However, the interplay of various factors affects prices overall. The maintenance of Ringhals 4 seems to influence intraday price and volatility during the period studied in the peak analysis since the peaks of price and volatility correspond with the unavailable capacity from the nuclear power plant.

Discussion

Multiple factors affect the intraday market. As mentioned above, the development of RES, day-ahead trades, grid connections, demand versus supply, and other macroeconomic indicators are crucially important for the intraday markets' price, volume, and volatility. This section will further discuss the influencing factors along with Svenska Kraftnät's future scenarios. Each correlation factor will be discussed, first from a historical perspective, followed by a discussion of the future outcome.

Intraday prices generally spiked during 2021 and 2022 and stabilised during 2023. Volumes traded on the intraday market increased at the end of 2023. Liquidity levels observed an increase in 2022 compared to the period from 2020 to 2022, according to ACER (ACER, 2023). Due to the higher volumes traded in 2023, as visualized in Figure 9, it can be concluded that the intraday market probably experienced an increase in liquidity in 2023. Following this trend, with the continuing increase in volumes traded on the intraday market, the rise in liquidity is likely to continue. Regarding price volatility, the intraday market turned out to be more volatile during 2021 and 2022 and decreased in volatility during 2023. This can be proved due to the more frequent peaks of price volatility when studying Figure 10 of intraday volatility. The results of the data analysis showed lower intraday prices during 2023 and also a higher correlation between intraday and day-ahead prices for 2023 indicating that the outlying values in 2021 and 2022 probably had an impact lowering the correlation for these years. Regarding wind power production, the correlation between intraday prices and wind power production remained low during the three years. However, the monthly effects of wind power on prices are proven by the monthly correlations, which showed a significant increase during some months. Further, it can be said that higher fluctuating intraday prices and spiking volatility affect the volumes traded on the intraday market. An indication of this is the lower intraday volumes observed around September and January 2022, when intraday prices spiked, in contrast to the autumn of 2023, when intraday prices decreased and intraday volumes increased significantly.

6.1 Renewable Deployment

The electricity production from fossil-free sources reached 98.7% in Sweden in 2023, where hydro and nuclear power have been stable, while wind and solar power have increased in recent years. The source of power impacts market design; therefore, the expansion of RES has influenced the outcome of the electricity market. However, as of today, solar power production in Sweden is still relatively small and does not impact the market to the same extent as wind power. With an anticipated increase in solar energy in the future, it may have a larger influence on the intraday market because of its similarities with wind power production as a VRES. Furthermore, wind power production significantly impacts the wholesale market. The seasonal variation in wind power production, characterised by higher output in winter and lower output in summer, affects wholesale markets due to variations in monthly correlations. This topic is further discussed in the following section. With an increased share of solar power production, the seasonality of wind power production could be compensated for by the seasonality of solar production, which peaks during summer and decreases during winter. However, this potential compensation has not been further investigated, as solar production currently represents a small proportion of electricity production in Sweden compared to wind power.

6.1.1 Seasonality of Wind Power and its Influence on Prices

Intraday prices and wind power production showed a negative correlation of -5%. Day-ahead prices showed a stronger correlation with wind power production at -28%. However, the lower correlation of intraday prices and wind power production is not representative when investigating monthly correlations, where the maximum correlation reached -39% in December, followed by -32% in June 2023. The same applies to volatility, where the highest negative correlations were identified in December and June with almost the same values. On a monthly basis, wind power significantly influences intraday prices and volatility. However, when examining the impact over a longer period of three years, the correlation values are much lower. Since wind power production accounted for around 20% of electricity production in Sweden in 2022, a monthly correlation close to -20% indicates that wind impacts prices to a large extent. However, the amount of wind power in the electricity system varies and is not always 20% each day throughout the year. For example, at the beginning of 2022, wind power production in Sweden increased from 20% to 40% over a few days, which could have impacted the higher correlations during this period. (Winberg, 2022). Furthermore, the impact of wind power on intraday prices could be overestimated since it is difficult to distinguish the actual cause of price fluctuations. Apart from the impact of the supply side, such as an increase in wind power production, the demand side plays a crucial role. For example, during a sunny and windy summer day it might seem like the wind power caused the low prices, while in reality, a decrease in demand might be the actual factor lowering the price. The supply contra demand side is further discussed in Section 6.4. At the same time, it is proven that wind power influences intraday prices, with some differences occurring between months and years. This corresponds to the results of (Sandberg, 2023), which show that wind energy causes a decrease in electricity prices. However, this effect is not as significant as shortages of electricity supply, such as when a nuclear power plant is temporarily shut down. This is further discussed in Section 6.6.

Regarding the day-ahead prices, the correlation with wind power production turned out to be higher than for the intraday. Apart from some exceptions, all distinguished monthly correlations were between 32% and 62% which is higher than the monthly correlations for the intraday price and volatility. Suppose that the expected increase of trading volumes on the intraday market takes place in the future. In that case, it is achievable that the monthly correlations for intraday price and volatility will also increase similarly to those for the day-ahead market. With an increase in VRES, it becomes more important to trade closer to the delivery time. Therefore, it is probable that the market will shift towards the intraday market. With a well-functioning intraday market adapted for an increased share of wind power, the future outcome of the intraday market might follow the trend of the day-ahead market, meaning that it will correlate with wind power production to a greater extent. As stated by Hu et al. (2021), since wind power is more crucial for electricity supply, the intraday market could become more attractive to trade imbalances in the most favourable way.

6.1.2 Future Possibilities

According to the long-term market analysis scenarios, wind power production is estimated to increase in all four scenarios. The differences lie in how much wind power production will increase. Depending on the amount of wind power production in the future electricity production mix, wind power generation will have a growing impact on electricity markets, especially real-time markets such as the intraday market. The increased importance of the intraday market is noted in the literature, which refers to the importance of real-time markets due to VRE. This is also proven in the data analysis, as the correlation between wind power production and intraday price and volatility showed a high negative correlation for specific months.

Therefore, the importance of wind power is likely to be greatest in the scenario of Small-Scale Renewable (SR) and the Renewable Electrification scenario (RE). In contrast, the risk of unpredictable events due to nuclear power shortages might be higher in the Mixed Roadmaps (MR) and Plannable Electrification (PE) scenarios, as nuclear power represents a larger share of the power mix in these scenarios.

6.2 Day-ahead Market

The intraday market functions as an extension of the day-ahead market. In the intraday market, adjustments are made based on the day-ahead market; therefore, the day-ahead market influences the intraday market. The prices in the day-ahead market showed varying patterns throughout 2021, 2022, and 2023, with prices higher in 2022 compared to both 2021 and 2023. Compared to the intraday market, prices in the day-ahead market remained higher throughout all years. With regard to volatility, day-ahead prices were more stable compared to intraday prices. Intraday prices were more volatile and exhibited higher price peaks than day-ahead prices. Investigating the future of the day-ahead market and its connection to the intraday market is crucial to understanding the evolving dynamics of energy trading. As energy markets continue to evolve, predicting trends and assessing the interplay between these two markets becomes important for understanding the development of the intraday market.

In a scenario with a high increase in RES, wind power production will become more dominant. The day-ahead prices have a strong negative correlation with wind power production, meaning that if wind power production increases, the day-ahead prices are likely to decrease. Due to the strong correlation between wind and day-ahead prices, trading in the day-ahead market will increase along with the increase in wind power production. However, the increasing wind power production as a VRES will also result in a higher importance of trading closer to the delivery hour. This suggests that the market will likely shift from the financial market to the wholesale markets, including both the day-ahead and intraday markets. It is difficult to identify the exact amount of trading that will shift towards the wholesale markets compared to the intraday market. It is important to note that day-ahead prices are influenced by various factors, not just wind power production. In the scenarios of MR and PE with more nuclear power, it will not be as important to trade close to the delivery hour due to the predictability of this energy resource. If energy resources shift towards more predictable energy production, prices are likely to stabilize and volatility will decrease. Less wind power production indicates higher day-ahead and intraday prices, reducing the incentive to trade closer to the delivery hour. The peak analysis suggests that nuclear power was most likely responsible for the highest intraday peaks, as the price spikes coincided with a nuclear power outage. Power sources like nuclear power carry a higher risk of market-impacting incidents if such events become more frequent. Therefore, while price volatility on the intraday market generally stabilizes with fewer variable renewable energy sources (VRESs), price peaks may still occur due to unpredictable events, temporarily increasing volatility.

6.3 mFRR Balancing Market

The intraday market is used to adjust trades to align with the system's needs and the predetermined amount of electricity for a specific time. Imbalances occur when there are discrepancies between predicted and actual production/consumption, which is why imbalance analysis is included in this study. However, the results, as shown in Figure 26, indicate a low correlation between imbalances and the intraday market. Therefore, the most significant finding regarding the balancing market is the correlation's direction. A high difference between day-ahead and intraday prices (day-ahead minus intraday) suggests low intraday prices and a likely surplus of supply, indicating that the system requires down-regulation. A downregulated system means that the difference between day-ahead price and imbalance (day-ahead minus imbalance) is negative. The other way around, if the difference between the day-ahead and intraday price (day-ahead minus intraday) is low, it means that the intraday prices are high and there is a high probability that there is a deficit of supply in the system which in turn means that the system needs up-regulation. An up-regulated system means the difference between day-ahead price and imbalance (day-ahead minus imbalance) is positive.

Historically, the main actors in the intraday market have been balance responsible parties. Due to the low liquidity experienced on the Swedish intraday market compared to the day-ahead market, participants may have been discouraged from participating in this market (Alvehag et al., 2017). According to Hu et al. (2021), a well-functioning intraday market could reduce the societal costs of intermittent power, benefiting wind producers who would otherwise have to trade their production generation imbalances on the balancing markets at a higher cost. A well-functioning intraday market will compel flexibility providers to trade in this market by sending the right price signals. Trading on the balancing markets in a situation where demand is high and supply is low will drive up prices, which might be favourable for a wind producer (ibid.). However, in the case of imbalances, the costs might be higher on the balancing market compared to an efficient intraday market, making a well-functioning intraday market a good opportunity for wind power producers. Imbalances can result from supply and demand mismatches, such as much higher wind power production than predicted or demand changes where consumers use more or less electricity than planned. A large share of wind power in the electricity system implies a higher risk of imbalances that need to be balanced to match demand and supply because of its intermittent nature. The option of trading on the intraday market could reduce these imbalance costs for wind producers who would otherwise have to use other balancing strategies, likely at a higher cost. In addition, the intraday market can function as a platform on which producers can buy and sell electricity based on the market price. This can be achieved by reducing their production and buying electricity if it is more profitable or by selling flexibility to other market participants who are willing to pay for it.

6.4 Demand and Supply Balance

Both the demand and supply sides will impact the outcome of the electricity market and the intraday market. Potential signs of inflexibility due to increased electricity supply could lead to increased demand for flexibility resources. Since the SR and MR scenarios are more similar to the current level of electricity generation, identified inflexible signals will cause an increased demand for flexibility in the electricity network. In future scenarios PE and EF, with a higher share of electrification, these inflexibility signals may play a more significant role due to higher electricity production. The difference between the two electrification scenarios lies in the amount of RES. In scenario EF, where the share of RES is the highest, the need for flexible resources will be even more amplified due to variations in production. At the same time, the demand side plays a crucial role, since both demand and supply set the market price. According to an article published by IEEE, increased elasticity on the demand side can stabilize wholesale electricity prices in a renewable power system (Harit et al., 2022). This is especially true in a system with a high share of VRES that incurs low marginal costs. Wind and solar power production tends to increase price variability, while demand-side flexibility helps stabilize wholesale electricity prices.

Increased volatility in future scenarios and increased variation in intraday prices might favour the development of flexible demand-side solutions, such as adapting high-load hours to match VRES production. As VRES grows in the power system, technologies that adapt electricity consumption based on price signals might become more favourable because they are more advantageous as electricity prices become more volatile. The willingness of consumers to adapt to a new market design will occur alongside supply-side adaptation (Helistö et al, 2023). In the future RE scenario, flexibility resources will be crucial both on the supply and on the demand side to balance the increased share of RES. A higher electrification rate will work as an incentive for suppliers to provide the power system with flexible resources. At the same time, the demand side might meet the need for flexibility, helping balance the system. This concept applies more or less to the other scenarios as well, with the difference that the need for an increase of flexibility as a result of an increased share of VRES is therefore the highest in the RE scenario.

6.5 Grid Connections

The Hansa Power Bridge is a new cable connection between Sweden and Germany planned to increase trading opportunities and secure electricity supply. The interconnection aims to support and promote a Nordic and European market for electricity, enhancing trading opportunities on common electricity markets such as SIDC. It will facilitate increased export possibilities for electricity producers in case of production surplus and enable greater import opportunities to southern Sweden during periods of electricity shortage. This cable connection plays a crucial role in improving the security of supply (source: SVK Hansa PowerBridge). However, the project has faced opposition due to concerns about increased electricity prices in Sweden. This concern arises because electricity prices in Sweden are normally lower than in other European countries, particularly Germany, which has been significantly affected by extremely high gas prices. According to Svenska Kraftnät, the price difference is expected to decrease in the long term as new interconnections are built, increasing the connection between the Nordics and Europe.

According to Svenska Kraftnät, the transmission capacity between bidding zones in Sweden as well as between the Nordics and the rest of Europe is expected to increase similarly across all scenarios mentioned. However,

with an increased share of RES, especially in the SR and RE scenarios, there will be a greater push for a more integrated transmission grid within Europe, since VRES drive the need for a more interconnected power system. An increased integration of the Swedish electricity system and the European electricity system will improve the security of supply as the increased share of VRES. At the same time, the occurrence of other macroeconomic factors that impact prices and volatility in Sweden will be increasingly influenced by the European market. One such event is the energy crisis which has proven to impact the energy market in Sweden. In the MR and PE scenarios, which include nuclear power, the need for an integrated power system might be lower because of the increased share of non-variable energy sources. The security of supply might be considered less vulnerable in these scenarios due to less variable power production. However, the risk of nuclear power shutdowns might increase, which would also impact the electricity market and intraday prices, as discussed in the Peak Analysis. In the PE and RE scenarios, with higher electrification rates, increased grid connections are necessary to limit bottlenecks. In addition, there may be a greater need for international grid connections, as they facilitate increased trading within Europe, which is favourable for power suppliers.

6.6 Macroeconomic Indicators

The gas crisis and the pandemic have significantly influenced the electricity market. These unpredictable macroeconomic events make future impacts difficult to forecast, despite their substantial effect on the market, including intraday trading. Therefore, the market must be prepared for such extreme events. Wind power and energy storage can help mitigate these fluctuations, due to the flexibility offered by wind power combined with storage solutions. In contrast, nuclear power increases risks under extreme conditions due to its inflexibility. Storage systems combined with variable renewable energy sources (VRES), in particular, can effectively cover unexpected events.

A clear example of the connection between intraday market variability and unpredictable events is the shutdown of Ringhals 4 in 2023. During the period when this nuclear power plant was out of operation, there was a notable correlation between the shutdown and peaks in intraday price and volatility data. The same pattern was observed for day-ahead prices and volatility. Since the shutdown date corresponded with the start of the intraday price and volatility peaks, there is likely a direct connection between these price peaks and the nuclear plant shutdown. However, there is no evident link to the valley in intraday price and volatility between the peaks. During this period, the correlation with wind was low, and the nuclear plant remained out of operation from the first peak to the end of the second peak. According to REMIT UMM, no clear connection was found to any events involving high unavailable capacity. In addition to specific events affecting price and volatility on the intraday market, the propagation of the energy crisis across Europe significantly influenced the electricity market, including the intraday market. Due to well-integrated markets in Europe, the energy crisis impacted the price and volatility in SE3 as well as the rest of Europe. Given the unpredictability of macroeconomic factors, it is challenging to distinguish differences between scenarios. These events will remain unreliable and hard to predict regardless of the scenario.

6.7 Future Work

The identified factors that affect the price of the intraday, the volatility of the price, and the volumes traded are the daily market, the use of renewables, the balance between demand and supply, the connections of the grid and macroeconomic indicators. The impact of these chosen correlation factors can be substantiated by the correlations found. However, these correlations only partially explain the evolution of intraday price, volatility, and volume. It is important to mention that there are likely other factors with a similar impact on the development of the intraday market that were not included in the study. During the research process, additional impacting factors were identified, such as flows between bidding zones, extreme weather events, and changes in market design, including intraday auctions. These factors were not further investigated in this report due to limited access to relevant data and time constraints. For a more comprehensive understanding of the development of the intraday market, it would be valuable to analyze these other factors. Due to the low share of solar power in Sweden, monthly correlations between solar power production and intraday prices have not been studied. In a future with a larger share of solar power, investigating this correlation could be of interest. To broaden the knowledge of intraday trading, volumes could be analyzed by measuring the correlation between trading volumes and identified correlation factors. This would improve the understanding of intraday liquidity. The report is limited to three years: 2021, 2022, and 2023. To gain a better overview of the development of intraday prices, volatility, and volumes, a longer time frame could be studied. In addition, it is crucial to consider the occurrence of unpredictable events and their consequences. Wholesale market prices have reflected the challenges that emerged in the past two years, particularly due to the pandemic and the energy crisis.

Conclusion

The intraday market has been ongoing since 1999 and allows the trading of electricity within the same day of the delivery of the electricity. The three years 2021, 2022, and 2023 have been studied in this report to develop an overview of the intraday market historically and in the future. The notable peaks of intraday prices occurred during 2021 and 2022 and the market stabilised during 2023, meaning that intraday prices showed a more volatile trend in 2021 and 2022, compared to 2023. The total volume of trades showed a stable pattern in 2021 and 2022, with around 50 GWh trades per month. At the end of 2023, the trading volume increased to 130 GWh. A comprehensive understanding of the market can be achieved by examining factors impacting intraday prices. Day-ahead trades, renewable deployment, the balance of demand and supply, grid connections and macroeconomic indicators.

Regarding renewable energy deployment, solar power accounts for a small part of electricity production and does not impact intraday prices to a large extent. With a larger share of solar power production, it could be expected that it will have an increased influence on intraday prices. Wind power, on the other hand, accounts for a larger share of electricity production and is impacting intraday prices to a higher extent, which is proven by the identified monthly correlations obtained on intraday prices and wind power production. There are seasonal variations of the monthly correlations which can be explained as the seasonality of wind power production but also due to adaptations from the demand side. Due to the influence of different markets on each other, the day-ahead market is important when analysing the intraday market. In general, higher prices and less volatile prices were distinguished for the day-ahead market compared to the intraday market. The results showed a high correlation between the day-ahead market and wind power production. However, the intraday market can follow this trend as more trade occurs closer to the delivery time, making it more attractive to market participants. Additionally, wind power production is expected to increase, in varying amounts depending on the scenario, which could further influence this trend.

An expanding share of wind power production not only increases the prevalence of VRES but also impacts the intraday market in three significant ways: first, by causing a shift in electricity market trading; second, by driving a surge in demand for flexibility resources within the electricity system; and third, by influencing the integration of the European market. The shift in electricity market trading means that VRES intensifies the incentives for trading to occur on the intraday market. Furthermore, the increased share of VRES results in an increased demand for flexibility within the electricity system. Depending on the scenario, those scenarios with the highest share of VRES exhibit a greater need for flexibility resources. Although increased wind power production drives the need for additional flexibility on the supply side, demand-side flexibility adaptations may help balance this requirement. Consequently, flexibility resources are expected to emerge on both the demand and supply sides in the future. Furthermore, an integrated European market is advantageous for maintaining the balance between supply and demand in a future dominated by a higher share of VRES. However, this integration also implies that the European market will increasingly influence the Swedish intraday market. Therefore, to accurately anticipate the future outcomes of intraday prices and volatility in Sweden, market integration must be taken into consideration. The prices of wholesale markets fully reflect the challenges that have emerged over the past two years, including the pandemic and the energy crisis. Regardless of the scenario, macroeconomic events will unfold unpredictably and will impact the market.

It has been seen that the factors studied in this report all affect intraday prices. The prices show a volatile pattern during the three studied years, with notable peaks and valleys and they will probably show similar patterns in the future. With an increased amount of trades, the liquidity of the intraday market will most likely increase in the future. The range of electrification and the increase of RES will impact the future intraday market.

References

- ACER (2019). “Annexes to the DECISION OF THE AGENCY FOR THE COOPERATION OF ENERGY REGULATORS No 01/2019”. *ACER*. Collected [2024-05-13]. URL: https://documents.acer.europa.eu/Official_documents/Acts_of_the_Agency/Pages/Annexes-to-the-DECISION-OF-THE-AGENCY-FOR-THE-COOPERATION-OF-ENERGY-REGULATORS-No-012019.aspx.
- ACER (2021). “Wholesale Electricity Market Monitoring 2021”. *Energy Community*. URL: https://www.acer.europa.eu/sites/default/files/documents/Publications/2023_MMR_Market_Integration.pdf.
- ACER (2023). “Progress of EU electricity wholesale market integration: 2023 MMR”.
- ACER (2024). “Key developments in EU electricity wholesale markets 2024 Market Monitoring Report”.
- Alvehag, K., Werther Öhling, K., Östman, K., Broström, E., Strömbäck, E., Klasman, B., Lahti, M., Morén, G. (2017). “Measures to increase demand side flexibility in the Swedish electricity system”. *Swedish Energy Markets Inspectorate Volume (10)*. URL: <https://www.ei.se/download/18.5b0e2a2a176843ef8f582/1608542148119/Measures-to-increase-demand-side-flexibility-in-the-Swedish-electricity-system-Ei-R2017-10.pdf>.
- Berezvai, Z., Hortay, O., Szóke, T. (2022). “The impact of COVID-19 measures on intraday electricity load curves in the European Union: A panel approach”. *Sustainable Energy, Grids and Networks Volume (100930)*. URL: <https://www.sciencedirect.com/science/article/pii/S2352467722001758>.
- Bergman, L. (2022). “Långsiktiga investeringar och handel på framtidens elmarknad”. *Energiforsk Volume (2022)*. URL: <https://energiforsk.se/media/31326/langsiktiga-investeringar-och-handel-pa-framtidens-elmarknad-energiforskrappport-2022-859.pdf>.
- Brännlund, R., Damsgaard, N., Diczfalusy, B., Tangerås, T., Unger, T. (2022). “Framtidens elmarknadsdesign”. *Energiforsk Volume (797)*. URL: <https://energiforsk.se/media/30200/intradagmarknaden-energiforskrappport-2021-797.pdf>.
- Brolin, M., Hamon, C., Nyström, S. (2021). “Intradagmarknaden”. *Energiforsk*.
- Christensen, A. B. (2023). “The energy crisis added EUR 336 billion to EU electricity bills in 2022”. *Ramboll*. Collected [2024-05-10]. URL: <https://www.ramboll.com/insights/decarbonise-for-net-zero/the-energy-crisis-added-eur-336-billion-to-eu-electricity-bills-in-2022>.
- Costanzo, G., Brindley, G. (2023). “Wind energy in Europe”.
- Cramer, E., Witthaut, D., Mitsos, A., Dahmen, M. (2023). “Multivariate probabilistic forecasting of intraday electricity prices using normalizing flows”. *Applied Energy Volume (346)*. URL: <https://www.sciencedirect.com/science/article/abs/pii/S0306261923007341>.
- Ei (2023a). “Elmarknaden”. *The Swedish Energy Markets Inspectorate*. Collected [2024-05-08]. URL: <https://ei.se/konsument/el/elmarknaden>.
- Ei (2023b). “Elpris”. *The Swedish Energy Markets Inspectorate*. Collected [2024-04-12]. URL: <https://ei.se/konsument/el/elmarknaden/elpris>.
- Eicke, A., Ruhnau, O., Hirth, L. (2021). “Electricity balancing as a market equilibrium: An instrument-based estimation of supply and demand for imbalance energy”. *Energy Economics Volume (105455)*. URL: <https://www.sciencedirect.com/science/article/pii/S014098832100342X>.
- Ember (2023). “Yearly Electricity Data (2023)”. *Our World in Data*. Collected [2024-05-03]. URL: <https://ember-climate.org/insights/research/european-electricity-review-2022/>.
- Energimyndigheten (2021). “Framtidens elektrifierade samhälle”. *The Swedish Energy Authority Volume (28)*. URL: <https://drive.google.com/file/d/11bIqk0dqSpxeqi4Pc5S8p7w9xf4TPmUz/view>.

- Energimyndigheten (2022). “Nuläget på elmarknaden Maj 2022”. Collected [2024-04-12]. URL: https://www.energimyndigheten.se/49c6a0/globalassets/om-oss/lagesrapporter/elmarknaden/2022/nulaget-pa-elmarknaden-maj-2022.pdf?t_id=haD8ANQ7iMUOpzEHZFD00w%3D%3D&t_uuid=c86romWmTziFhwCrN9cFoA&t_q=energy+in+sweden+20&t_tags=language%3Aen%2Candquerymatch&t_hit.id=Energimyndigheten_Content_Media_CustomFile/_1e77d6c5-1889-47c4-beba-0ef99250524f&t_hit.pos=4196.
- EPEX SPOT (2023). “EPEX SPOT Annual Market Review 2023”. *EPEX SPOT*.
- eSett (2024). “Nordic Imbalance Settlement Handbook”. *eSett*. Collected [2024-05-09]. URL: <https://www.esett.com/handbook/>.
- European Centre for Disease Prevention and Control (n.d.). “COVID-19”. *European Centre for Disease Prevention and Control*. Collected [2024-04-16]. URL: <https://www.ecdc.europa.eu/en/covid-19>.
- European Commission (2018). “A Clean Planet for all”. *European Commission*. Collected [2024-04-16]. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2018:773:FIN>.
- European Commission (n.d.). “European Climate Law”. *European Commission*. Collected [2024-04-11]. URL: https://climate.ec.europa.eu/eu-action/european-climate-law_en#x.
- Göransson, L., Johnsson, F. (2023). “Ett framtida elsystem med och utan kärnkraft – vad är skillnaden?” *Chalmers*. URL: https://research.chalmers.se/publication/536840/file/536840_Fulltext.pdf.
- gridX (2024). “Demand-Side Flexibility”. *gridX*. Collected [2024-05-08]. URL: <https://www.gridx.ai/knowledge/demand-side-flexibility>.
- Harit, A., Jain, P., Yamujala, S., Bhakar, R. (2022). “Quantification of Power System Flexibility: A Review”. *IEEE Xplore*. DOI: 10.1109/OTCON56053.2023.10113939. URL: <https://ieeexplore.ieee.org/document/10113939>.
- Hayes, A. (2023). “Volatility: Meaning in Finance and How it Works with Stocks”. *Investopedia*. Collected [2024-02-21]. URL: <https://www.investopedia.com/terms/v/volatility.asp>.
- Holmberg, P., Tangerås, T. P. (2023). “The Swedish electricity market – today and in the future”. *Sveriges Riksbank*. URL: https://www.riksbank.se/globalassets/media/rapporter/pov/artiklar/engelska/2023/230512/2023_1-the-swedish-electricity-market--today-and-in-the-future.pdf.
- Hu, X., Jaraité, J., Kažukauskas, A. (2021). “The effects of wind power on electricity markets: A case study of the Swedish intraday market”. *Energy Economics Volume (96):105159*. URL: <https://www.sciencedirect.com/science/article/pii/S0140988321000645?via%3Dihub>.
- IEA (2022). “National Survey Report of PV Power Applications in Sweden 2022”. *Swedish Energy Agency*.
- International Energy Agency (2023). “Global Energy Crisis”. *International Energy Agency*. Collected [2024-05-10]. URL: <https://www.iea.org/topics/global-energy-crisis>.
- International Renewable Energy Agency (2019). “Demand-side flexibility for power sector transformation”. URL: <https://www.irena.org/publications/2019/Dec/Demand-side-flexibility-for-power-sector-transformation>.
- Jaraité, J., Kazukauskas, A., Brännlund, R., Kiran, C., Kriström, B. (2019). “Intermittency and pricing flexibility in electricity markets”. *Energiforsk Volume (588)*. URL: <https://energiforsk.se/media/26463/intermittency-and-pricing-flexibility-in-electricity-markets-energiforskrappport-2019-588.pdf>.
- Lokhande, S., Bichpuriya, Y., Ankur, K., Sarangan, V. (2023). “An optimized trading strategy for an energy storage systems aggregator in an ancillary service market”. *Journal of Energy Storage Volume (108588)*. URL: <https://www.sciencedirect.com/science/article/abs/pii/S2352152X23019850>.

- Naturskyddsföreningen (2022). “Hur sätts elpriset och varför går det upp?” *Naturskyddsföreningen*. Collected [2024-05-10]. URL: <https://www.naturskyddsforeningen.se/artiklar/hur-satts-elpriset-och-varfor-ar-det-hogt/>.
- Nord Pool (2024). “REMIT UMM”. Collected [2024-04-26]. URL: <https://umm.nordpoolgroup.com/#/messages/52b6c17e-401f-442b-bf20-13f81f3d46be/16>.
- Nord Pool (n.d.[a]). “Day-ahead market”. *Nord Pool*. Collected [2024-02-21]. URL: <https://www.nordpoolgroup.com/en/the-power-market/Day-ahead-market/>.
- Nord Pool (n.d.[b]). “History”. *Nord Pool*. Collected [2024-02-21]. URL: <https://www.nordpoolgroup.com/en/About-us/History/>.
- Nordic Transmission System Operators (2023). “Nordic Grid Development Perspective 2023”. *Svenska Kraftnät*. URL: https://www.svk.se/siteassets/om-oss/rapporter/2023/svk_ngpd2023.pdf.
- Nycander, E., Jakobsson, T., Hellström, E. (2023). “Långsiktig marknadsanalys”. *Svenska Kraftnät*.
- OTE (2024). “Short-Term Markets”. *OTE*. Collected [2024-05-13]. URL: <https://www.ote-cr.cz/en/short-term-markets/market-coupling-intraday-market/intraday-auctions>.
- Pandas Documentation (2024). “pandas.DataFrame.corr”. *pandas*. Collected [2024-05-09]. URL: <https://pandas.pydata.org/docs/reference/api/pandas.DataFrame.corr.html#pandas.DataFrame.corr>.
- Sandberg, R. (2023). “Wind and Electricity Prices in Sweden – a Statistical Analysis”. *Energiforsk*.
- Simonsen, M.-M., Haakestad, P. (2022). “Nordic utilities: north-south markets diverge”. *Scope Group*.
- Söder, L., Amelin, M. (2011). “Effektiv drift och planering av kraftsystem”. URL: [https://www.kth.se/social/files/54b38a05f2765439b73adab7/EG2050+Kompodium+2011+\(sve\).pdf](https://www.kth.se/social/files/54b38a05f2765439b73adab7/EG2050+Kompodium+2011+(sve).pdf).
- Spodniak, P., Ollikka, K., Honkapuro, S. (2021). “The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case”. *Applied Energy Volume(283): 116063*. URL: <https://www.sciencedirect.com/science/article/pii/S030626192031494X>.
- Statistikmyndigheten (2023). “Elproduktion och förbrukning i Sverige”. *Statistikmyndigheten*. Collected [2024-02-28]. URL: <https://www.scb.se/hitta-statistik/sverige-i-siffror/miljo/elektricitet-i-sverige/>.
- Statistikmyndigheten (2024). “Elproduktion efter produktionsslag månadsvis”. *Statistikmyndigheten*. Collected [2024-06-23]. URL: <https://www.scb.se/hitta-statistik/statistik-efter-amne/energi/tillforsel-och-anvandning-av-energi/manatlig-elstatistik-och-byten-av-elleverantor/pong/tabell-och-diagram/elproduktion-efter-produktionsslag-manadsvis/>.
- Svenska Kraftnät (2021a). “Balance responsibility”. *Svenska Kraftnät*. Collected [2024-02-21]. URL: <https://www.svk.se/en/stakeholders-portal/electricity-market/balance-responsibility/#:~:text=An%20electricity%20supplier%20must%20deliver,This%20is%20called%20balance%20responsibility>.
- Svenska Kraftnät (2021b). “Electricity’s route”. *Svenska Kraftnät*. Collected [2024-04-18]. URL: <https://www.svk.se/en/national-grid/operations-and-electricity-markets/electricitys-route/>.
- Svenska Kraftnät (2021c). “Elområden”. *Svenska Kraftnät*. Collected [2024-02-21]. URL: <https://www.svk.se/om-kraftsystemet/om-elmarknaden/elomraden/>.
- Svenska Kraftnät (2021d). “NordBalt”. *Svenska Kraftnät*. Collected [2024-04-212]. URL: <https://www.svk.se/utveckling-av-kraftsystemet/transmissionsnatet/avslutade-transmissionsnatsprojekt/nordbalt/>.
- Svenska Kraftnät (2022). “Om Enätet”. *Svenska Kraftnät*. Collected [2024-02-28]. URL: <https://www.svk.se/om-kraftsystemet/oversikt-av-kraftsystemet/sveriges-elnat/>.

- Svenska Kraftnät (2023a). "Balansering av kraftsystemet". *Svenska Kraftnät*. Collected [2024-03-15]. URL: <https://www.svk.se/om-kraftsystemet/om-systemansvaret/balansering-av-kraftsystemet/>.
- Svenska Kraftnät (2023b). "Intradagsmarknaden – justering av dagen före-handel". *Svenska Kraftnät*. Collected [2024-03-20]. URL: <https://www.svk.se/om-kraftsystemet/om-elmarknaden/intradagsmarknaden--justering-av-dagen-fore-handel/>.
- Svenska Kraftnät (2023c). "Om Elmarknaden". *Svenska Kraftnät*. Collected [2024-02-21]. URL: <https://www.svk.se/om-kraftsystemet/om-elmarknaden/>.
- Svenska Kraftnät (2024). "15 minuters tidsupplösning". *Svenska Kraftnät*. URL: <https://www.svk.se/utveckling-av-kraftsystemet/systemansvar--elmarknad/ny-nordisk-balanseringsmodell-nbm/15-minuters-tidsupplösning/>.
- Svenska Kraftnät (n.d.). "Produktionsstatistik". *Mimer*. Collected [2024-04-08]. URL: <https://mimer.svk.se/ProductionConsumption/ProductionIndex>.
- Swedish Energy Agency (2023). "Resan till ett mer elektrifierat samhälle". *Swedish Energy Agency*. Collected [2024-04-11]. URL: <https://www.energimyndigheten.se/klimat--miljo/sveriges-elektrifiering/>.
- The Swedish Energy Agency (2023). "Energy in Sweden 2022". *The Swedish Energy Agency*. URL: <https://energimyndigheten.a-w2m.se/FolderContents.mvc/Download?ResourceId=212980>.
- Van Zoest, V., Lindberg, K., El Gohary, F., Bartusch, C. (2023). "Evaluating the effects of the COVID-19 pandemic on electricity consumption patterns in the residential, public, commercial and industrial sectors in Sweden". *Energy and AI Volume (100298)*. URL: <https://www.sciencedirect.com/science/article/pii/S2666546823000708>.
- Vattenfall (n.d.). "Porjus". *Vattenfall*. Collected [2024-03-14]. URL: <https://powerplants.vattenfall.com/sv/porjus/>.
- Winberg, J. Z. (2022). "Blåsiga dagar ger rekord för vindkraften". *SVT*. Collected [2024-05-05]. URL: <https://www.svt.se/nyheter/inrikes/blasiga-dagar-ger-rekord-for-vindkraften>.