Powering up profits

Integrating Power Purchase Agreements and Battery Systems for Nordic Power Futures

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LUNDS
UNIVERSITET
Lunds Tekniska Högskola

LTH School of Engineering

Department of Energy Sciences

Thesis for degree Master of Science – Mechanical Engineering
Spring 2023

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Sammanfattning

Denna masteruppstats ämnar utröna lönsamheten och de faktorer som påverkar lönsamheten vid ingåendet av en kort position i finansiella derivat på den nordiska elmarknaden samtidigt som motsvarade position anskaffas genom handel på Nord Pools day-ahead (DA) marknad och via så kallade pay-as-produce Power Purchase Agreements (PPA), samt genom tillämpandet av batterilager för att mitigera effekterna av prisstegringar på DA-marknaden. Studien har applicerat en mixad metod genom att kombinera kvantitativ analys med kvalitativa iakttagelser. Först genomfördes en kvalitativ förstudie, följt av konstruerandet av en matematisk modell för att simulera handelsstrategins energi- och kassaflöden samt kvantifiera strategins ekonomiska genomförbarhet. Den kvalitativa förstudien bidrog med ytterligare sammanhang och förståelse för resultaten från simulationsmodellen.

Resultat för flera scenarier genererades genom att variera inputparametrar inom den matematiska modellen för att bedöma påverkan på lönsamheten. Resultaten påvisade vilka nyckelfaktorer som påverkade lönsamheten för den undersökta strategin. Prisnivåerna för PPA visade sig vara en avgörande faktor, tillsammans med riskpremien för finansiella derivat samt investeringskostnaderna för batterilager. Dessa faktorer visade sig ha störst inflytande på de finansiella resultaten för den implementerade handelsstrategin.

Det finns dock flertalet begränsningar i hur modellen simulerades samt eventuella avvikelser i valda inputparametrarna. Framtida studier inom området bör avse förbättra noggrannheten i simulationen och genomföra mer djupgående simuleringar som specifikt fokuserar på batterilagringskomponenten samt utforskar framtida marknadsbeteenden som volatilitet och kannibalisering. Dessa insatser skulle vidare kunna bidra till en mer robust förståelse av lönsamheten och genomförbarheten av att ingå en kort position i finansiella derivat i kombination med PPA och batterilager, vilket i slutändan kan komma att underlätta för informerade beslut inom energimarknaden.

Abstract

This master's thesis aims to assess the profitability and the factors impacting the profitability of entering a short position in financial derivative contracts on the Nordic power market while procuring electricity through a pay-as-produced power purchase contract and on the day-ahead (DA) market, simultaneously the strategy utilizes a battery storage system to mitigate the effects of price spikes. The research adopted a mixed-method approach by combining quantitative analysis with qualitative findings. First, a qualitative pre-study was conducted, followed by the development of a mathematical model to simulate the strategy's energy and cash flows to quantify the investment's financial viability. The qualitative pre-study provided additional context and understanding of the simulation model results.

Results from multiple scenarios were generated by varying input parameters within the mathematical model to assess the impact on profitability. The findings highlighted key factors impacting the profitability of the examined strategy, including the price levels of power purchase agreements that emerged as a critical determinant, along with the risk premium associated with financial futures contracts and the investment costs of battery storage systems. These factors were found to have the most substantial influence on the financial outcomes of the implemented strategy.

Several limitations exist regarding how the system was simulated, such as inherent biases in the chosen input parameters. Therefore, future research should address these gaps in understanding by developing the accuracy of the simulation, as well as by conducting more in-depth simulations specifically focused on the battery storage component and delving into the exploration of future market behaviors such as volatility and cannibalization. Such research efforts will contribute to a more robust understanding of the profitability and viability of short positions in financial derivative contracts in conjunction with power purchase agreements and BESS, ultimately aiding in informed decision-making within the energy market.

Acknowledgments

We want to express our gratitude to all those who have contributed to completing this master's thesis.

First, we would like to thank Flower for offering us the opportunity and privilege to write our thesis with you. It has been an absolute joy to become acquainted with Flower as a company and to get to know each of you personally. Above all, we want to thank our supervisor John Diklev for his exceptional guidance, expertise, and support throughout this project. Your insights and advice have been invaluable for us in executing this thesis.

Furthermore, we are very grateful for the continuous support from our supervisor at Lund University, Martin Andersson, who has guided us through all of the highs and lows of this project.

We would also like to give special thanks to everyone else who has shown interest in our project. Arne Bergvik at Sigholm, and Rickard Green, who engaged in fruitful conversions with us and provided valuable perspectives, greatly enriched the research process. Also, we would like to thank Bixia, Nasdaq Listing Operations, Nord Pool, and Montel for their generous provision of essential information and data.

Lastly, we want to send our appreciation to friends and classmates – thank you for making our years at LTH so memorable!

Ellen Jinglöv & William Thorwaldson
June 2023
Lund, Sweden

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Abbreviations

BESS	Battery Electric Storage System
DA	Day-ahead
DAM	Day-ahead Market
DCF	Discounted Cash Flow
CV	Coefficient of Variation
EFET	European Federation of Energy Traders
EPAD	Electricity Price Area Differential
Ei	Swedish Energy Markets Inspectorate *(Energimarknadsinspektionen)*
EU	European Union
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
Li-Ion	Lithium-Ion
NPV	Net Present Value
OFAT	One Factor At a Time
OTC	Over-The-Counter
PAP	Pay-As-Produced
PPA	Power Purchase Agreement
PV	Photovoltaic
REC	Renewable Energy Certificate
RES	Renewable Energy Sources
RSD	Relative Standard Deviation
SvK	Svenska Kraftnät
STD	Standard Deviation
TSO	Transmission System Operator
VPP	Virtual Power Plant
VRE	Variable Renewable Energy
WACC	Weighted Average Cost of Cap

Chapter 1.

Introduction

The Swedish power system is undergoing a significant transition driven by climate goals, aiming for a higher share of renewable energy production. Meanwhile, electrification of the transportation and industry sectors contributes to increased electricity demand. However, the increased penetration of intermittent power resources, such as solar and wind, presents challenges in maintaining grid stability and managing increased grid variability. [1]

Additionally, the increased variability in electricity supply affects electricity market prices, which have seen high levels of volatility in recent years. [1] [2] As a result, actors in the Swedish energy industry have sought protection and profitability through various means. One means of managing risk is trading on the financial market to hedge against adverse price movements. [3] During the last decade, however, bilateral contracts known as power purchase agreements (PPAs) between power producers and consumers have gained traction and played a significant role in the increasing renewable power generation in the Nordics. [4]

Simultaneously, to achieve a green and stable energy system, energy storage can facilitate renewable integration while providing grid flexibility. As a result, battery energy storage systems (BESS) have experienced significant growth, particularly in ancillary service applications, where immense profitability has been observed due to high market prices. [5] However, given the dynamic nature of the markets and the risk of market saturation due to increased competition, it becomes imperative to investigate the potential of new business models and ways of profit generation for actors in the energy industry.

1.1. Problem statement

In the context of investigating profit generation, this thesis aims to investigate a specific trading strategy in which a company, or actor, integrates a pay-as-produced power purchase agreement with a Battery Energy Storage System to be able to take the position as a seller of a financial contract for power futures in the Swedish market.

The proposed system involves a combination of electricity trading strategies. Its core objective is to assess the viability of an actor entering into a pay-as-produced power purchase agreement while simultaneously engaging in baseload financial contracts such as electricity price area differentials (EPADs) and Nordic Power Futures. To ensure the ability to fulfill the baseload profile specified by the financial contracts, the system utilizes a BESS. The trading activities are conducted on the day-ahead market to manage the required volume balance. The trading strategy's main elements and their interrelations are illustrated in Figure 1 below.

The primary challenge this research addresses is mitigating shape and price risks inherent in the energy market by incorporating a battery energy storage system. By examining the potential synergy between pay-as-produced power purchase agreements, financial contracts, and BESS, this study aims to provide insights into the feasibility and effectiveness of this integrated approach in managing shape and price risks, thereby facilitating sustainable growth of the green energy system.

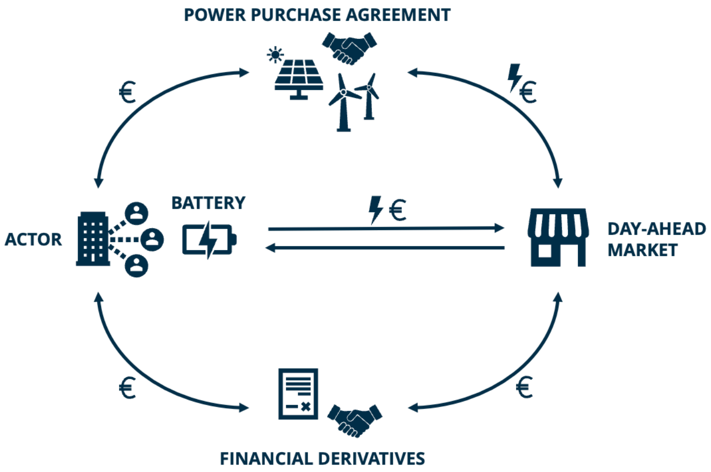

Figure 1. The trading strategy's main elements and their interrelations

1.2. Research questions

The research and objectives of the thesis are based on the two research questions below:

Q1. What is the level of financial feasibility for the proposed strategy in terms of profitability?

Q2. How do the individual components and their respective characteristics impact the profitability of the proposed strategy?

1.3. Scope and delimitations

The following table presents the general delimitations that define the scope of the thesis project and the topics that it will address.

Table 1. Thesis project scope delimitations.

Area	*Description*
Location	The study is limited to the Swedish electricity market.
Bidding zone	All assets and all trading are assumed to belong to the bidding zone SE4.
Physical marketplace	The market is strictly limited to the Nord Pool markets, mainly focusing on the day-ahead market.
Financial marketplace	The financial market refers in the thesis to Nasdaq OMX Commodities. Other exchanges or OTC-markets are not considered.

Variable renewable electricity production	When discussing variable renewable energy generation, the focus is on solar and wind power. Other technologies are not included in the scope of the thesis.
Solar power	The mentioning of solar power refers to utility-scale photovoltaic (PV) solar power.
Wind power	The mentioning of wind power refers to large-scale on-shore wind farms.
Battery storage	The mentioning of battery storage systems refers to grid-scale Li-Ion battery energy storage systems (BESS).

1.4. Division of work

The authors of this report, Ellen Jinglöv and William Thorwaldson, have collaborated closely throughout this project, making joint decisions and sharing responsibility. The workload has been equally dispersed between the authors who have actively been involved in each part of the research process.

1.5. Structure of the report

The first two chapters of the report, *Chapter 1. Introduction* and *Chapter 2. Method,* present the problem to investigate and the methodology chosen to do so. The following chapters each represent one of the main stages of the research process.

Chapter 3. Theory and pre-study findings established the theoretical background of the research and findings from the pre-study to support understanding of quantitative results.

Chapter 4. Data preparation describes how the data is collected, explored, and processed into datasets for input into the simulation model.

Chapter 5. Model development presents the process of conceptualizing the system to be modeled, followed by how the simulation model was constructed and structured.

Chapter 6. Application of the model explains how the finished model was used to generate results to answer the research questions and what input data was used for each simulation.

Chapter 7. Results presents results generated through the application of the simulation model.

Chapter 8. Analysis analyzes and interprets results from the simulation model and findings from pre-study.

Chapter 9. Discussion aims to analyze the methodology and results while also communicating general thoughts about the topic and the general context of this thesis.

The last chapter, *Chapter 10. Conclusions,* presents the conclusions derived from the study and areas of future research.

Chapter 2.

Method

This section explains the approach and research design chosen for this thesis to answer research questions. After this, the overall research process is described, followed by descriptions of each project stage.

2.1. Research design

The research design refers to the overall strategy used to answer research questions, which includes selecting the appropriate methods, techniques for data collection and analysis, and how to use them to combine findings appropriately. This component is vital, as it guides the research process and determines the quality and validity of the findings. [6]

2.1.1. Research design strategies

There are three types of research designs: quantitative, qualitative, and mixed methods. Quantitative research tests objective theories by examining relationships among variables using numbered data. Qualitative research can complement quantitative analysis by providing a deeper understanding of the context through qualitative data collection regarding emergent questions and themes. The mixed-method approach combines both approaches to draw on the benefits and strengths of each method to make the quality of the study's overall findings greater. A mixed-method approach is especially useful when either the quantitative or qualitative approach is inadequate to understand a research problem. [6]

Creswell and Plano Clark [6] propose four design types within mixed-methods research: triangulation design, embedded design, explanatory design, and exploratory design. Triangulation design involves using multiple methods to corroborate findings, while embedded design involves one method supporting the other. Explanatory design involves collecting and analyzing quantitative data to explain qualitative findings, and exploratory design involves using qualitative data to generate quantitative research questions. These design types can be used in various combinations depending on the research question and the study' goals. [6]

2.1.2. Research design selection

Based on the proposed concepts and frameworks developed by Creswell and Plano Clark, [6] the research design for this thesis was selected. The method chosen entailed a mixed-method approach to use the strengths of both qualitative and quantitative methods to provide a more comprehensive and accurate understanding of the research problem. Specifically, based on the research question and objectives of the project, the research design selected was the embedded design type in which the qualitative study was embedded to support and validate the quantitative findings. [6]

2.1.3. Method selection

Since the research questions entail assessing the profitability and impact of different factors and elements, a quantitative method was deemed suitable as it allows for actual numerical measurement of the profitability. Furthermore, it enables applications of statistical methods to analyze data and identify patterns or findings that may not have been immediately visible through qualitative methods. The specific method chosen for evaluating the profitability of the strategy chosen was discounted cash flow (DCF) method, in combination with calculations of the net present value (NPV) and internal rate of return (IRR). To conduct this method, the investment's cash flows need to be estimated. Therefore, a quantitative deductive method was selected by constructing a mathematical simulation model that models the strategy as a closed system. Specifically, this model simulates the behavior of the elements within the strategy which generate cash flows.

Due to the complexity and uncertainty associated with the system, a qualitative method element was used to complement quantitative findings and motivate and enhance the study’s validity, reliability, and overall quality. Furthermore, findings were used to substantiate and justify the construction of the model to increase its relevance and reliability and to explain and contextualize the quantitative results.

2.2. Research process

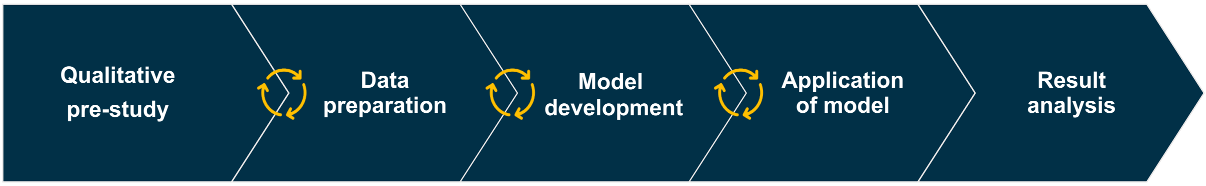

Figure 2. Stages of the research process.

The research process for this project was categorized into four main stages, each consisting of several sub-steps. Figure 2 provides a conceptual overview of the stages of the research process. The pre-study, data preparation, model development, and application of the model were generally performed sequentially, with the output from one stage serving as input for the next. However, an iterative approach was also adopted to accommodate any necessary adjustments or additions prompted by findings from the following stages. By repeating these steps, we refined the simulation model, aligning it with our deep understanding of the system and ensuring its accuracy and relevance in addressing the problem.

2.2.1. Qualitative Pre-study

Figure 3. Qualitative pre-study stage.

The main objective of the qualitative pre-study is to develop an understanding of the strategy. This involved reviewing relevant literature, research, and publications on the thesis topic. In the pre-study existing knowledge, key concepts, and themes were identified to establish a theoretical foundation for the subsequent quantitative analysis and further exploration. The findings and insights derived from the pre-study are presented in Chapter 3. Theory and pre-study findings.

Areas of particular interest were, for instance: solar power production, wind power production, variable renewable production, physical electricity markets, financial electricity markets, power futures, power purchase agreements, and grid-scale battery energy storage systems.

2.2.2. Data Preparation

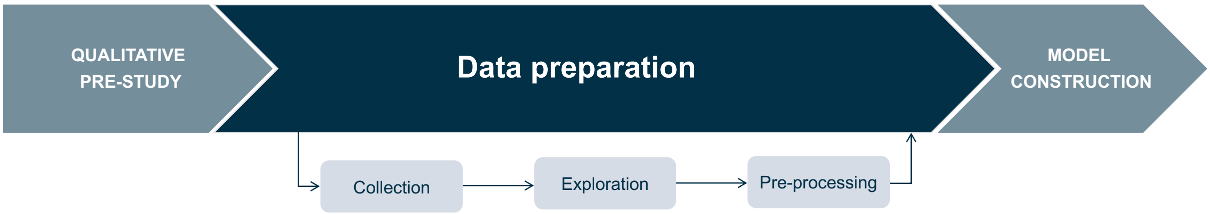

Figure 4. Data preparation stage and included steps.

Before constructing the simulation model, the required input data was gathered and processed to ensure the model was built on reliable and well-structured data. Data preparation for the simulation model was divided into three steps: collection, exploration, and processing.

Data collection involved gathering the relevant data from appropriate sources needed for the simulation modeling process. Then, the collected data was systematically analyzed during the data exploration step to uncover patterns, trends, and potential outliers or errors. These insights informed subsequent data processing and modeling stages, which focused on cleaning, transforming, and preparing the data for use in the model. By ensuring the accuracy and reliability of the data, the processing stage aimed to create high-quality datasets that facilitate accurate and relevant model output.

2.2.3. Simulation model development

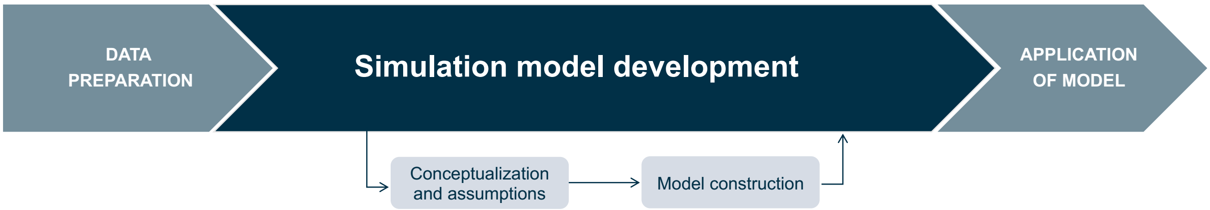

Figure 5. Simulation model development stage and included steps.

A simulation model was constructed to evaluate the financial viability of an investment in and operation of the trading strategy in question. The simulation model development consisted of two main steps: conceptualization and assumptions, followed by the actual construction of the simulation model.

Conceptualization and assumptions

In order to develop a relevant and accurate model to address this thesis's research questions and purpose, the initial step involved conceptualizing the system by mapping out elements and interrelationships based on the findings from the qualitative pre-study. The purpose of the conceptualization step was to present a clear and well-defined representation of the system investigated to make the simulation model easier to construct, interpret and analyze.

The conceptualization step involved identifying the boundaries of the model, the characteristics of the elements in the model, and defining key relationships between the elements. It also involved establishing which assumptions and simplifications to apply to the system to make the simulation model easier to construct, more effective, and reduce the overall complexity. This included simplifying relationships between variables, ignoring certain less significant factors, and imposing constraints to create a more feasible, robust, and reliable model. For this step, decisions must be underpinned with an understanding of their impact on the model, their implementation must be valid, and their assumptions must be communicated. Once the conceptualization and limitations were established, the simulation model was constructed.

Construction of the simulation model

Based on the definitions of the system and assumptions from the conceptualization stage, a simulation model that models hourly energy and cash flows during the investment period and evaluates the profitability of the investment using financial evaluation methods.

In order to account for the inherent uncertainty of the system being simulated, a stochastic approach was employed during the model construction. This involved utilizing a *random bootstrapping* technique to generate datasets for each model iteration from datasets with historical data to capture the inherent probability within the system. This approach allowed for the incorporation of randomness and variability, enhancing the accuracy of the simulation results.

A combination of the software Microsoft Excel and the open-source programming language Python was used to construct the model. Python offers access to packages for efficient handling, exploring, and visualizing large data sets. Therefore, all data processing, exploration, and bootstrapping computations were conducted using Python through the web-based platform Jupyter Notebooks. Microsoft Excel was used for system behavior simulations, profitability calculations, and recording of results. The choice of using Excel for these parts was to ensure ease of use and interpretability of the model by any user.

2.2.4. Application of the model

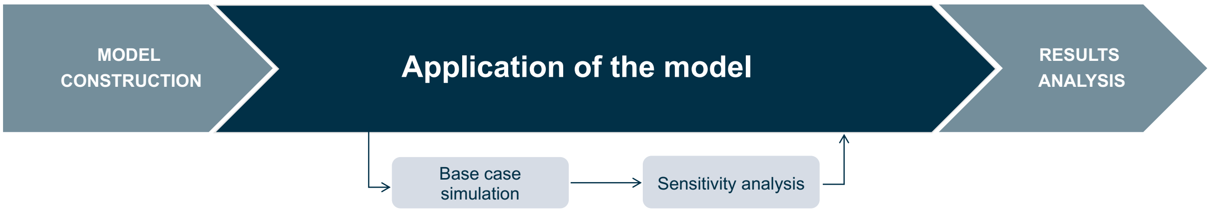

Figure 6. Application of model stage and steps.

Applying the constructed simulation model to generate results involved two main steps: simulating a base case and conducting a sensitivity analysis. The combination of the base case simulation and the subsequent sensitivity allows for a deeper understanding of the factors at play and their implications within the system under investigation.

Base case

The base case aimed to answer the first research question by generating results for a baseline representation of the system under study. In this sense, the base case simulation served as a starting point for understanding the behavior and outcomes of the system and as a benchmark against which the results from simulating other scenarios were compared.

In selecting the input for the base case, the aim was to use values deemed probable when the system is assumed to be implemented, i.e., at the beginning of 2024. Values were determined through benchmarking using both external sources (e.g., primary data from market actors), as well as with the help of experts on the subject matter at hand to validate the values' plausibility.

Sensitivity analysis

Following the base case simulation, a sensitivity analysis was performed to explore the impact of various factors and, in doing so, be able to address the second research question of this thesis and further evaluate the first research question.

The *One Factor At a Time* (OFAT) method was used for the sensitivity analysis, which entails that we systematically vary each input parameter individually while holding all other parameters at their base case values By examining the model's output under different high and low values for each parameter, the influence of individual parameters on the overall output was addressed. This analysis helps us identify the most important parameters in the model and understand how they affect the output. This method was chosen due to its computational efficiency. However, a disadvantage of the method is that it does not consider the interactions between input parameters, which may impact the results of the sensitivity analysis. Therefore, results are analyzed and discussed based on findings from the pre-study.

Chapter 3.

Theory and pre-study findings

This chapter presents the findings from the qualitative pre-study and the theoretical background underpinning this thesis's methodology, analysis, and results. Further, this will serve as a foundation for understanding the research problem and questions addressed. The aim is to provide the reader with a base of knowledge to understand the following sections in this report while also presenting discoveries from the study that will be used to analyze the results.

3.1. Variable renewable power generation

Variable renewable power generation refers to producing electricity from renewable energy sources that exhibit variability in output due to external factors such as weather conditions and natural resource availability. Unlike conventional power plants that can operate at a consistent and controllable capacity, variable renewable power sources experience fluctuations in their energy production. They are non-dispatchable, meaning they cannot be quickly scheduled according to demand. [1] The most prominent examples of variable renewable power sources are solar photovoltaic (PV) and wind power. [7] In the upcoming sections, we will delve deeper into the topics of solar and wind energy production, specifically focusing on the Swedish electricity sector and technical considerations.

3.1.1. Renewables in Sweden

Sweden has established national energy goals based on the climate and energy policies and legislations set by the European Union. Among these, Sweden has set a target for 100 percent renewable energy production by 2040. However, this target does not explicitly prohibit fossil-free nuclear power. [8] To achieve this goal, a large share of the Swedish electricity mix will have to come from renewable sources, such as solar and wind. [4]

In 2020, the total electricity generation in Sweden was 166 TWh, of which the share of renewables was approximately 60 percent. A large part of this share is attributed to hydropower, which constituted 42 percent of Sweden's total electricity generation in the same year. The variable renewable energy (VRE) sources, wind and solar, provided 17 and 1 percent of the generation, respectively. [9] from

Sweden's electricity system has historically relied on large-scale centralized production, primarily hydropower, and nuclear power. However, in the last decade, wind power generation has increased significantly. In recent years, solar power production has grown rapidly, partly replacing controllable energy sources such as nuclear and combined heat and power generation. [10] [1] These developments can be seen in Figure 7. The replacement of plannable production has been especially prevalent in southern Sweden, which between 2012-2021, experienced a decrease of 21%. [1]

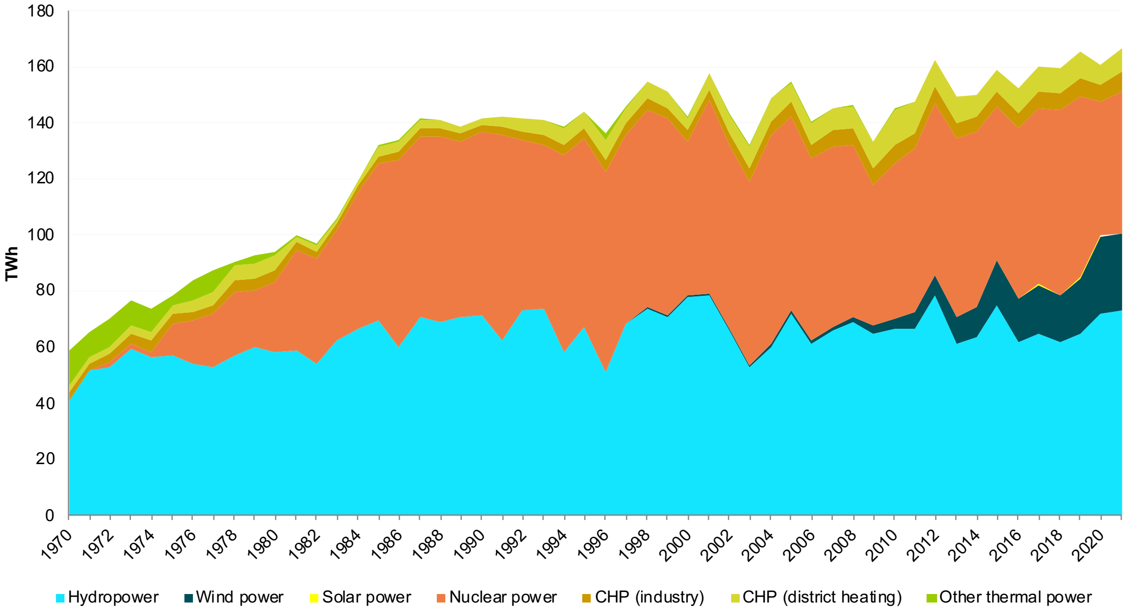

Figure 7. Net electricity production in Sweden 1970-2021, in TWh. [10]

Wind power deployment in Sweden

In 2017, the total installed capacity in Sweden was 40 GW, an increase of more than 18% since 2000. This increase can mainly be attributed to the surge of installed capacity from wind power, which went from 209 to 6611 MW during the same period. [11] One of the main contributors to the significant rise of wind power in Sweden was introducing the electricity certificate system, which triggered high growth rates from 2006 onwards. However, the system's effectiveness diminished as it struggled to keep up with the increasing supply of wind power. Although there was a brief resurgence in 2018-2019, the support system is a less significant driver for new investments. [4]

However, the expansion of wind power in Sweden has continued. In February 2023, Sweden generated 27% of its electricity from wind, corresponding to 4 TWh, a record-high share for the country. [12] A contributing factor to the continuous growth of wind power in Sweden is the increased adoption of bilateral contracts between power producers to ensure stable prices and secure financing for wind projects. These bilateral contracts are referred to as Power Purchase Agreements (PPAs). [4] In subsection

3.3. Power Purchase Agreements these contracts are explored in greater depth.

Solar power deployment in Sweden

Solar power in Sweden has seen significant growth in recent years, primarily due to technological advancements and favorable government policies. According to data from Swedish Energy Agency (Energimyndigheten) [10], solar power accounted for 1% of the electricity generation in 2020. However, between 2020 and 2021, the number of grid-connected photovoltaic (PV) systems surged by 46%. As a result, by 2021, the total installed count of solar PV systems in Sweden reached 92 350, with a total installed power of 1 587 MW. [10] Declining costs, particularly in offshore wind and PV systems, have markedly improved the competitiveness of renewable energy sources compared to conventional fossil fuel-based generation.

Furthermore, governmental intervention in the form of investment aid has played a pivotal role. Specifically, a 30 percent subsidy has been offered for PV cells, incentivizing investments in solar power infrastructure. [11]

Effects of transition to renewables

The Swedish energy sector faces several challenges transitioning to a renewable electricity system. Historically, electricity use in Sweden has been stable, with a slight decrease during the past two decades, amounting to a total use of 135 TWh in 2020. [10] However, the Swedish Energy Agency predicted in their 2018 report "Vägen till ett 100 procent förnybart elsystem. Delrapport 1: Framtidens elsystem och Sveriges förutsättningar" [13] that by 2045 electricity demand would increase to between 200-220 TWh. The extensive electrification of the transportation and industry sectors is a key reason for this increase. [1] [13] To keep up with this demand increase, between 60-120 TWh of new production must be constructed by 2045, of which at least 100 TWh will have to come from renewable power production sites. For this to happen, significant investments must occur within the renewable energy industry. [13]

The integration of more variable renewable energy sources, such as wind and solar power, introduces challenges related to intermittency and uncertainty in the electricity mix. As a result, integrating these energy sources requires support services to keep the system stable. Furthermore, there is potential to enhance flexibility both on the consumer side and within the electricity grid through utilizing energy storage technologies. [13]

3.1.2. Production characteristics

Both wind and solar power generation output have fluctuating production profiles. The ability to generate electricity through each technology depends on if renewable sources are available. Therefore, when these sources are unavailable, periods of low or zero production output occur when unfavorable conditions occur. The variability of these technologies exhibits patterns on different time scales, i.e., within a year, as well as within a day. [7]

Wind power production

Wind power production heavily relies on the wind's speed and consistency and may produce power all hours of the day. The geographical location also influences wind power generation. However, wind power production varies from hour to hour, resulting in a curve that shows momentary spikes of increased or decreased production. This fluctuation occurs because there are instances with no wind or when the wind is so strong that production sites must be temporarily shut down. [4]

The ratio of actual energy production to the maximum potential energy production of a wind turbine operated at its rated capacity is referred to as the capacity factor of a wind turbine. It represents the actual utilization and efficiency of the wind turbine and plays a significant role in wind power generation. Off-shore wind farms, characterized by larger physical size and higher rated power capacity, have demonstrated capacity factors exceeding 50% in areas with high-quality wind resources. However, these numbers are subject to wake losses. [14] However, for on-shore wind, Sweden's average capacity factor was 37% in 2020, according to Svensk Vindenergi. [15]

Solar power production

Various weather-dependent factors also influence solar power production. Solar photovoltaic (PV) systems produce more electricity in direct sunlight, while cloudy conditions result in reduced production. [4] Furthermore, there is no production during the night, making the production profile of solar quite predictable. [4] [2] According to IEA, the global average capacity factor for solar PV technologies was around 14% in 2018. However, in their report "Levelized Cost of Energy" from 2023 [16], Lazard assumed that the capacity factor of utility-scale solar PV was between 15-30%.

Combining solar and wind power generation

As wind and solar production profiles differ, combining the two makes it possible to balance the hourly variation of supply and demand more effectively. An efficient hybrid mix of wind and solar power production can adjust the total supply demand to a specific demand profile. [7]

In the article "Design of wind and solar energy supply to match energy demand", S. Mertens explores how to combine solar PV and wind energy production to achieve different production profiles based on energy demand profiles. To determine the optimal share of wind and solar PV, Mertens suggests modeling a curve on the normalized monthly energy yields, using effects triggered by the angle of the sun and its irradiation. The curve is determined through two goniometric formulas describing the monthly energy yield of wind and solar power. The formulas proposed by Mertens are presented below. [7]

$$E_s = C_1 + C_2 \times \cos\left(\frac{m \times \pi}{6}\right) \tag{3.1}$$

$$E_w = C_3 + C_4 \times \cos\left(\frac{(m + C_5) \times \pi}{6}\right) \tag{3.2}$$

in which

E_S = Monthly energy yield solar
E_W = Monthly energy yield wind
$C_{1\text{-}4}$ = Fit constants
C_5 = Phase shift
m = Number of months in a year

Mertens indicates that this method is justified when the correlation between solar and wind energy on an hourly level is weak, as the proposed method assumes that wind and solar energy is independent on an hourly time frame. [7]

To achieve a flat production profile through the combination of solar PV and wind S. Mertens derives the relationship indicated by equations (3.3) and (3.4) below. To account for the capacity factors of wind and solar, Mertens proposes equation (3.5) to find the required amount of installed power for a baseload mix of solar and wind energy.

$$E_{tot} = E_s + C \times E_w \tag{3.3}$$

$$C = \frac{-C_2}{C_4} \tag{3.4}$$

$$P_w = C \frac{C_{f,s}}{C_{f,w}} P_s \tag{3.5}$$

in which

E_{tot} = Total energy yield
E_S = Energy yield solar
E_w = Energy yield wind
C = Solar / wind ratio factor
C_2 = Fit constant
C_4 = Fit constant
P_w = Wind power
P_s = Solar power

3.2. Swedish electricity markets

The Swedish electricity market is a dynamic system where buying and selling electricity for power supply and trading occurs across multiple markets. This section presents an overview of the Swedish market, followed by descriptions and investigations of the physical and financial markets.

3.2.1. Market overview

The Swedish electricity market is deregulated, into network activities, such as transmission and distribution, and competitive activities, such as power generation and trade, are separated. This deregulation occurred during the 1990s, with the primary objective of promoting market competition within the generation and trade of electricity while maintaining transmission and distribution of electricity as natural or local natural monopolies. Apart from opening the market, the aim was also to ensure market-determined investments in new power capacity. [17]

In 1996 the Swedish and Norwegian power markets were consolidated, forming the common marketplace Nord Pool, for free trade of wholesale electricity. [17] The market was expanded even further to include the rest of the Nordic countries by the end of the 1990s, followed by the Baltic countries, Latvia, Estonia, and Lithuania, in the early 2010s [18].

Trading of electricity as a commodity

Electricity is traded similarly to other commodities, but its market differs due to some distinct characteristics that set it apart. Unlike many commodities, electricity cannot be easily stored in large quantities at a reasonable cost. As a result, for the electricity system to function effectively, the production and supply of electricity must align with real-time consumption, thereby maintaining a certain equilibrium between supply and demand. This equilibrium is vital to meet consumer demand and ensure the operational safety and reliability of the transmission network. [19] In Sweden, the state enterprise Svenska Kraftnät (SvK) is the authority responsible for ensuring that the energy system is balanced. SvK is also responsible for managing and developing the transmission network in its role as transmission system operator (TSO). [3]

After the deregulation, the Swedish electricity market has become a complex system consisting of several submarkets working together to set the electricity price, ensure delivery reliability, and maintain balance. These markets differ depending on whether the commodity is physical electricity, i.e., buying or selling electricity for actual physical transfer to buyers, or financial, which does not involve actual physical delivery of electricity. The physical markets, also differ depending on the time scale at which the electricity is delivered. [3] The four submarkets forming the electricity trade system are presented in Figure 8. Together, these markets enable the planning and trade of electricity at different times prior to physical delivery. [3]

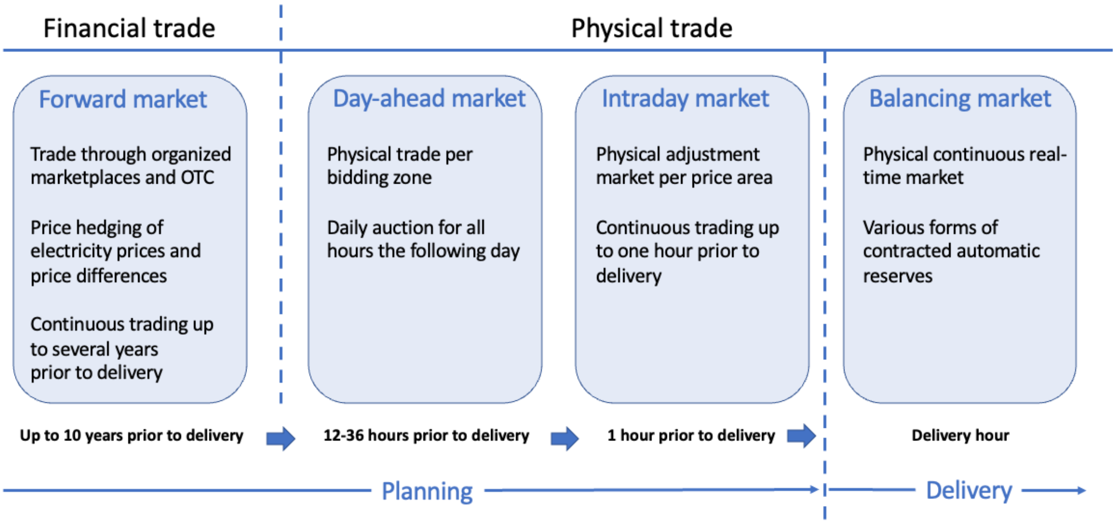

Figure 8. The four submarkets of the Swedish electricity trade system (adapted from [3]).

System price and bidding zones

Nord Pool Spot calculates the common system price for the Nordic-Baltic trading area, which works as a reference price and indicates the price of electricity that would be prevalent without restrictions in the transmission network. The system price is calculated for each hour of the following day. [20]

Due to congestion and constraints in the transmission network, bidding zones have been established to highlight areas where bottlenecks in the transmission network appear. If there is enough transmission capacity between zones, a single price area will form, and the price will be the same in all these areas. On the contrary, if the transmission capacity is insufficient, different price regions will emerge with varying prices. A price region can include one or more bidding zones. [21]

Since 2011 Sweden has been divided into four bidding zones: SE1, SE2, SE3, and SE4. In 2021, the price of electricity in the bidding zones was mainly reflected in the four bidding zones divided into two price regions: the northern bidding zones SE1 and SE2 and the southern bidding zones SE3 and SE4. [3] Since the establishment of the Swedish bidding zones in 2011, there have been notable changes in the conditions surrounding the division of the power system. These changes include various factors, including the emergence of new transmission constraints and reduced ability to ensure safe operations of the power system. Therefore in 2022, ACER (European Union Agency for the Cooperation of Energy Regulators) presented four alternative divisions of bidding zones that are being evaluated and later decided upon by Svenska Kraftnät (SvK). If a decision is made to change the bidding zones, it will be implemented no earlier than 2027. [22]

Integration of the Swedish market with European

Since the electricity market reformation in the 1990s, European electricity markets have become increasingly integrated. Before this, the price of electricity in Sweden was decided based on domestic supply and demand. Today, however, electricity prices in Sweden depend on supply and demand dynamics beyond national borders. The process of integrating the European markets has been made possible by establishing physical interconnections, i.e., transmission links between European countries, enabling day-ahead markets in different countries to be coupled directly and indirectly. Moreover, directives and regulations issued by the EU Commission both have and are further promoting the integration of markets aiming to create a common European electricity market. [23]

3.2.2. Physical electricity markets

Physical electricity markets are marketplaces through which electricity is traded physically between various market participants, including generators, suppliers, and consumers. These markets are designed to enable efficient and reliable electricity grid operation by providing mechanisms for price discovery, supply-demand balancing, and real-time management of electricity production and consumption. [3] The physical electricity submarkets include the day-ahead market, intraday market, and balancing market, each of which serves a specific purpose in ensuring the effective functioning of the electricity system (see Figure 8). This section will provide an overview of these markets, including their characteristics and key features.

Day-ahead market

The day-ahead market (DAM), also known as the spot market, is the primary marketplace for physical electricity trade in the Swedish electricity system. This organized marketplace enables hourly electricity trading for the following day, where participants can place buy or sell orders specifying a certain price and volume based on their estimation of supply or demand. The market aims to ensure a reliable electricity supply by matching supply with demand at the lowest possible cost. [3]

The current market price on the day-ahead market for a unit of electricity, or the spot price, is determined depending on hourly supply and demand dynamics. Bids corresponding to specific bidding zones are submitted to the exchange by noon the day before delivery, requiring market participants to estimate their supply or demand within 12 to 36 hours before physical delivery or consumption. Once all bids are submitted, the spot price for each bidding zone is calculated by Nord Pool. This price is determined by the intersection between the aggregated buy and sell orders for each hour and is the same for all transactions on the market in the same bidding zone. If a sell order has a price below the market price, the holder is obliged to produce and sell their electricity. Conversely, holders of buy orders higher than the market price must buy electricity. As a result, the lowest marginal cost generation technologies are prioritized, and the price is set by the most expensive generator needed to meet demand. [3] Figure 9 below includes a graphical representation of this process, and how prices are set based on marginal cost.

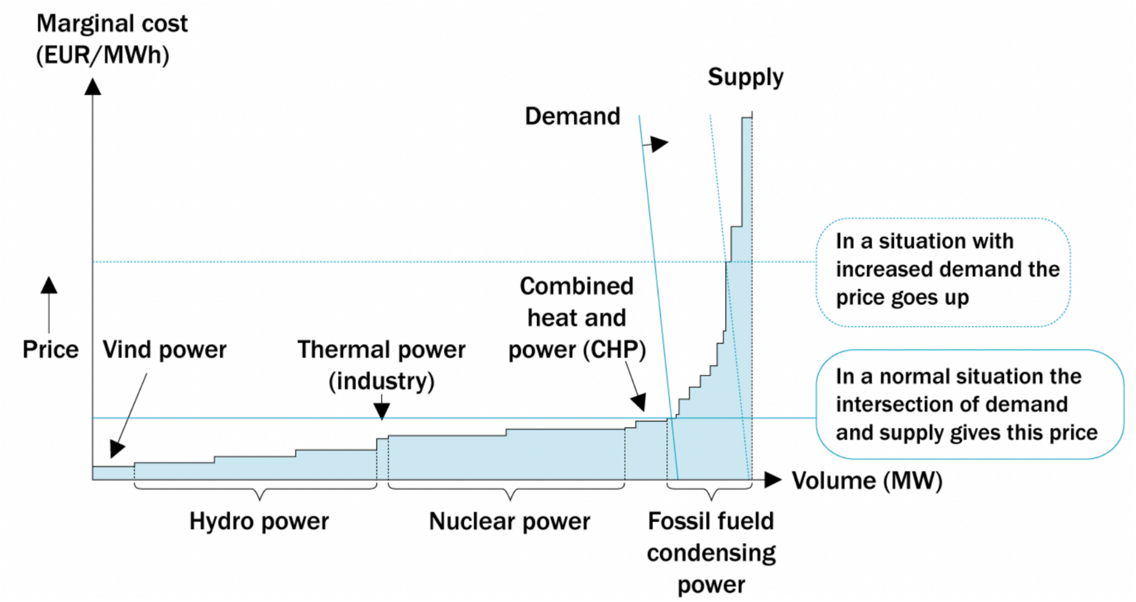

Figure 9. The marginal pricing of power generation technologies. [3]

Intraday market

The intraday market, offered by Nord Pool, is an adjustment market that enables actors in the electricity market to trade in balance if their conditions have changed after the closure of the day-ahead market. The intraday market allows trade closer to the physical delivery, with the flexibility to balance a trade up to one hour before delivery. Unlike the day-ahead market, the pricing process in the intraday market follows the principle of first come, first served. This continuous market matches bids between two actors when their bids align without affecting the pricing of other biddings. However, compared to the day-ahead market, the traded volume on the intraday market is lower, accounting for only 7% of the day-ahead market's traded volume in 2021. [3]

Balancing markets

The balance between electricity supply and demand is primarily achieved through physical trading on the day-ahead and intraday markets as participants fulfill their buy-and-sell contracts. Nonetheless, due to unexpected occurrences or imbalances occurring at the minute or second level, it is necessary to maintain balance in real-time, within the hour. To this end, Svenska Kraftnät (SvK) manages markets for regulating power to fulfill their responsibility of balancing the electricity system. Through these markets, SvK procures balance services, such as frequency regulation and ancillary services. The balancing markets will undergo significant changes in the coming years by implementing new methods, terms, and conditions developed through the joint Nordic project *Nordic Balancing Power*. [3]

3.2.3. Day-ahead market prices

Given the project's scope and focus on the day-ahead market, this section will delve deeper into the characteristics and dynamics of day-ahead market prices and the methods employed for price forecasting.

Characteristics and key drivers of day-ahead prices

The spot price of electricity is influenced by various factors that can cause it to exhibit significant fluctuations over time. The volatility of electricity spot prices is much higher than for other commodities. [2] These fluctuations can be more or less predictable and differ in time scale, such as sudden increases in price levels, either for more extended periods (referred to as jumps) or more short-lived spikes. This uncertainty is partly attributed to the challenges in seamlessly matching supply and demand due to the limitations in storing electricity. [24]

Understanding the drivers of spot price levels and variations is vital for electricity market participants, as it can impact their profitability and risk exposure. For instance, spot prices tend to follow specific patterns over different periods, such as within a day or depending on the time of year. This seasonality depends on both weather patterns, as well as shifts in consumer demand. [24] [25] In the following subsections, some of the factors impacting spot price levels and the characteristics they contribute to are presented.

Demand

Like for other tradable assets, electricity prices are primarily driven by demand. Higher demand leads to a higher spot price, while lower demand results in a lower price. Moreover, the historically observed seasonality of the spot price is linked to the non-static nature of electricity demand. The demand for electricity shows cyclic behavior yearly, weekly, and daily due to weather conditions and social or economic activities. In Sweden and the Nordic region, demand is usually higher during colder winters due to the increased need for heating. Additionally, social and economic activities result in shorter weekly and daily cycles. On a weekly basis, the demand is often lower on weekends due to a decrease in economic activity. [26] On a daily basis, the varying demand within the day has created the so-called peak (08:00 to 20:00) and off-peak hours (20:00 to 08:00), as defined by Nord Pool. [27] Moreover, electricity demand is expected to increase as a result of the extensive electrification being planned of both industry and transportation. [1]

However, SvKs report “Långsiktig marknadsanalys 2021” found through investigation of long-term scenarios for the Nordic electricity system that depending on how developments in the electricity sector continue, these seasonal patterns can become less prevalent. Instead, a less predictable power system is anticipated. This report suggests that the historically regular patterns of electricity prices following a daily pattern due to demand will be disrupted. Prices are expected to become more volatile and closely tied to production variations. [25]

Variable electricity production

With the growing penetration of variable renewable energy (VRE) sources in Sweden, the spot price has been significantly influenced. Both wind and solar have low marginal costs, which places them at the forefront of the merit order. Therefore, a reduction or increase in production from renewables will shift the supply line on the merit order, either right or left, resulting in a lower or higher spot price. [26] As a result, more VRE is introduced into the Swedish electricity system, the increased supply during certain hours will result in lower spot prices. [2] This effect on the market is mostly attributed to wind power, as it has a significant share of the production mix in Sweden than solar. [26]

In the long-term, the viability of renewables may be affected by this emerging phenomenon. Commonly, this is referred to as the *cannibalization effect*, as renewable resources are essentially cannibalizing on their own revenues with increased penetration in the electricity mix. However, it is also often referred to in terms of *profile risk*, i.e., the risk derived from the production profiles of these intermittent energy sources. This effect can be measured by the use of the capture price to which the producers of VRE are exposed. Specifically, the capture price presents the average realized volume-weighted price a generation technology receives for its production. For baseload power technologies generating the same amount throughout the day, the capture price would simply correspond to the baseload price, i.e., the average price over a selected timeframe. However, for intermittent wind and solar, the capture price may be lower if its production occurs when the spot price is lower than the baseload price. The profile risk affects both wind and solar power technologies, however, it may be less challenging to mitigate these risks for solar due to the predictability of its production profile. As of 2021, the capture price for on-shore wind in Sweden was half that of the baseload price. [2]

The variability due to an increase in the share of variable renewable power production has also resulted in more significant periodical deficits, creating a greater need for the import of electricity from other countries. Due to this, European prices have influenced Swedish prices, specifically the southern region, while northern Sweden has been shielded from the impact due to domestic transmission bottlenecks. [1]

Fuel cost

Fuel and carbon emissions quota costs are critical drivers in power price and, in turn, contributors to price fluctuations. [26] [28] Due to the marginal pricing method of spot prices, so will the clearing price in the merit order when fuel prices increase. Understandably, the effect of fuel cost is lower for countries less reliant on fossil fuel-powered plants. [26] However, as Sweden is part of the common European electricity market, the elevated electricity prices observed from countries more dependent on fossil fuels for power generation are imported to a certain extent. An example of this is the recent soaring price of natural gas that has taken place due to the Russian invasion of Ukraine. As electricity production from natural gas-fired power plants is essential for many European countries, the marginal cost for these power plants has surged, setting a new, higher clearing price for electricity. Subsequently, when there is no limitation in the transmission capacity between bidding zones, the higher price in one bidding zone will influence the price of the other. Surging electricity prices has especially been the case in the southern bidding zones in Sweden since 2022. [29]

Other factors

It is also important to mention hydrological resources influencing the spot price. Hydropower produces a big share of the total electricity produced in Sweden. Therefore, factors influencing the ability of hydropower, such as precipitation level, will also influence the spot prices. Other notable factors influencing the spot price are nuclear power, transmission capacity, and outages. [26]

Spot price forecasting

Forecasting electricity prices is crucial for actors engaged in electricity trading, enabling informed and accurate decision-making. Price forecasts may concern short-term or long-term horizons depending on the actor's specific needs. Short-term forecasting primarily focuses on predicting hourly electricity prices for the upcoming day, usually one day in advance. Conversely, medium- to long-term forecasting spans from weeks to years ahead. [30]

Short-term forecasting

Short-term forecasting is crucial for enabling effective trade on the day-ahead market. It provides valuable insights for actors on when to dispatch power plants, schedule industrial operations, or trade on the intraday or balancing market. Various models have been explored to forecast short-term electricity prices accurately. These models include statistical approaches, machine learning, game-theoretic methods, fundamental analyses, and reduced-form models. [30]

Long-term forecasting

Market participants typically face limited availability of price information, typically restricted to the day ahead of delivery. Long-term forecasting enables actors to predict price information for extended periods, ranging from weeks to years, before the actual delivery timeframe. Moreover, it is important for these actors to have access to hourly predictions within this long-term forecast. The granularity of hourly forecasts is vital for numerous applications, including power plant dispatch planning, production scheduling, risk management, and contract valuation. One approach to achieve long-term forecasting is to examine the futures market. The futures market provides price information for contracts with varying maturities, ranging from a single day to several years. These prices can then be utilized to construct an hourly price forward curve (HPFC). The HPFC incorporates historical day-ahead prices to derive an hourly price profile. Multiple models exist to accomplish this, generally involving two key steps. The first step involves generating an hourly price profile based on historical day-ahead price data, and the second step incorporates market prices for futures contracts to accomplish an arbitrage-free HPFC. [30]

3.2.3. Financial electricity markets

In addition to the physical markets for the trade of electricity, there are also financial markets in which contracts are settled without actual electricity delivery. These markets provide tools for market participants to manage and hedge risks associated with the physical markets, such as price variations that may occur over time or between bidding zones. However, these markets also offer speculation and arbitrage trade possibilities, in which the purpose is not to protect against price variation but rather to profit from price movements or discrepancies. [3]

Derivatives are one of the essential financial tools in financial markets. These financial contracts derive their value from other underlying variables, often called the underlying. The underlying variables may refer to a specific asset, a collection of of assets, or a benchmark value. [31]

Marketplaces for derivative trade

Trade of derivatives can be made over-the-counter (OTC) or via organized exchanges. Trade in derivative contracts OTC may be pre-arranged by a broker or negotiated bilaterally between two parties, with the obligation or option to register the trade for clearing at an exchange. However, the primary purpose of an exchange is to enable equitable and systematic transactions and provide market transparency. Another critical function of an exchange is to limit the so-called counterparty risk that arises from the failure of a buyer or seller to fulfill their contractual obligations. To participate in exchange-traded contracts, each participant appoints a clearing member (CM), typically a bank, as their payment agent. The financial settlement is between the CM and the exchange's clearing house. Through this, the clearing house acts as a central counterparty between both contract parties. Being the buyer to every seller and seller to every buyer on the exchange. [32]

Power futures

The futures contract is the most commonly used derivative in the Swedish electricity market. [33] A futures contract is a type of derivative that involves an agreement between two parties to buy or sell an asset for an agreed-upon price at a specific time. A participant can take a long or short position by entering a futures contract. By taking a long position, the participant is obligated to buy the contracts underlying asset for the agreed-upon price at a specified time in the future. In contrast, by taking a short position, the participant is obligated to sell the same asset at the same price at the same time in the future. Futures contracts are standardized contracts, meaning they follow a specific framework set by an exchange. [31]

Nasdaq OMX Commodities Europe is Sweden’s leading exchange for trade in electricity futures. [33] Nasdaq offers financially settled futures and options on the Nordic power market with different tenors and loads. [34] Two main tools for hedging activities on the Nasdaq exchange are the system price futures and the so-called Electricity Price Area Differential futures (EPADs). [3] The following sections will explore these Nasdaq power future derivatives in further detail.

The system price electricity futures offered by Nasdaq is referred to as Nordic Power Futures. These futures are traded with the Nordic system price as underlying with a base load structure. Delivery periods for the Nordic Power Futures can be days, weeks, months, quarters, and years, with the longest delivery period being 10 years. The settlement for futures contracts with a daily, quarterly, or yearly delivery period are calculated as the hourly spread between the Nordic system price and the futures price. For weekly and monthly futures, the settlement is instead calculated as the difference between the mean of the hourly system prices in the delivery period and the futures price. Furthermore, as these contracts are traded with the system price as underlying, they can effectively hedge the price risk in the system price. [34]

For a participant active in a certain bidding zone, there will, however, still be a price risk regarding the price difference between the bidding zone and the system price. Therefore, to fully hedge the electricity price in a certain bidding zone Nordic Power Futures may be completed with EPAD futures. [33] EPADs are a type of future where the underlying is the price difference between a certain bidding zone and the system price. EPADs are traded as base load futures with delivery periods of weeks, months, quarters, and years, with the longest delivery period being 10 years. The settlement of an EPAD follows that of the daily, quarterly, or yearly Nordic Power Futures. Furthermore, both EPADs and Nordic Power Futures have daily mark-to-market settlement. [35]

EPADs and Nordic Power Futures are typically quoted in EUR/MWh, with a standard contract base of 1 MWh and a trading lot size of 1 MW. This means that participants can hedge against price changes in 1 MW of electricity production per hour over the delivery period of the contract. [35]

To illustrate, suppose a wind farm located in SE4 seeks to hedge 2 MW of electricity production every hour for an entire month at a fixed price of 30 EUR/MWh. The wind farm can use monthly Nordic Power Futures in combination with a monthly EPAD contract for bidding zone SE4 to hedge the electricity price in the bidding zone fully. The total contract volume is the lot size by the number of hours in the contract period, i.e., a month in this example. Therefore, the contract volume, in this case, is 1488 MWh. During the month, the wind farm sells 2 MWh of electricity each hour on the DA market for an average price of 28 EUR/MWh. However, since the wind farm has hedged its production using the two futures contracts, it will also receive a payoff from these contracts. The difference between the fixed price of the futures contract and the spot price by the contract volume determines the payoff. In this example, the payoffs from the futures would result in 2 EUR/MWh. Thus, for each MWh produced, the wind farm will receive the DA price (average of 28 EUR/MWh) and the payoff of 2 EUR/MWh, totaling the sought-after price of 30 EUR/MWh.

Risks in the financial market

Actors in financial markets are inherently exposed to certain risks due to factors such as market dynamics and conditions and the counterparty in the agreements. Three main risks are counterparty risk, basis risk, and liquidity risk. The following sections will describe these in further detail, followed by a shorter presentation of other potential risks.

Counterparty risk

The counterparty risk involves the counterparty in the financial contract not being able or willing to fulfill the contract obligations due to changed market conditions or insufficient financial resources. Exchanges mitigate this risk through the use of margin accounts. When a derivatives contract is entered by a party, being either long or short, an open position is created, meaning that the full notional value of the contract is not settled financially right away. However, when the contract is entered, each counterparty must deposit an initial margin to its margin account. The initial margin functions as a security and is reimbursed to the counterparty when the delivery period of a contract has ended. [32] The exchange sets the value of the initial margin, and it is often a percentage of the full notional value of the contract. Initial margin may differ depending on several parameters, such as the underlying liquidity and volatility, contract size, and tenor. Furthermore, most exchange-traded derivatives follow a daily mark-to-market settlement during the delivery period of a contract. This means the margin account at the end of each trading day is adjusted depending on daily gains or losses. In turn, this implies that the value of the margin account may be greater or less than the initial value.

To handle cases when the value of the margin account is less than the initial margin, a so-called maintenance margin, slightly lower than the initial margin, is established. Suppose the funds in the margin account fall below the maintenance margin. In that case, the account holder receives a margin call from the exchange and is obliged to replenish the margin account to reach the initial margin level. [31] These margin requirements serve an essential function and enable exchanges to manage counterparty risk and provide viability to the market. [32]

Liquidity risk

An important function of a derivative exchange is to provide liquidity and transparency to the market. Access to liquid hedging tools helps market participants effectively hedge market prices to reach more stable and predictable financial results. [33] The liquidity risk refers to the potential for the trading volume on an exchange to decrease or become insufficient significantly. When an asset is considered illiquid, there is limited trading activity, low trading volumes, and/or a lack of buyers and sellers in the market. [36]

If a hedging tool gets illiquid, a market participant's direct costs associated with hedging increase, and it gets more challenging to exit positions quickly and cost-effectively. Furthermore, in an illiquid market, bid-ask spreads tend to be larger, which makes it more expensive to enter and exit financial positions. The time to find a counterparty to trade and settle a transaction may increase. Another important feature of a liquid market is that it provides important and informed pricing signals to the physical market. [33]

Nordic Power Futures and EPADs are Sweden's leading derivatives for hedging purposes. The liquidity in Nordic Power Futures, referring to the traded volume and open interest in the contract, has declined over a longer period. Since introducing new regulations in 2016, the market has experienced a great drop in liquidity (MiFID II, EMIR, and the removal of bank guarantees). As for EPADs, the contract's traded volume decreased between 2015-2020 but has since increased somewhat due to the great price spreads between the Nordic system price and the Swedish bidding zone prices. [33]

Basis risk

Basis risk is a fundamental risk inherent in hedging activities such as being short in futures. It refers to the potential for divergence or mismatch between price movements of financial derivatives and their underlying asset. This can result in a hedging strategy not providing the intended protection or risk reduction. This mismatched correlation in prices may occur due to the timing of price change, meaning if prices on the DA market were to significantly change with a delay until the price of the derivative contracts changes. Another factor that may impact the basis risk size is the market liquidity in question. In illiquid markets, where trading volumes are low, such as the Nasdaq Nordics Power Future market, basis risk may increase due to less efficient price discovery. [33] Due to the complexity of modeling and forecasting prices on the wholesale electricity market [30], even for exchanges such as Nasdaq, basis risk is an inherent challenge that market participants must carefully manage and account for in their risk management strategies. Depending on the magnitude of the price changes, and the volume of electricity involved, the off-taker may experience losses or reduced gains, as the intended risk mitigation may not be fully achieved due to this basis risk. EPADs can mitigate this risk for traders of power futures. However, they cannot fully mitigate the decreased correlation between EPAD and underlying bidding zone prices, leaving the trader with a "residual basis risk." [33]

Other risks

Beyond counterparty risk and liquidity risk, there are other risks that an actor in a financial market is exposed to. For instance, market risk refers to the uncertainties and fluctuations associated with the marketplace. Furthermore, operational risk includes the effects of various hazards and or failures that directly affect daily business activities. [37] Lastly, currency risk emerges due to disparities in foreign exchange rates used for trading financial derivatives and the underlying. In the Swedish electricity market, financial trade on Nasdaq is conducted in euros, while Nord Pool day-ahead trades are carried out in Swedish Crowns. Consequently, discrepancies between these two currency rates give rise to foreign exchange risk that necessitates consideration. [36]

3.3. Power Purchase Agreements

Power Purchase Agreements (PPAs) are long-term electricity trading and supply agreements. These agreements do not take place on any specific energy trading market. Instead, they are bilateral agreements between a buyer (so-called off-taker) and an owner or producer of an electricity asset, in which the off-taker agrees to purchase a specific volume or share of the total energy produced over a set period for a pre-agreed price. Therefore, these contracts allow for increased long-term security in both price and delivery for the parties involved. [4]

3.3.1. Power purchase agreements and renewables

During the past decade, power purchase agreements (PPAs) have become the predominant financing tool for renewable energy projects in the Nordic region. [4] Since the first large PPA contract was signed in 2013 between Google and OX2 for the on-shore wind park in Maevaara, PPAs have become the standard way of obtaining project financing for renewable power generation. [4] [38] This shift has been driven by multiple factors, which have created appropriate prerequisites for making PPAs an attractive option for developers seeking bankability for wind and solar power developments. Some of the factors contributing to this development are described below.

The Nordic region has experienced a surge in demand for renewable energy sources (RES). However, the inherent characteristics of variable renewables, such as solar and wind, present significant challenges in terms of financing. The intermittent nature of the production of electricity via these resources creates a considerable risk for investors compared to traditional energy sources, making it more difficult for developers to secure financing and loans for VRE projects. [4]

A critical factor in the emergence of PPAs in the Nordic region is the withdrawal of governmental subsidies supporting renewable power developments. This has created a need for RES developers to incorporate risk management tools to manage price risks and ensure the bankability of their projects. [39] One of the reasons for the shift from government support schemes in the Nordics is the maturity of the wind power market, which has resulted in lower costs for wind power. With further deployment, the need for governmental support is lessened making it more difficult for governments to keep up with financing. [4] Therefore, the move to open markets has pushed developers to turn to market-based mechanisms to reduce their financial risk and find long-term revenue security.

Although financial markets are a commonly used market-based tool for mitigating price risk by locking in prices for future periods, in the Nordic power derivative market, the lack of market depth and liquidity in financial contracts maturities beyond 5-10 years is not considered a viable option for price risk management. [40] [39] Thus, PPAs have become a more suitable alternative as the market-based solution for supporting investments and developments in the Nordic region's renewable power production projects.

3.3.2. Parties involved

Generally, the parties involved in a PPA are the operator of the energy asset and the off-taker, i.e., a seller and a buyer of electricity. However, other parties can also be involved, such as a lender, commonly a bank, to finance the investment, and a balancing agent, an intermediary between the energy buyer and the seller. [4] In the following paragraphs, these roles and their motivation for entering into a PPA arrangement are described in further detail.

The seller

In a PPA arrangement, the seller is the party that owns or manages the renewable asset. Various actors can enter into a PPA as the electricity seller for various reasons. However, the types of actors who can assume this role can be divided into two main groups based on their main purpose for entering into a PPA contract.

The first type of developer consists of companies whose primary interest is securing financing for an electricity production project and who depend on doing so through loans. This includes large electricity- and energy companies and independent power producers. [4] Most often, this is to secure financing for developing new power plants. These generation project developers enter into PPAs to ensure long-term revenue assurance to financial investors by gaining protection from the risks derived from the volatility of spot prices. However, existing producers may also decide to utilize PPA contracts to manage long-term risks. [40] [4]

The second group of actors consists of investment companies and renewable energy fund managers, which can either partially or fully own the project. In recent years, customer demand for green investments has seen a significant rise, and as a result, fund managers are looking for projects that can provide long-term returns. Therefore, these actors are motivated to invest in renewable energy assets through PPAs to produce electricity and increase their portfolios' share of green investments. [4]

The off-taker

In a PPA, the off-taker is the actor who agrees to purchase the electricity. The motivation for doing so may vary between actors, but the main incentives are economic, environmental, and reputational. For off-takers, PPAs can provide long-term cost stability and predictability while offering the opportunity for off-takers to progress towards sustainability targets and, as a result, gain recognition for their commitments to renewable energy. Although any electricity consumer or buyer can assume the role of the off-taker in a PPA arrangement, there are three most common types of off-takers: corporate buyers, electric utility companies, and actors within the heavy industry sector.

Corporate buyers are often large corporations with high electricity consumption, aiming to reduce their carbon footprint and energy costs as part of their sustainability strategy. [41] For instance, Google signed a corporate power purchase agreement in 2019 to buy wind energy for their data centers from a 175 MW wind power park to be developed in Sweden. [42] In recent years, corporate PPAs have had a prominent role in driving Europe’s PPA market due to the increasing need to hedge against rising and volatile prices. In 2022, the contracted volumes for corporate PPAs increased by at least 20% across Europe and were responsible for a significant majority of deal count and contracted volumes, accounting for 80% and 83%, respectively. [43] Low wind generation costs in Sweden have also recently contributed to a large corporate PPA market expansion. [44]

Electric utility companies, i.e., electricity- and energy companies, can also undertake the role of the seller in a PPA with their assets. They may assume the role of a buyer instead to increase the share of renewable electricity they produce or manage to meet customer demand, achieve internal sustainability goals, or adhere to national green energy targets. [4]

Lastly, industrial actors are increasingly participating in PPAs for a share of their energy needs. By doing this, they secure part of their energy needs at a fixed price for an extended period, facilitating the planning of energy expenses while increasing the share of renewable energy sources. [4]

Balancing agent

Due to the weather dependency and intermittent nature of wind- and solar power production, a balancing agent is needed in PPAs in which a minimum guaranteed amount of energy generation was agreed upon in the contract. The balancing agent has access to various energy sources, which allows them to cover potential shortages when the seller cannot meet its delivery obligations in the PPA through its production, irrespective of weather conditions. [4]

3.3.3. Contents of the agreement

Power purchase agreements are custom bilateral agreements negotiated between the buyer and seller to meet their specific needs and requirements for a particular project. Efforts are being made towards developing standardized PPA contracts, for instance, the template developed by European Federation of Energy Traders (EFET). However, still, terms included in PPA arrangements vary greatly. Factors that may influence the agreement's contents are, for instance, what actors are involved, their criteria and abilities, market characteristics, contract structure, policies, and regulations. However, there are a few predominant options that can be discerned. [4] The following sections describe the most common components of PPAs and the typical configuration types of each in further detail.

Delivery structures

Power Purchase Agreements can be divided into two main structures based on how the electricity is delivered and accounted for: physical and financial PPAs. The principal difference is how the electricity produced is allocated to the off-taker. [45]

A physical PPA contract involves the delivering of electricity to the buyer for their electricity consumption. The payment between the two parties is the agreed price for the volume of electricity produced and delivered. Generally, these contracts do not include a direct connection between the two parties. Instead, the electricity from the generator is fed into the grid, from which the buyer receives the corresponding volume from the general electricity mix. [4] For delivery of electricity via the electricity grid to be possible, the producer and off-taker must exist in the same electricity market. Typically, this physical delivery of electricity occurs in shorter settlement periods, nearing real-time. How the imbalance between delivery volume and contracted volume should be handled, and therefore which of the parties carries the main price risk, may vary depending on what is agreed upon in the contract. [45] In Europe, physical PPAs are the most prevalent since most PPAs are entered into by large electricity consumers with the purpose of hedging against large price fluctuations. [4]

On the other hand, in a financial PPA, there is no transfer of electricity between the parties in the agreement. Instead, the contract is an exclusively financial transaction, similar to the power futures that can be purchased on Nasdaq. [45] The generator sells the electricity produced on the spot market, while the price agreed upon in the contract is settled between the two parties separately. If the agreed price is lower than the price on the spot market, the buyer receives a payment for the difference in price from the generator. In the opposite case, the generator gets a payment from the buyer. [4], [46] This settlement between the parties is generally realized with the help of a balancing agent. [4] Since settlement periods for financial PPAs are typically on a longer time scale, the price risk is transferred to the party in the agreement, whom trades electricity in real-time, which will depend on the commercial structure of the PPA. [45] Although financial PPAs are uncommon in the Nordics, they do occur, for instance, when large multinational corporates enter into PPAs with the purpose of securing guarantees of origin and green certificates for use in the wider European market. [4]

Volume structures

The volume of the power purchase agreement is the amount of electricity the buyer agrees to purchase from the power producer. The structure of PPAs varies based on how the volume is contracted within the agreement, depending on the off-takers needs. The two main distinguishable types of volume structures for PPAs are baseload and pay-as-produced.

Baseload

In a baseload PPA, the power producer and the buyer agree to a fixed amount of electricity that will be generated and delivered over a set period of time at a fixed price. The electricity is supplied at a fixed volume, regardless of the electricity demand or market price fluctuations. Therefore, baseload PPAs are often used for power generation sources with consistent power output. In these contracts, the producer bears the risk of delivery shortages and, in turn, fluctuations in the electricity market. In the case of underproduction, the producer may need to purchase electricity on the wholesale market to be able to deliver the contracted volume. However, at times of high production, the producer can benefit from selling excess electricity on the market and generating additional revenues. Since the off-taker is able to avoid volume risk, the price set in baseload contracts includes a pricing premium compared to pay-as-produced contracts. Off-takers are commonly large electricity consumers looking to ensure a reliable and consistent supply of electricity at a stable price. [4]

Pay-as-produced

In the pay-as-produced (PAP) structure, the off-taker only pays for the actual amount of electricity produced, although the price per volume is constant. Usually, this entails contracting a certain percentage of the electricity produced, regardless of fluctuations in produced volume over time. This type of contract is commonly used for intermittent sources of power generation, such as wind and solar energy, where output levels can vary widely based on weather conditions. Therefore, in PAP agreements, the off-taker takes part in the volume risk as they are exposed to the variability of renewable energy generation. If the produced volume is lower than the demand of the off-taker, they may have to turn to the day-ahead market or with other means acquire the electricity needed. Therefore, this contract is generally more suitable for off-takers that can manage fluctuations and variable generation or even reap benefits from this contract structure. [4]

Previously, PAP has been the most popular volume structure. However, in recent years, off-takers have become more cautious about entering PAP contracts due to the exposure to cannibalization and profile risks. Instead, the demand for baseload contracts has increased. This deviation from PAP contracts has been most prominent in developed PPA markets and markets with the largest growth of renewables, where the exposure to cannibalization effects in pricing is the strongest. [47] However, according to the “European PPA Market Outlook 2023” report published by PexaPark, projections show that there may be a resurgence in demand for PAP structures from off-takers in the Nordics during 2023. This is attributed to the increased electricity prices, which renders the discounted price associated with PAP contracts more appealing to electricity buyers. Simultaneously, sellers will seek to attract buyers with these discounts while mitigating their risks. [43]

Pricing

The market for power purchase agreements is characterized by low transparency and a lack of readily available pricing information. [40] [4] [39] This is primarily due to the bilateral negotiation process of PPA contracts, which results in tailored agreements that reflect the specific needs and conditions of the parties involved for each project. Consequently, the market lacks standardization, making comparing contracts across different technologies, locations, pricing, and risk-sharing arrangements challenging. [4] [39] Although some price reporting for PPAs are available, these prices generally represent average price levels for specific markets and do not reflect actual transaction prices. Transaction prices can still vary largely depending on different variables affecting the contract. Therefore, available price reporting provides a general idea of the market's pricing trend rather than a precise representation of actual transaction prices. [4]

Despite the challenges posed by the lack of transparency in PPA markets, several factors significantly impact the pricing of PPA contracts. The following paragraphs provide a detailed discussion of these key parameters.

Levelized Cost of Electricity

The price of electricity production is one of the primary factors that influence the pricing of a PPA contract. Depending on the price contracted in the PPA, the profitability for the seller of electricity and in the case of new project installations, will affect the investment's payback time. In Sweden, PPAs are primarily linked to new installations, and the marginal production cost, balancing fees, insurance, and seller profit margin are crucial for setting the price. [4] Generally, the price of electricity production is measured in terms of the levelized cost of electricity (LCOE), comprised of all the costs associated with generating electricity over the plant's lifetime divided by the total amount of electricity generated. For electricity sellers, it is essential that the nominal PPA price is higher than the LCOE to make a profit. Therefore, LCOE has previously been used to set a price floor for PPA contracts. [48] The LCOE depends on various factors, such as the production technology used and the plant's location. According to BloombergNEF, European solar power PPAs are generally more expensive than wind power PPAs, by up to 10 euros/MWh in 2022. [49] Similarly, price levels vary depending on if the PPA in question is connected to new installations of solar or wind power production due to upfront costs for the producer. This is commonly referred to as "additionality". [4]

Wholesale market prices

While the seller aims to secure a PPA price higher than their cost of production, the off-taker seeks to achieve a price lower than the market price or the price they are currently paying for electricity. PPA pricing may use spot prices as a reference point in negotiations to arrive at a fair price. As such, the prevailing prices on the spot market can impact PPA prices, and, in turn, PPA prices have been lower than those on the spot market. For instance, in the Nordic region, PPA prices have historically been lower than those in other European markets, owing to the lower spot prices in the region. However, there have been instances when PPA prices have exceeded those on the spot market. As was the case in early 2020, when spot prices dipped in the Nordic region, and PPAs were purchased at a premium. [4]

Typically, PPA pricing has been based on monthly or yearly prices derived from forecasts for the market in which the electricity produced would be sold if not through the PPA. However, due to the increasing share of renewable energy sources in the energy mix, this method has become less suitable as it does not account for certain dynamic risks apparent in markets with a large percentage of renewables. To accommodate these risks, there is a trend towards more market-based structures, with many buyers looking for innovative pricing structures that give them more possibilities for hedging. [50]

Financial derivatives pricing

The prices of financial derivatives are often used as reference prices in PPA contracting, such as traded forward contracts. Historically, prices have often been set with LCOE as the floor, while the prices of power derivatives have acted as a price ceiling. Thus, PPA prices are subject to fluctuations and volatility in financial derivatives' pricing. [43, 39] The lack of liquidity in the Nordics derivatives market, especially for contracts with long-term maturities, does, however, increase the difficulty in using future prices as a reference in PPA pricing. Additionally, the lack of long-term EPADs have become a greater concern, particularly with the divergence of bidding zone prices from the Nordic system price. This divergence has created uncertainty in the pricing of PPAs, as there is a lack of clear reference prices for long-term contracts. Furthermore, with an increase in volumes being hedged bilaterally, separate from the financial market, the liquidity in the financial power market is further decreasing. [39]

Contract characteristics

Depending on the type of contract, in terms of structure, tenor and which technology it concerns, the price will also vary. For instance, typically pay-as-produced PPAs have lower prices associated with them, due to the allocation of risk to the off-taker compared to baseload PPA contracts. [4] [2]

Additionally, the tenor of the contract impacts the pricing. PexaPark reported in their yearly report “European PPA Market Outlook 2023” [43] that the disparity in prices between long-term and short-term contracts increased in 2022 due to what they refer to as “extreme backwardation” of the future market. Essentially, the price of electricity for immediate delivery was much higher than the price for future delivery. Therefore, to take advantage of these higher prices, power producers chose to sign short-term contracts over the more common long-term contracts, which created a difference in price between the two types of contracts, with short-term contracts priced significantly higher. [43]

3.3.4. Risks associated with PPA contracts

Entering a power purchase agreement (PPA) involves various risks that could impact both the buyer and the seller. The two main sources of uncertainty in renewable PPAs are variable renewable energy (VRE) production characteristics and the dynamics in electricity markets. As discussed in previous sections, both of these areas are associated with high unpredictability, which can be particularly challenging when considering a long-term perspective. Managing these two sources of risks give rise to challenges in the formulation of a PPA contract. [4] This section will outline a selection of risks that may arise as a result of these uncertainties.

Renewable energy generation risks

The intermittency of variable renewable energy generation creates challenges for accurately predicting the actual electricity output from a production site and the timing of production in relation to demand. In other words, the volume and shape risk, respectively.

The term volume risk refers to the uncertainty of the amount of electricity generated from a renewable energy project over time. Although the annual energy production of a renewable asset is typically assessed based on long-term meteorological data, the forecasted production for variable renewable energy sources is an estimation. Hence, if the actual production falls below the contracted amount, the deficit in produced volumes may need to be purchased on the spot market instead, by one of the parties (which will depend on the volume structure of the agreement). In this case, the party in question is exposed to the market pricing dynamics, which can result in either lost revenue or additional costs. [41]

Shape risk, on the other hand, relates to the unpredictability of the shape of the energy output profile of a power generation facility. Even supposing the overall volume of a production plant can be forecasted over time, the hourly output will vary depending on weather conditions, seasonality, and time of day. As a result, the energy generated by a renewable energy facility may not match the energy demand profile of the purchaser at a given moment. Similar to the effects of volume risk, it may result in additional costs for the off-taker to balance the supply and demand. Furthermore, the financial impact of the renewables shape risk is further increased by the cannibalization effect, in which the increased share of renewables on the market leads to a reduction in the capture price for renewables. For instance, in a pay-as-produced PPA arrangement, the off-taker may need to buy additional power from the grid during low-generation periods, which may occur when the wholesale prices are high. [47]

Electricity market risks

While one of the main purposes of a power purchase agreement (PPA) is to provide protection against market signals for the parties involved, due to the fluctuation of market prices over time, risks associated with pricing still exist. This section presents potential risks that derive from the variability of electricity markets.

The price risk refers to the risk of losses due to variations in the electricity market which affects the profitability and relevancy of the agreed price within the PPA contract over time. This risk occurs as a result of electricity prices varying over time on the open market, and therefore their relation to the set PPA pricing varies. Depending on the pricing structure of the PPA, this risk could affect both the buyer and the seller. [41] This risk is also amplified by the effects of cannibalization. For the off-taker, as the average market prices decrease due to cannibalization, the price set in the PPA contract may end up being higher than if the power was purchased on the day-ahead market instead. [47]

Basis risk refers to the potential for financial loss arising from a mismatch between the reference price for payments under a PPA and the price the buyer is exposed to in their broader electricity supply arrangements. Specifically, risk occurs when the price of the underlying commodity and the benchmark price used in the PPA move in opposite directions. For instance, for an off-taker of a PPA, basis risk arises when the reference price in the PPA does not align with the price they would pay for the electricity from other sources, such as the grid and existing supply schemes, due to the exposure to different electricity prices. This discrepancy in pricing can result in a buyer being exposed to additional costs or losing an opportunity for cost savings. [41]

3.4. Battery energy storage systems

The EU's Clean Energy Package defines energy storage as systems for "deferring the final use of electricity to a moment later than when it was generated, or the conversion of electrical energy into a form of energy which can be stored, the storing of such energy, and the subsequent reconversion of such energy into electrical energy or use as another energy carrier".[1]

These systems help to balance the supply and demand of electricity on the grid, which can contribute to improve grid stability and reliability. Specifically, storage systems can protect against market prices, support the electrification of various sectors, and contribute to the security of energy supply. Also, energy storage systems are crucial for the integration of variable renewable energy sources (such as wind and solar power) into national power grids by storing excess electricity generated during periods of high production and supplying energy during periods of low production. [51] This helps smooth out the variability of renewables and ensures a more consistent and reliable power supply.

Various energy storage systems exist, and their suitability for applications depends on the specific technology employed. However, batteries, or battery energy storage systems (BESS), are a chemical form of energy storage that has recently seen increased adoption due to technical advancements and effectiveness in various applications. [52] The most prominent BESS technology deployed is Lithium-Ion (Li-Ion) batteries, which have a 90% share of the deployment of grid-scale BESS in 2020-2021. Mainly due to key technical advantages such as high energy density, fast response time, and high round-trip efficiency. [51] [52] In 2022, the estimated global investments in BESS doubled compared to the previous year and reached an all-time high of USD 20 billion [53]. In Sweden, the market has grown substantially, with an estimated 100-200 MW of grid-scale battery storage deployment in 2023. [54] The following sections investigate technical specifications, market trends, and investment opportunities for Li-Ion batteries.

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[1] EU (2019) Directive 2019/944 of the EU parliament and the council on common rules for the internal market for electricity. Article 2, Paragraph (59)

3.4.1. Technical specifications

Depending on the application, BESS may be connected either front-of-the-meter (FTM) or behind-the-meter (BTM). FTM concerns BESS, connected directly to the distribution- or transmission network or in conjunction with a generation facility, whereas BTM refers to a connection behind the utility meter. BTM BESS applications often aim to reduce electricity bill costs through demand-side management. FTM BESS can be called utility-scale, large-scale, or grid-scale battery storage. As for grid-scale battery energy storage systems, the capacity differs and may range from a few MWh to several hundred MWh. [55]

Below follows some short definitions of common specifications of battery energy storage systems.

- *Rated Power* – Represents a battery's maximum rate at which it can provide energy to a load, often in the unit of kilowatts (kW) or megawatts (MW). [55]
- *Energy capacity* – Refers to the maximum amount in stored energy, often in the unit of kilowatt-hours (kWh) or megawatt-hours MWh. [55]
- *State of charge (SOC)* – Representation of the battery's current capacity expressed as a percentage of the battery maximum capacity, ranging from fully charged to fully discharged. [55]
- *Depth of charge (DOC)* – Representation of the battery's discharge as a percentage of its maximum capacity, i.e., the amount of battery capacity that has been discharged. [55]
- *Cycle life* – Number of times a battery can be discharged and recharged before it fails to meet specific performance criteria. [55]
- *C-rating* – A metric of the rate at which a battery is discharged relative to its maximum capacity. Specifically, a battery with a 1C rate means that the discharge current will discharge the entire battery in 1 hour. Furthermore, a battery with a 2C rate means a faster discharge rate, and it would instead take 30 minutes to discharge the battery completely at this rate. [55]

Over time, the performance of Battery Energy Storage Systems (BESS) tends to decrease, a phenomenon known as degradation. Degradation, in practice, refers to the gradual deterioration of the battery's capacity and overall performance. Several factors contribute to this degradation, including cyclic degradation from charge and discharge cycles, calendar aging even during periods of non-use, exposure to high temperatures, extreme states of charge, impacts of fast charging, and cell imbalances. These factors collectively impact the longevity and efficiency of the BESS. From an investment standpoint, degradation must be considered as it affects the return on investment and the overall cost-effectiveness of the system. Understanding the degradation patterns and employing appropriate management strategies can help mitigate the impact and optimize the investment in BESS, ensuring long-term viability and performance. [56]

3.4.2. Applications for grid-scale BESS

Grid-scale battery energy storage systems are mainly applied for short-term areas of use, with a typical energy duration of two hours or less. However, they demonstrate great adaptability and are used for more diverse purposes. [53] The areas where BESS may be used can be divided into five main categories of services with subsequent benefits, as illustrated in Figure 10. [57]

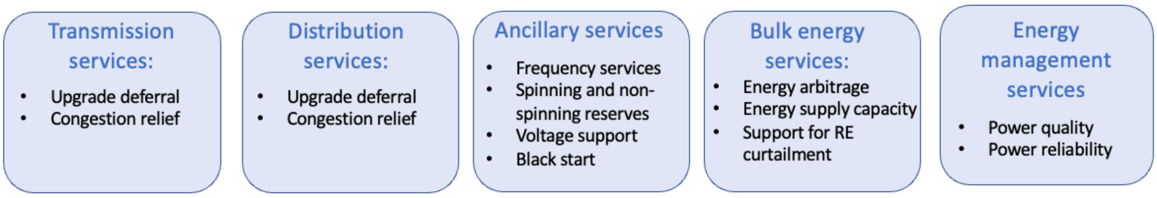

Figure 10. Main areas of use for grid-scale BESS (adapted from [57])

Initial studies of usage areas for energy storage systems involved applications for demand management, such as peak shaving and grid support. However, attention has shifted more towards using BESS in supporting the integration of intermittent renewable resources into the grid, and to the economic case of these applications. [5]

Ancillary services

Previously, the main use for grid-scale BESS has been frequency control regulation. Between 2010-2018 this application represented over 60% of deployed capacity globally. [53]. As an effect of the global energy crisis from 2021, the prices of ancillary services, including frequency regulation, have significantly risen, leading to substantial revenue increases for BESS assets across Europe. These assets have earned up to four times the expected revenue in some instances. [58] Prices for ancillary services in Sweden have surged by more than 200% between 2020 and the spring of 2023. [54]

Bulk energy services

Despite the high profitability seen in ancillary service applications of BESS, as more energy storage is deployed for ancillary services, the markets on which they act will get more saturated. This creates a need for BESS actors to look to deeper markets beyond ancillary services. [58] Therefore, actors in both Sweden and Europe are looking for other bulk services to provide a more long-term business case. [58] [54]

Battery energy storage systems (BESS) can be utilized for various bulk energy service applications, as illustrated in Figure 10. They provide valuable solutions, supplying energy capacity during peak demand by reducing reliance on high-capacity generation systems and supporting renewable energy curtailment by storing and releasing excess energy, ensuring a more efficient and stable power supply. [57] Additionally, energy arbitrage refers to taking advantage of price differences in the energy market to buy and sell electricity profitably. Arbitrage is commonly differentiated into spatial arbitrage, in which the price difference between markets is taken advantage of, and inter-temporal arbitrage occurs in the same market but at different time points. [52] For instance, storing energy when demand and price are low and selling that stored energy when both have increased. [57] In this way, the profit of energy arbitrage will be the difference between revenue from energy sales at discharge and the charging costs for off-peak energy over a specific period. [5] This type of trading can occur on day-ahead, intraday, or imbalance markets. [58]

Profitability of day-ahead energy arbitrage

Evaluation of business cases for energy arbitrage has been conducted by multiple actors, on different European markets. The Energy Transition Expertise Centre (EnTEC), set up by the European Commission, investigated arbitrage trading on the French day-ahead spot market in their “Study on Energy storage” report from 2022. [59] The study showed that BESS deployed exclusively for energy arbitrage proved profitable during 2021-2022. These specific years showcased significantly high average electricity prices and volatility compared to previous years. However, for the years 2018-2020, the revenues did not prove adequate to compensate for the investment and operational costs of the BESS. Furthermore, the study found greater price spreads on the intraday markets compared to the DA markets suggesting that revenues might be higher on the intraday markets. [59]

Lampropoulos, I. et. al [60] investigated in their article “Day-ahead economic scheduling of energy arbitrage” the maximization of revenues for energy arbitrage on the Amsterdam power exchange. They found that financial gains for energy arbitrage applications of this kind to result in a low or negative return on investment over a period of time. Furthermore, they note that for these applications to be profitable, the capital expenditures for Lithium-Ion storage solutions need to decrease. [60]

The article ”Potential utilization of battery energy storage systems (BESS) in the major European electricity markets” published in the journal Applied Energy, Hu. Y. et al [56] investigates potential usage areas of BESS in major European electricity markets. Their findings show that battery wear cost resulting from degradation effects hinders the profitability of energy arbitrage in most European markets. This suggests that the cost of battery degradation outweighs the potential gains from selling electricity at different price levels. Further, they found that markets, where flexibility is already provided by other energy sources like hydropower and pumped hydro storage systems, have limited potential profitability for energy arbitrage with BESS, such as Norway and Spain. [56]

Walawalkar, R. et al [5] found that the most critical factors impacting Battery Energy Storage Systems (BESS) economics were revenue, charging costs, capital costs, and round trip efficiency. Further, they noted that round trip efficiency affects the ability to store and dispatch energy effectively, maximizing the price differentials that the BESS is exposed to. Therefore, lower efficiency reduces net revenues and less favorable operating modes for energy arbitrage. [5]

Capital costs

Despite recent advancements, the upfront investment cost remains a significant barrier to the widespread deployment of BESS. Over the past decade, BESS's cost has steeply declined. Between 2010–2019, the price of Li-Ion batteries in Sweden fell by 87%. Forecasts showed that due to new manufacturing techniques and simplifications in design for battery cell assembly into battery packs, further price reductions of 30% are expected by 2030. [61]

However, falling prices reversed at the end of 2021, indicated by an increase of over 500% between 2021-2022. Reasons include component shortages and rising prices of crucial raw materials. For instance, during that time period, cobalt and nickel prices more than doubled. Therefore, previous forecasts are considered more uncertain due to the recent increases in raw material prices. [61] In 2022, BloombergNEF predicted that global battery prices would remain at the level seen at the time until 2024 before dropping again. They noted that the main factors that would reduce costs in the next decade included manufacturing process improvements, investments in R&D, and capacity expansion across the supply chains. [62]

3.5. Financial Evaluation of Investment Opportunities

Financial analysis before an investment opportunity is critical to determine how a potential investment is likely to perform and make an informed decision about if a particular investment is suitable to pursue. [63] In the following sections, the Discounted Cash Flow method is presented, followed by a description of the metrics' Net Present Value (NPV) and Internal Rate of Return (IRR).

3.5.1. Discounted Cash Flow

The financial valuation method of Discounted Cash Flow (DCF) aims to determine the value of an investment over time. This method is based on the expected cash flows that the investment will generate, adjusted for the time value of money. In this way, DCF considers that the value of money today is worth more than the same amount in the future due to, for instance, the opportunity cost of money and the impact of inflation. Therefore, DCF is a suitable tool for when an investment cost is made in the present and the cash returns are expected in the future. [64]

The DCF analysis involves three main steps: estimating the future cash flows that the investment is expected to generate over a specific period, applying an appropriate discount rate for the specific investment, and discounting the cash flows back to their present value (see Equation 2.6 below) A higher discount rate will result in a lower present value of future cash flows, while a lower discount rate will result in a higher present value of future cash flows. The discount rate is commonly calculated using the Weighted Average Cost of Capital (WACC). Finally, if the calculated DCF value is higher than the investment cost, the investment may result in positive returns. [64]

The main advantages of DCF analysis are that it can be used to evaluate the profitability of various types of investments and that the predictions can be easily altered to assess different investment scenarios. However, the major drawback is that the method relies on assumptions of future cash flows that can be difficult to predict. Therefore, results are not certain, especially if estimations of future cash flows are made incorrectly. [64]

3.5.2. Net Present Value and Internal Rate of Return

The Net Present Value (NPV) and Internal Rate of Return (IRR) are common financial metrics in investment analysis. Similar to DCF analysis, both are based on the time value of money. However, they represent different perspectives in evaluating the profitability of an investment. [65]

NPV indicates the difference between the present value of an investment's cash inflows and outflows. Therefore, it can be considered a fourth additional step to the DCF process in which the discounted cash flows are summed up and then subtracted the initial investment costs (see Equation 3.6 below). A positive NPV implies that the investment is profitable, while a negative NPV means the opposite. [65]

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t} \tag{3.6}$$

in which

R = Net cash inflows-outflows during a single period,
i_t = Discount rate or return that could be earned in alternative investments,
t = Number of timer periods

The IRR, however, calculates the discount rate at which the present value of the expected cash inflows is equal to the present value of the expected cash outflows, meaning the NPV is equal to zero. If the IRR of an investment is greater than the required rate of return or the cost of capital, then it can be considered profitable. [65]

3.6. Key takeaways

To summarize some of the key findings from the sections presented in this chapter, Table 2 below, highlights the key takeaways to keep in mind mowing forward into the following chapters.

Table 2 Key takeaways from the theory and pre-study.

Day-ahead market and pricing
• Primary marketplace for physical trade • Hourly electricity trading for the following day • Consists of several so-called bidding zones • Follows the principle of marginal pricing • Price influenced by factors such as demand, variable electricity production and fuel costs • Spot price forecasting is important for informed decision-making in electricity trading
Financial Power markets
• Allows market participants to manage and hedge risk associated with the physical market • Derivatives are financial tools that “derive” their value from underlying variables • Futures are standardized contracts that follow a specific framework set by an exchange • Nordic Power Futures are futures contracts with the Nordic system price as the underlying • Electricity Price Area Differentials (EPADs) are futures contracts where the underlying is the price difference between a specific bidding zone and the system price • Initial margin is the required deposition needed to enter a financial position • Participating in financial trade induce certain risks such as counterparty risk, liquidity risk and market risk.
Power purchase agreements (PPA)
• PPAs are long-term electricity trading and supply agreements • Enables market participants to secure price and delivery • Have become an important financing tool for renewable energy projects • Can have physical or financial delivery structures • Can have a baseload or pay-as-produced volume structure • The pricing of PPAs is influenced by factors such as market conditions and LCOE • The market for PPAs lacks transparency and the contracts are not standardized
Battery energy storage system (BESS)
• Lithium-Ion BESS are the most widely deployed battery technology • Many areas of application such as ancillary services, bulk energy services and energy arbitrage • Ancillary services have been the main application of grid-scale BESS • The trend of decreasing capital cost have lessened due to component shortages and rising raw material prices

Chapter 4.

Data preparation

This section of the thesis presents the data collection, exploration, and processing procedures to provide reliable and accurate input of datasets for the simulation model. First, each step is described for the PPA production volumes. Then the same steps are presented for the historical spot price datasets. Ultimately, the output of these steps is two groups of datasets ready to be used in the simulation model.

4.1. Power purchase agreement production datasets

To accurately simulate the inflow of renewable electricity through the power purchase agreement (PPA) contract, the study required reliable data on hourly production volumes throughout the selected geographical area, specifically the southern regions of Sweden. For use in the model, these datasets needed to be processed so that production volumes could be simulated differently for each iteration of the simulation model, while keeping seasonal and daily patterns.

4.1.1. Data collection

Solar and wind production data was collected from Renewables.ninja, an open-access platform providing data on renewable energy resources and production. This website offers estimates of the electricity that wind turbines and solar panels can produce in different locations globally. The platform was developed by a team of researchers at the Technical University of Denmark (DTU) and is available for public use online. [66] [67] [68]

For the model, solar PV and wind production data was collected from Renewables.ninja for six locations in the Swedish bidding zone SE4, along the coast and inland (see Figure 11). For each location, solar and wind production data was collected years 2016-2020 for production sites with a peak capacity of 1 MW. For the wind power production data, the turbine's hub height was assumed to be 155 m, and the turbine model Vestas V150 2000. Furthermore, for the solar power production data, single-axis tracking was assumed with a tilt of 40° and azimuth of 180°.

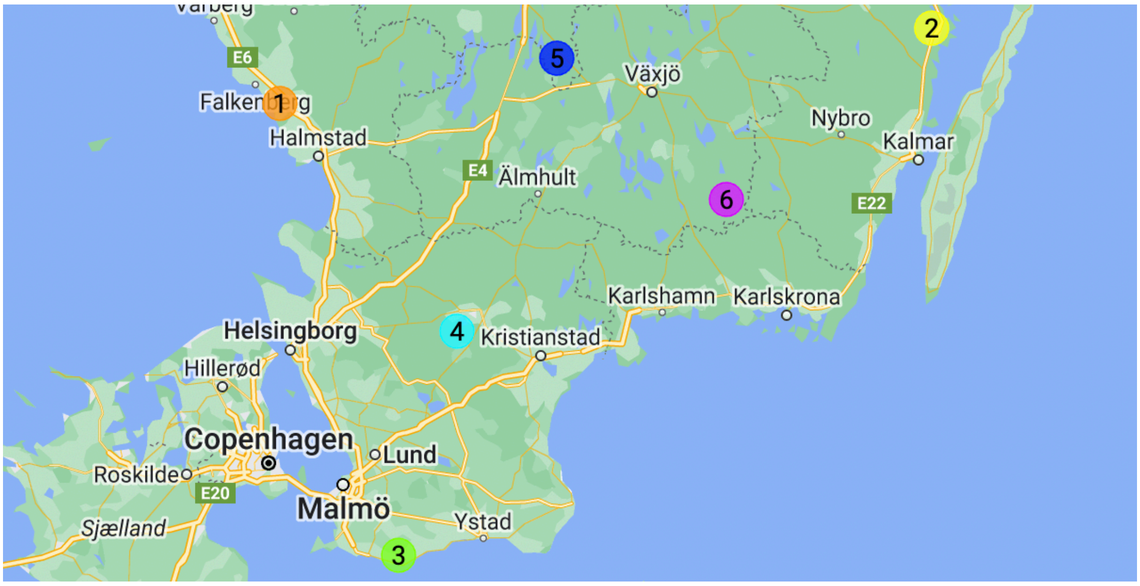

Figure 11. Map of the six locations from which production data was collected.

4.1.2. Data exploration

Data for each production technology were investigated separately to explore the characteristics of the production data gathered from wind and solar PV production. This was done by investigating the raw data's general features, the hourly and monthly characteristics, and the correlation between wind and solar production of different time scales. Initial data investigation of the raw data basic features is presented in Table 3 below.[2]

Table 3. Raw production datasets characteristics.

Capacity factor		*Relative standard deviation*	
Wind power	Solar power	Wind power	Solar power
56.7%	16.3%	44%	147%

Hourly characteristics

By aggregating the average values for each hour in a day across all of the subsequent years 2016–2022, from which production data for the six sites was collected, the hourly average tendencies for each of the power generation technologies on a daily basis were explored, as illustrated in Figure 12.

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[2] Capacity factors from the raw data deviates from findings in the theory, the implications of this are discussed in greater detail in chapter 9. Discussion.

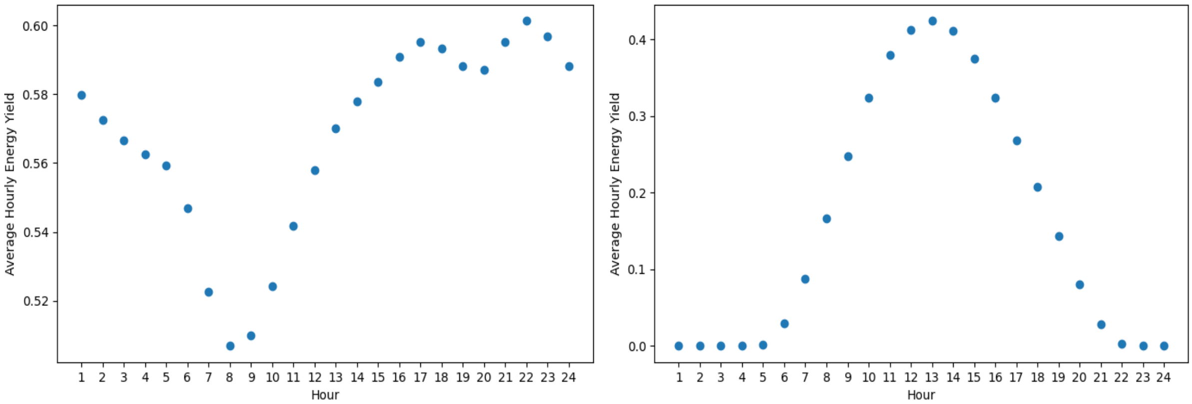

Figure 12. Average hourly energy yield from wind (left) and solar power (right) from collected data.

Observation of wind data reveals distinct hourly tendencies in energy yield, with a decrease from later hours to the lowest point at approximately 08:00, followed by an increase to maximum production at 22:00. In contrast, solar energy production tends to follow a predictable pattern based on the cycle of sunlight and darkness throughout the day. As a result, there is no energy yield for solar PV from around 22:00 until 05:00.

Monthly characteristics

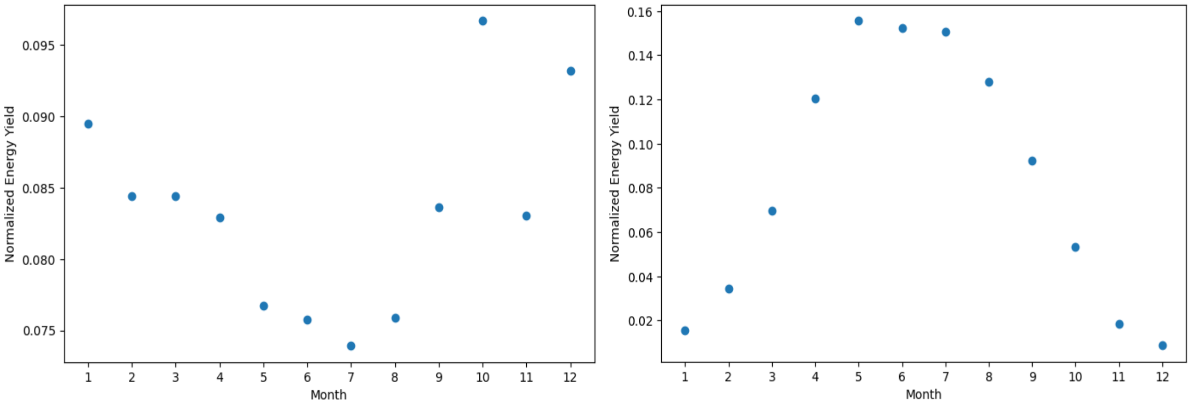

Figure 13. Normalized monthly energy yield from wind (left) and solar power (right).

As Figure 13 illustrates, both the wind and solar electricity generation data indicate seasonal patterns in which the production volumes vary over of the year. Wind production data exhibits a higher energy yield during winter, with the lowest yield during summer. However, the data indicates inconsistencies for October and November, with October having the maximum energy yield. November is significantly lower than October and December. Conversely, solar PV production seems to follow a more predictable energy yield profile with the highest energy yield during the summer and the lowest during the winter months.

Correlation between solar and wind production

On an hourly time scale, a weak and negative correlation was found between solar and wind production values (R^2 = 0.032). The correlation value indicates that the strength of the relationship between hourly solar PV and wind production data is very low and suggests that the share of solar and wind power should not be optimized on the same timeframe. However, on a monthly timespan, the correlation was stronger ($R^2 = 0.639$), implying that optimizing the share based on the monthly energy yields is possible. This conclusion is the same as presented by S. Mertens when investigating the correlation between wind and solar power generation in the Netherlands. [7]

4.1.3. Data processing

The data processing of the renewables production data consisted of two separate steps. First, the optimal share of wind and solar to achieve a baseload profile based on the raw production data was determined. Subsequently, the raw data was organized into datasets to be used as input in the simulation model. The process of each of the steps is described below.

Optimizing solar and wind share for baseload profile

Since the data exploration showed a strong correlation between wind and solar production values on a monthly rather than an hourly time scale, the method proposed by S. Mertens was used to find optimal percentages of solar and wind that should be combined in order to achieve flat power output profile for the specific production data collected. [7] First, the curve was modeled based on normalized monthly production outputs for the data by calculating fit constants and phase shift using equations (3.1) and (3.2). When fit constants were calculated, the optimal ratio between solar and wind was calculated using equation (3.4). Fit constant values and the optimal ratio are presented in Table 4 below. The optimal fit curve for the normalized monthly energy yield values for both wind and solar is presented in Figure 14.

Table 4. Values for constants C1-C4, phase shift C5 and optimal ratio factor C.

C_1	C_2	C_3	C_4	C_5	C
0.0833	-0.0767	0.0833	0.0079	-0.0359	9.674

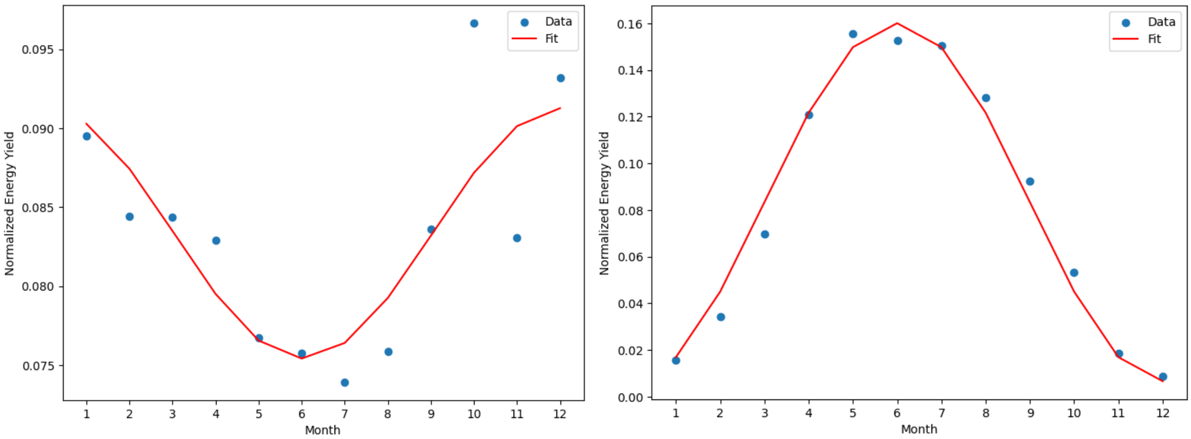

Figure 14. Average normalized production data for wind (left) and solar (right) with fit curve.

The value for C (presented in Table 4) shows that the energy yield from wind production should be 9.674 times greater than that from solar power if the aim is to achieve a flat production profile. Combining the power generation technologies with this ratio results in a flatter production profile. As illustrated in Figure 15, the resulting total energy yield of E_{tot} displays a flatter profile than those of E_w and E_s. However, the energy yield still follows wind movements during the winter months when production from solar PV is more absent.

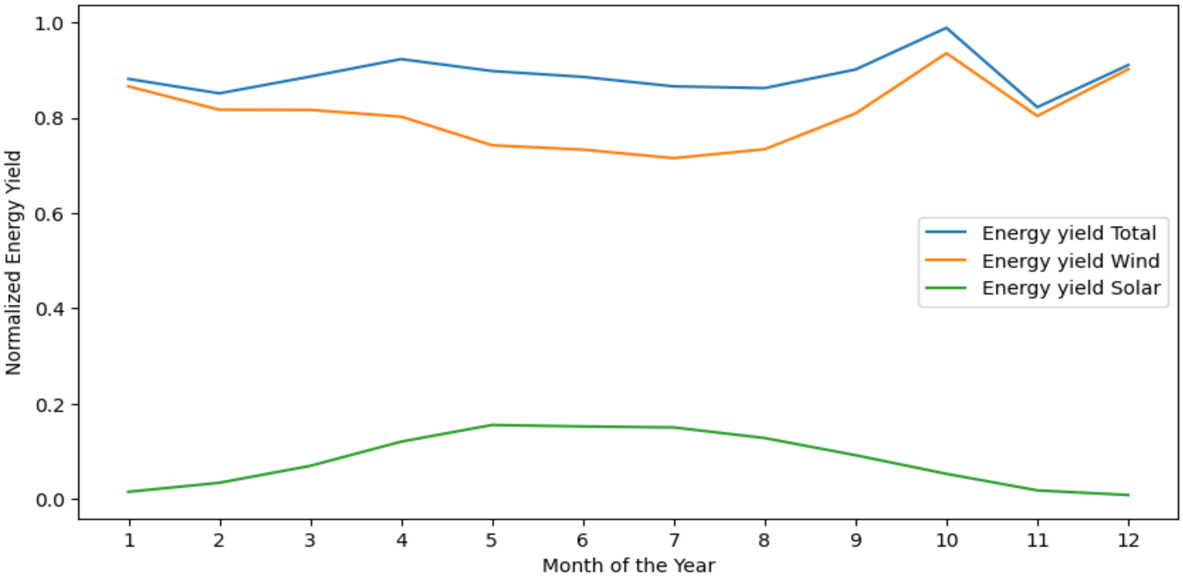

Figure 15. Production profile of baseload mix with wind and solar power.

By using the average capacity factors for the production data, the ratio between the required installed power of wind and solar to achieve a baseload power profile was calculated using equation (3.5), which resulted in the ratios presented in Table 5 below.

Table 5. Optimal share percentages for the baseload profile's wind and solar power data.

	Wind power	Solar power
Optimal share	73.5%	26.5%

Preparing the input datasets

To prepare production volume data for use as input in the simulation model, the raw data was organized into separate datasets for solar and wind power based on the hour of the day and month of the year. A total of 288 datasets (12 x 24) for each energy source was created, with each dataset containing production volumes for every location observed during a specific month and hour. To ensure that the irregular production data values do not affect the model, we combined the production values for the different locations for each observed hour in the datasets. To achieve this, we calculated optimal weight factors for the data from each specific site to minimize the standard deviation of the combined output of values for all locations for each dataset. Lastly, the datasets for wind and solar were combined for each hour in each month using the optimal ratio of solar and wind volumes for baseload profiles calculated in the exploration of the data. The result is a set of 288 datasets containing production output values for a specific hour and month to be used as input in the simulation model.

4.2. Spot price datasets

Historical spot price data was collected and transformed to simulate future spot prices during the investment period in the model. Steps taken to collect, explore and process the historical spot price data are described below.

4.2.1. Data collection

As part of the simulation model, historical spot prices were collected from the Nord Pool FTP (File Transfer Protocol) server. Nord Pool is the leading power market operator in the Nordics, and the data on the server is collected from actual electricity market transactions and based on real market activity. [69] Hourly day-ahead spot prices from 2011-2022 for all four Swedish bidding zones were collected from Nord Pool FTP.

4.2.2. Data exploration

In the following section, the price data received from the Nord Pool FTP has been analyzed to highlight trends occurring within different time intervals and between the bidding zones' prices and system prices.

Figure 16 displays the relations between the Swedish bidding zones and the Nord Pool System price. The figure shows that the electricity prices in the northernmost bidding zones, SE1 and

SE2, were, on average, significantly lower compared to the system price and the southernmost bidding zones, SE3 and SE4, during 2011-2022. Additionally, SE1 and SE2 had similar pricing compared to each other. On the other hand, SE3's price was mostly above that of the system price and the northern bidding zones but consistently lower than that of SE4. SE4 had on average, the highest prices across all months.

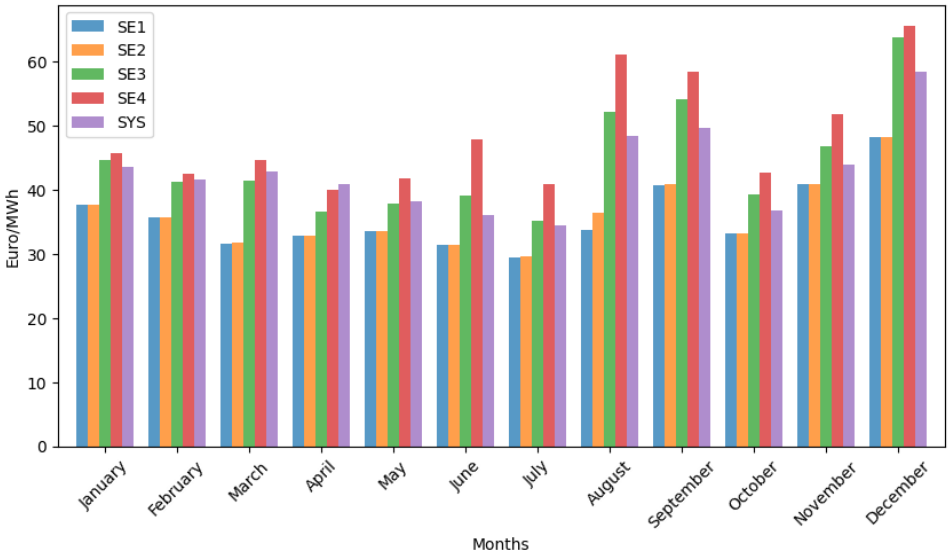

Figure 16. Monthly average bidding zone and system prices.

From mid-2021, the price trend for both SE4 and the system showcased more extreme prices than the previous decade in price levels and fluctuations (see Figure 17). Using the standard deviation as a measure of volatility, Figure 18 illustrates the sharp increase in volatility during 2021-2022. Due to the considerable differences between the two most recent years and the years prior, these periods were examined separately in the further exploration of the data.

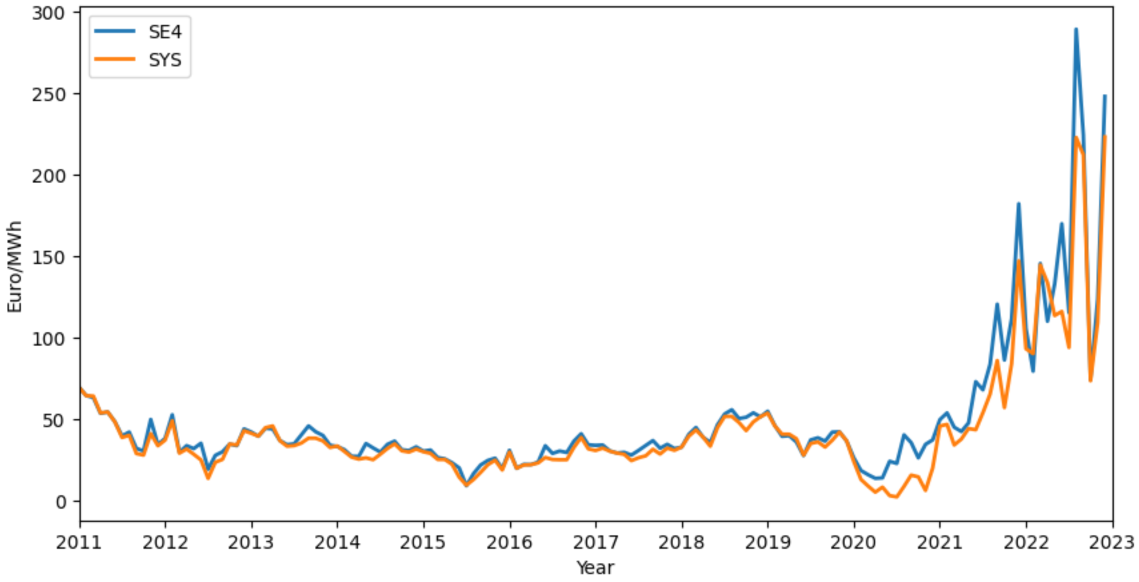

Figure 17. Monthly average of spot prices in SE4 and of system price 2011-2022.

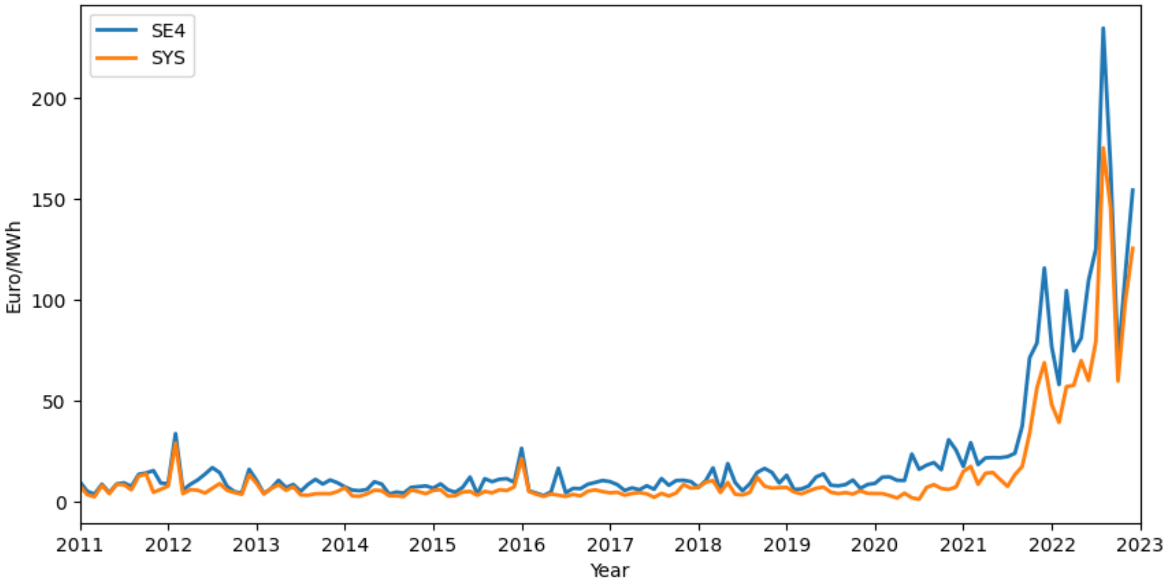

Figure 18. The standard deviation of monthly spot prices in SE4 and the system price 2011-2022.

When examining the electricity price's historical progression since 2011, it becomes apparent that more recent years, like 2021 and 2022, deviate from certain patterns highlighted in the theory section, such as monthly seasonality. As illustrated in Figure 19, for the dataset consisting of the years 2011 to 2017, it is possible to identify some trends, such as slightly higher electricity prices during some of the winter months (January, February, and November) and slightly lower electricity prices during the summer months (June, July, and August). However, when using a dataset consisting of 2018 to 2022, these trends are almost non-apparent, with much higher electricity prices than in previous years. One common denominator for both figures is that electricity prices vary widely monthly.

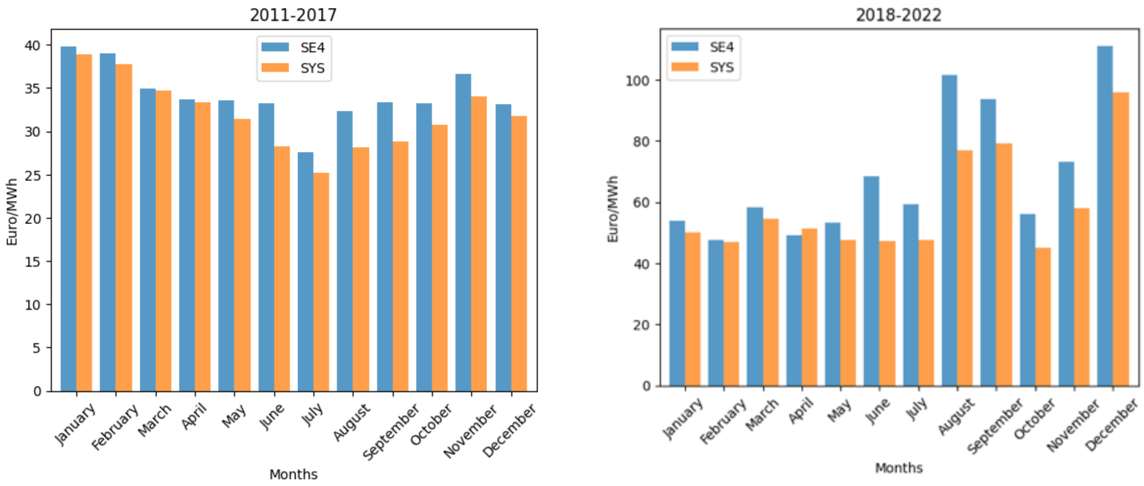

Figure 19. Monthly averages for SE4 and system price, 2011-2017 (left) and 2018-2022 (right).

Figure 20 below illustrates the hourly trends displayed by the electricity prices. Both for the periods of 2011-2017 and 2018-2022, the general trends mentioned in the theory section remain applicable, such as lower prices during off-peak hours of 20:00 to 08:00 and higher prices during peak hours, suggesting that the high prices and volatility of recent years have not change the hourly price characteristics. Furthermore, both datasets exhibit the highest prices during the morning at 08:00 and evening at 18:00. Even though the graphs display the same characteristics, a significant difference is that the latter dataset has a greater magnitude of the price difference between hours, indicating increased volatility throughout the day. All monthly averages normalized by yearly averages can be found in Appendix A.

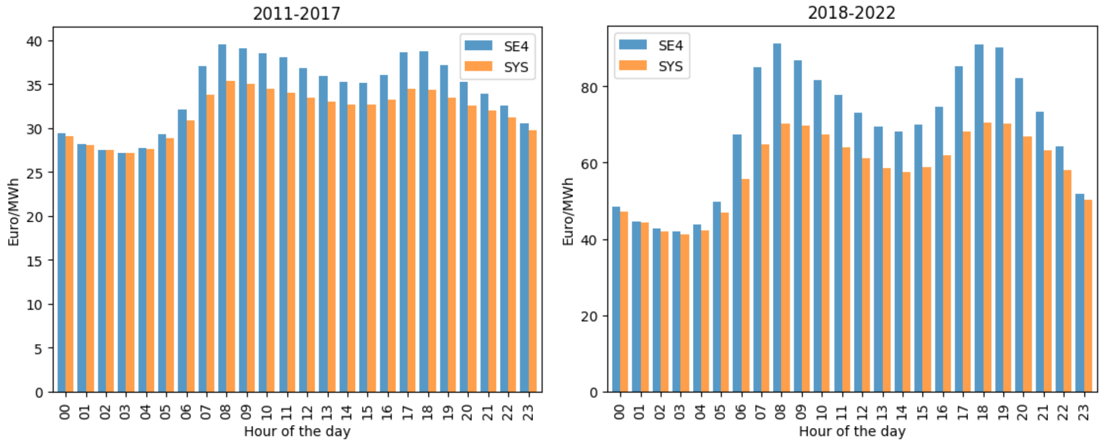

Figure 20. Hourly average SE4 spot and system prices in 2011-2022 (left) and 2018-2022 (right).

Figure 21 below illustrates the average daily means for the 2011-2017 and 2018-2022 data. Both figures show decreasing electricity prices on the weekend. This is in line with the trends described in the theory section in which the electricity demand generally is lower during this time, hence lowering the prices. Furthermore, coherent with the previously analyzed time frames (hourly and monthly), the 2018-2022 dataset has much higher prices.

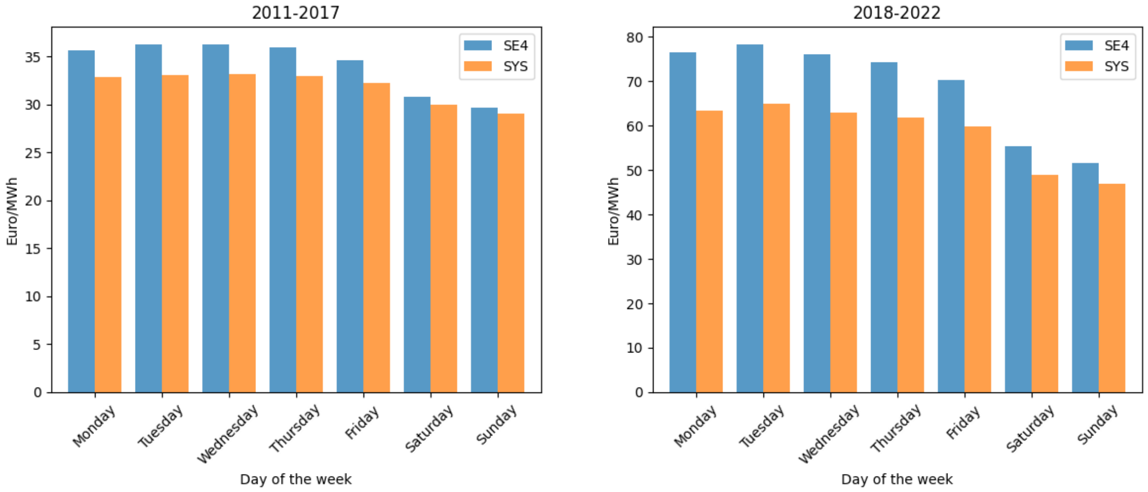

Figure 21. Daily average price SE4 and SYS, 2011-2017 (left) and 2018-2022 (right).

4.2.3. Data processing

For the purpose of the model, datasets of normalized spot prices on an hourly timescale were generated from the historical spot price data. This was done by combining normalized average monthly and hourly prices into an aggregated normalized value for each hour of the raw data. Therefore, weekly variations in spot prices, i.e., price level differences between weekends and weekdays, were omitted.

Historical spot prices from the bidding zone SE4 and 2018-2022 were selected. This timespan was selected due to recent years' extreme price level and volatility shift. The aim was to incorporate some of the more current volatility and price jumps into our generated day-ahead prices. The data exploration showed that this certain timeframe would include the years 2018-2020, which do not deviate greatly from the historical prices and movements, and the years 2021-2022, showing an extreme rise in prices and volatility.

To compute the hourly scales, an hourly ratio was first calculated by dividing each hourly value by its corresponding monthly mean. Furthermore, to normalize the hourly ratio, two means were computed. The first was the common yearly mean for 2018-2022, which served as a baseline for the entire period. The second mean was the common mean for each individual month (Jan-Dec) over that same period; this allowed us to identify any monthly patterns in the data. To obtain a normalized monthly scale, the mean for each month was divided by the common yearly mean. This resulted in twelve monthly scales, as shown in Table 6.

Table 6. Normalized monthly scales as factor of total average spot price.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.783	0.690	0.845	0.712	0.773	0.991	0.862	1.474	1.357	0.813	1.063	1.613

Each computed hourly ratio was multiplied by its corresponding normalized monthly scale to arrive at the hourly scales. This approach allowed us to account for hourly and monthly data variability when incorporating the hourly scales into hour-generated future prices. The derived hourly scales were then organized into twelve datasets corresponding to each month of the year (January-December).

Chapter 5.

Model development

This chapter describes the two steps of the model development phase. First, the conceptualization step is covered, in which the fundamental system design is described, including the simplifications made to feasibly and effectively model the system. After that, the actual simulation model is described in detail, including structure, inputs, calculations, and outputs.

5.1. Conceptualization and assumptions

The conceptualization step acts as the first step in developing the simulation model. It includes the decision-making of determining key elements, inherent relationships, and characteristics to include in the simulated system. Moreover, this step also includes the definition of assumptions made to simplify both the modeling process and the model complexity and the virtual system to increase feasibility, interpretability, and effectiveness.

5.1.1. System design

The hedging strategy of the actor is modeled as an isolated system in which electricity is traded and transferred between a number of key elements. The behavior of external factors impacts the system's behavior, i.e., how electricity is traded and transferred within the system. These behaviors are modeled for the entirety of a specific investment period.

The main elements of the system are the long-term PPA contracts from which the actor purchases electricity on an hourly basis, financial derivatives trading on the financial power market, and a BESS owned by the actor, which charges and dispatches electricity when needed.

Specifically, the system involves the implementation of two 10-year bilateral pay-as-produced PPAs with wind and solar production sites, which provides varying production volumes each hour to the system at a fixed price per unit volume. Also, the actor enters two short Nasdaq baseload futures contracts, a Nordic Power Future and an EPAD, in which the actor agrees to sell a consistent amount of power over the course of a specific period. Physical trading is assumed to be done on the day-ahead market, disregarding trade on the intraday market or cost related to imbalances.

Additionally, the actor owns and manages a battery storage system that is used within the trading system. For instance, the battery can be charged when prices are relatively low and then discharged when production is too low and prices on the day-ahead market (DAM) are high. The BESS may be used for other services unrelated to the trading system by the actor, such as ancillary services. Therefore, whether the BESS is used at any given hour in the model depends on market prices and the opportunity cost associated with utilizing the BESS to support the trading system versus other services. However, investigating these other areas of use is beyond this project's scope and will not be further explored.

Hourly mechanisms of the system

The procurement system relies on a balance of volumes. This equilibrium is achieved through a combination of contracted volumes from PPAs, battery dispatch, and purchases on the day-ahead market, which must correspond to the volumes traded on the financial market. While inflows from PPA contracts vary hourly and are outside the actor's control, the outflow to the financial contracts remains fixed throughout the investment period. Electricity is traded on the DA market to maintain balance, and the BESS is deployed as needed to maximize cost efficiency.

The mechanisms of how electricity flows hourly will depend on two main factors: the volume supplied by the PPA and the spot price. Suppose the PPA supply to the system is lower than the volume obligation of the futures contract. In that case, the actor will acquire more electricity either by purchasing from the wholesale market or by dispatching stored energy from the BESS, to maintain the system's balance. The system employs two types of DA support depending on the market conditions:

- *DA Support A* – If the market price for electricity on the DA market is lower than the sum of the financial derivatives' price and the BESS's opportunity cost, then obtaining the missing volumes through trade on the DA market is considered profitable. These purchases are referred to as “Support A” and are the most preferable option for the system.
- *DA Support B* – If the spot price is higher than the sum of the price of financial contracts and the opportunity cost of the BESS, the actor will employ the BESS to mitigate the impact of the high prices affecting the level of profitability. If the amount of electricity that can be dispatched from the BESS is insufficient, the remaining volume must be acquired on the DA market, despite unfavorable spot prices. These purchases are referred to as “Support B”, as they are the “plan B” and least preferable option for the system.

In addition to the purchases through Support A or Support B on the day-ahead market, volumes may also be purchased on the DA market to charge the BESS, depending on the spot price levels at any given hour. If the volumes procured from the PPA result in a surplus for any given hour, the excess can be sold on the DA market or stored in the BESS. If the spot price is higher than the price paid for the electricity by the PPA, then the electricity can be sold at a profit. However, if this is not the case, there is a risk that the electricity must be sold at a loss.

In essence, the whole system aims to stay in balance by procuring the same volume as is sold in the form of future contracts and determining the most cost-effective way to do so for each given hour in the investment period based on a set of conditions.

5.1.2. Assumptions and simplifications

The following table contains a selection of assumptions and simplifications applied on the system and when constructing the model. These were done with the purpose of achieving a more manageable and comprehensible model and limit the computational complexity.

Table 7. Assumptions and simplifications of system and model.

Assumption	**Description**
General	
Location	All physical and financial trading activity refers to bidding zone SE4
Investment period	10-years, starting from the beginning of 2024
Currency	All prices are assumed to be in EUR
Physical trading and pricing	
Market	The market is strictly limited Nord Pool day-ahead market. Other markets such as intraday or the balancing market are not considered in the model
Imbalances	Energy inflows and outflows in the model are always considered correct, hence disregarding additional costs for imbalances
Seasonal patterns	Monthly and hourly patterns are used in the simulation of prices, however weekly patterns are not considered
Financial trading and pricing	
Initial margin and collateral	Initial margin with cash as collateral is deposited at the initiation of new futures contracts and reimbursed at the end of the contracts. By consistently meeting the volume requirements of the futures contracts, margin requirements are consistently satisfied
Derivatives	Trading on the financial market is done with one baseload EPAD and one baseload Nordic Power Future with the same volume
Tenor	Length of each futures contract are 1-year
Settlement	Assumed hourly revenue, instead of daily mark-to-market settlement
Transaction costs	No transaction costs regarding trade of futures are assumed
Currency risk	All prices are set to be in EUR, hence disregarding currency risk, i.e., no risk of losses due to fluctuations in exchange rates between currencies
Battery energy storage system	
Starting charge	Assumed to be fully charged at the start of each simulated investment period
Degradation	Battery degradation is not taken into consideration
Round-trip-efficiency	Is assumed to be 100% throughout the investment period, i.e. with no losses
Costs	Assumed total costs are costs to purchase, no other investment costs or operational costs are considered.
End-of-life value	Depreciation in value over 10 years is assumed to be 20%

Opportunity cost	The BESS is assumed to have an opportunity cost as it may be used for other services
Optimization	BESS is charged as soon as capacity is missing and prices are considered low, not actually optimized
Power purchase agreements	
Volume structure	Pay-as-produced with a fixed price per unit volume
Settlement	Hourly settlement of the contracts is assumed
Technologies	Grid-scale wind and solar PV
Pricing	Fixed pricing in EUR/MWh
Tenor	Length of contracts set to 10 years, same as the investment period

5.2. Simulation model development

The simulation model is structured into four interconnected sub-models, each serving a specific purpose to achieve the model's aim. The sub-models are designed to operate sequentially, with the output of one sub-model as the input for the next. Figure 22 provides a graphical representation of this process. A brief explanation of the purpose and output of each sub-model is listed below.

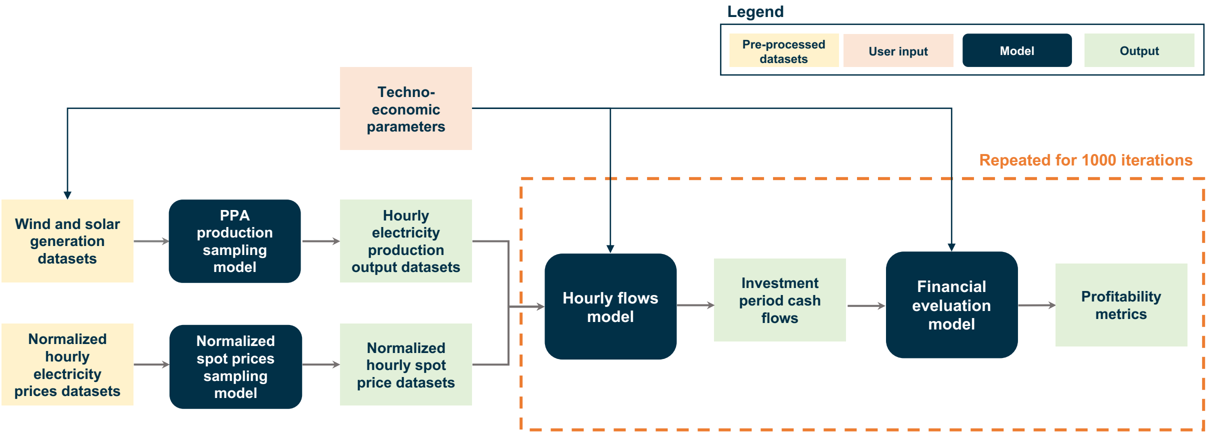

Figure 22. Graphical representation of the structure of the simulation model.

- *PPA production sampling model* – Generates datasets of normalized electricity production volumes for each hour in the investment period by random sampling from prepared datasets
- *Spot prices sampling model* – Generates datasets of normalized day-ahead prices for each hour in the investment period by random sampling from prepared datasets
- *Hourly flows model* – Simulates the hourly mechanisms of the system, i.e., the selling and purchasing of electricity, and the charging and discharging of the BESS

- *Financial Evaluation Model* – Evaluating the cash flows generated by the hourly energy and cash flows model through discounted cash flow analysis and deriving metrics to assess various aspects of the system's context and behavior.

Further details of the processes within each sub-model and their outputs are presented in the following sections.

5.2.1. Techno-economic parameters

The model comprises a set of several techno-economic parameters that allow the user to define the characteristics of the elements within the system. Each parameter and a short description are presented in Table 8 below.

Table 8. Techno-economic parameters for the simulation model with descriptions.

Input	Unit	Description
Investment parameters		
Discount rate	%	Interest rate used to determine the present value of future cash flows.
Investment period length	years	Duration of the investment timeframe.
Power purchase agreement parameters		
Price for wind power	EUR/MWh	Price contracted for the pay-as-produced wind power PPA modeled.
Price for solar power	EUR/MWh	Price contracted for the pay-as-produced solar power PPA modeled.
Total contracted capacity	MW	Contracted capacity for the wind and solar power PPAs, e.g., the peak capacity of the production plant by the percentage of output contracted summed.
Share wind power	%	Share of total contracted capacity from PPA is contracted via the wind power PPA.
Financial derivatives parameters		
Volume	MW	Volume of the future contracts and EPAD contracts traded on the financial market.
Yearly prices Nordic Power Futures	EUR	Forecasted future contract prices for each of the years in the investment period.
Yearly prices EPADs	EUR	Forecasted EPAD prices for each of the years in the investment period.
Initial margin future contract	%	Required initial deposit for opening the futures position as percentage of the contract value.
Initial margin EPAD	%	Required initial deposit for opening the EPAD position as percentage of the contract value.
Battery energy storage system parameters		
Investment cost	EUR/MWh	Price for purchasing battery for unit of capacity in MWh.
Capacity	MWh	Amount of electrical energy that can be stored in the BESS.
Power	MW	Amount of electrical energy that can be delivered by the BESS during an hour.
Opportunity cost	EUR/MW	Value of forgone profit when utilizing the battery for purposes of supporting the system.
Wholesale market parameters		
Yearly average	EUR	Expected yearly average price on the DA market for each year in the investment period.
Risk premium	%	Percentage of difference between average DA prices and financial contracts prices

5.2.2. Electricity production sampling model

To model the hourly energy and cash flows for the system, this sub-model generates a set of 1000 datasets. Each dataset represents a different set of randomly sampled hourly production volumes from the PPA to the actor throughout the investment period. Specifically, each dataset provides a unique version of the investment period regarding hourly production volumes.

The input data for this sub-model consists of datasets containing hourly production data from wind and solar generation. To capture the seasonality of renewable energy production and hourly variations within a day, the model samples from 24 x 12 datasets, each corresponding to a specific hour of the day and month (e.g., January at 00:00, January at 01:00, (…), until December at 23:00). The process of preparing these datasets and collecting the data is described in section *4.1.3. Data processing*.

During the simulated investment period, the sub-model enters the corresponding dataset for each hour of the day and month and randomly selects an output value using a bootstrapping sampling method with replacement. This means that a particular value might get sampled more than once.

5.2.3. Day-ahead spot prices sampling model

The sub-model for randomly sampling spot prices generates a dataset of spot prices for each hour of the investment period, which is used as input data for the hourly energy and cash flow model. To do this, the sub-model relies on a collection of prepared datasets containing hourly normalized spot prices based on historical spot price data. These datasets are organized by month and contain hourly normalized spot price values for actual days. The process of preparing these datasets is presented in section *4.2.3. Data processing*.

To create the spot price dataset for each hour of the investment period, the sub-model employs a bootstrapping technique with replacement. For each day to be simulated, the sub-model randomly samples a daily profile of hourly prices from the dataset for the specific month. This keeps the inherent patterns and correlations in spot prices throughout a specific day. This process is repeated for all the days in the investment period, and the selected days are combined to create a dataset representing the investment period.

The sub-model generates 1000 versions of the investment period, each with a different combination of randomly selected daily profiles of hourly prices. These 1000 versions represent different scenarios for the spot prices during the investment period.

5.2.5. Hourly flows model

This sub-model simulates the behavior of the system on an hourly basis. These hourly operations are characterized by two interconnected components: energy flows and cash flows. Energy flows represent the volumes of electricity traded via the PPA, financial contracts and DA-market, and the dispatched and charged electricity from the BESS. Cash flows reflect the associated costs and revenues of these transactions. Therefore, the model simulates the interplay between price and energy variables, further determining the buying and selling of electricity for each hour in the investment period. The following sections describe how this was done in detail. A screenshot of the model can be found in Appendix B.

Inputs

The hourly flows model is driven by three inputs, as presented in Figure 22. These inputs include the hourly datasets of production volumes from the PPA, the dataset for normalized historical spot prices, and the techno-economic parameters. Together, these inputs define the characteristics of the system elements and the context in which the system operates. Both datasets for spot prices and production volume contain hourly values for the entire investment period (i.e., $I \in \{ 1, \dots, I \}$) for each of the 1000 iterations of the simulation model. Meaning they contain 1000 versions of the investment period on an hourly level. These datasets are crucial for evaluating the performance of the simulation model over a range of scenarios.

Calculations

Before any other calculations are conducted, the input datasets for normalized hourly spot prices and hourly volume supplied by the PPA are scaled up based on the fixed input defined by the techno-economic parameters. Normalized hourly spot prices are transformed by being multiplied by the yearly average spot price for each year in the investment period, and standardized production volumes are scaled up by the total capacity contracted in the PPA contracts. In addition to the volume supplied by the PPA and the spot price, the system will also be affected by whether stored energy is available in the BESS for discharge. Each condition and the calculations for hourly energy and cash flows are explained below.

The difference between the contracted volume of the financial derivatives and the volume supplied for each given hour by the PPA (noted as ΔVi) determines if there is an electricity surplus or deficit for each hour.

$$\Delta V_i < 0 \text{ indicates electricity deficit for hour } i \tag{3.1a}$$

$$\Delta V_i > 0 \text{ indicates electricity surplus for hour } i \tag{3.1b}$$

in which

ΔV_i = Difference in financial derivatives volume and volume supplied by PPA for an hour i

If the spot price is relatively high or low depends on if the spot price is higher than the value of financial derivatives for each hour summed with the opportunity cost of the BESS.

$$F + C_{Opp} \geq y_i \text{ indicates a favorable spot price} \tag{3.2a}$$

$$F + C_{Opp} < y_i \text{ indicates an unfavorable spot price} \tag{3.2b}$$

in which

F = Price of financial derivatives,
C_{Opp} = Opportunity cost for utilizing the BESS,
y_i = Spot price for the hour *i,*

The available capacity in the BESS for each hour i is determined based on the previous hours' available energy, and the volume of energy charged or discharged that hour. The BESS is assumed to be fully charged for the first hour in the investment period.

$$q_i = q_{i-1} + u_{c,i} + u_{d,i} \tag{3.3}$$

in which

q_i = Available capacity in BESS during hour i [MWh],
q_{i-1} = Available capacity in BESS at hour $(i-1)$ [MWh],
$u_{c,i}$ = Energy charged to the BESS during hour i [MWh],
$u_{d,i}$ = Energy discharged from the BESS during hour i [MWh],

Based on the conditions described by equation (3.1), (3.2) and (3.3) electricity will be bought, sold, dispatched or charged differently. If the condition described by (3.1b) is true, then there has been an excess volume produced by the PPA which is sold on the day-ahead market for the spot price at that hour. However, if instead (3.1a) stands true, then there has been a volume deficit produced by the PPA which will either be procured on the day-ahead market or discharged from the battery to keep the system in balance.

In the case that both (3.1a) and (3.2a) is true, the spot price is advantageous for purchasing directly on the DA-market without comprising profitability. Hence the production deficit is balanced through purchasing electricity on the DA market, these purchases are referred to as DA Support A. In contrast, if (3.2b) were true, the production deficit is either covered by dispatching energy from the BESS or from unfavorable purchase on the DA market. The amount dispatched from the BESS is dependent on its rated power, as well as its available energy at the given hour.

$$q_{d,i} = \begin{cases} min\{P, (E - c_i)\} & if\ \Delta V_i < 0\ and\ c_i < C \\ 0 & if\ \Delta V_i < 0\ and\ c_i > C \end{cases} \tag{3.4}$$

in which

$q_{d,i}$ = Volume of electricity dispatched from the BESS during hour *i,*
P = Rated power of the BESS [MW],
E = Total capacity of the BESS [MWh],
c_i = Available capacity during hour *i,*

If volume of electricity dispatched from the storage system is not enough to cover the entire deficit, the rest is procured on the DA Support B.

5.2.6. Financial evaluation model

The financial evaluation model uses a discounted cash flow method to evaluate the investment in the system by estimating the present value of future cash flows during every year in the investment period starting from the year before the trading strategy starts, i.e., each year $n \in \{0,\ldots, N\}$. This model's input (see Figure 22 for a graphical presentation) is the outputted investment period cash flows generated from the hourly flows model and the techno-economic parameters presented Table 9. For each constituent year in the investment period, cash flows are calculated, the cost and revenue classifications used in the cash flow calculations are presented in Table 9 below.

Table 9. Revenues and costs used in the calculation of yearly cash flows.

Revenue / Cost type	**Description**
Upfront costs	
BESS investment cost	Total cost for purchasing BESS, paid once during year before the investment period.
Financial derivatives initial margin payment	Cash deposition needed to initiate position for futures and EPAD contracts
Revenues	
Financial derivatives revenue	Revenues as generated by the settlement of futures contracts
Financial margin payout	At expiration of futures, deposited initial margin is reimbursed
DA for BESS discharging	Revenues from discharging the BESS on the DA market
Procurement costs	
PPA costs	Costs for purchasing energy supplied via the pay-as-produced PPA
DA Support A	Purchases made on the DA market when spot prices are considered relatively low, or favorable for trading
DA Support B	Purchases made on the DA market when spot prices are considered relatively high, or unfavorable
DA for BESS charging	Cost of purchases on DA market for charging BESS

Assessment metrics

This subsection focuses on various metrics employed to assess different aspects of the simulated investment period. These metrics were divided into three main areas: *profitability*, *dataset characteristics*, and *hedging efficiency*. Calculation of each metric was done for each iteration in the simulation of the model. The metrics and their purpose are presented and described in the subsections below.

Profitability metrics

Based on the generated cash flows, profitability metrics such as net present value (NPV) and internal rate of return (IRR) were calculated for the entire investment period. This was done following the steps presented in *3.5.1. Discounted Cash Flow.* Specifically, a discount rate, as specified in the techno-economic parameters, was applied to future cash flows estimated in the hourly flows model. Next, the NPV was calculated using equation (2.6), as listed in section *3.5.2. Net Present Value and Internal Rate of Return*, by use of the built-in function in Excel. IRR was also calculated using Excel's respective built-in function.

Dataset characteristics metrics

In order to properly understand and evaluate the conditions on which the model has simulated the system, metrics to capture the characteristics of each of the two primary datasets (spot prices and PPA production volumes) used as input into the simulation model were measured. These metrics were calculated for each iteration in the simulation. In the following

Table 10, the dataset characteristics metrics are presented.

Table 10. Dataset characteristics metrics with descriptions.

Metric	*Description*
Volatility of production volumes	Measured as the relative standard deviation (RSD) of the production volumes in each simulated investment period. Due to production volumes being randomly sampled, volatility will vary between iterations.
Average spot prices	Indicates the average price on the day-ahead market in each simulated investment period.
Volatility of spot prices	Measured as the relative standard deviation (RSD) of the spot prices in each simulated investment period. Due to spot prices being randomly sampled from the dataset, volatility will vary between iterations.
Share of hours with spot prices below PPA prices	The percentage of hours during which the spot price is lower than the prices contracted in the PPAs. Allows for understanding of relationship between price levels of each iteration.

Share of hours with spot prices above futures contract prices	The percentage of hours during which the spot price is higher than the pricing of the futures contracts on the financial market. Allows for understanding of relationship between price levels for each iteration.

Hedging efficiency metrics

How volume was procured during hours of deficits was measured through two metrics indicating the share of volume deficit acquired using DA Support B and dispatch of the BESS. Additionally, to assess the effectiveness and cost efficiency of trades conducted via DA support A and B, capture factors for each support category were measured for every simulation iteration. Furthermore, an avoided cost factor was calculated for every simulation iteration to assess the economic benefits and advantages of employing the BESS. The hedging efficiency metrics are presented in Table 11 below.

Table 11. Hedging efficiency metrics with descriptions.

Metric	*Description*
Share of volume deficit procured from DA Support B	The percentage of the total volume of deficit throughout the investment period in each specific simulation which was acquired from the DA-market and classified as Support B, i.e., unprofitable procurement.
Share of volume deficit covered by dispatch from BESS	The percentage of the total volume of deficit throughout the investment period in each specific simulation which was acquired through dispatch of the BESS.
Capture factor for purchases on DA Support A	The average price of purchases classified as DA Support A on the DA market, normalized based on the total average spot price during the investment period.
Capture factor for purchases on DA Support B	The average price of purchases classified as DA Support B on the DA market, normalized based on the total average spot price during the investment period.
Avoided cost factor at discharge of BESS	The average price on the DA market at time of dispatch of BESS, normalized based on the total average spot price during investment period, i.e., indicating the price avoided through the utilization of the BESS instead of procurement on the DA-market.

Chapter 6.

Application of the model

This section outlines the process of using the model to generate results. It involves selecting the input data for both the base case and the scenarios examined in the sensitivity analysis. Detailed explanations are provided in the following sections regarding how input parameter values were chosen, starting with the base case and then moving on to the sensitivity analysis.

6.1. Defining the base case

In the following sections, the description and rationale behind the chosen values for the techno-economic parameters set in the base case are presented.

6.1.1. Investment

The investment period is set to 10 years. The discounted cash flow analysis set the discount rate to 9%. This was based on discussions with the company and benchmarking against other discount rates.

The cost of financing renewable power generation has been low for the past ten years. The weighted average cost of capital (WACC), the average cost of all different sources of financing used to fund a project or investment, has been historically low at a rate of approximately 3-4%. In 2021, a discount rate (WACC) of 2.35% was presented by the Swedish Energy Markets Inspectorate (Ei) for calculating revenue caps for electricity network companies per the Swedish regulatory framework. This is lower than the 5.85% rate in the previous regulatory period. [70] The base case discount rate was determined by adding a risk premium to these discount rates.

6.1.2. Day-ahead market

The yearly average prices assumed on the spot market to assign the base case, and the following sensitivity analysis, was determined by benchmarking long-term forecasted values provided by personal communications with power company Bixia (2023-04-13), long-term scenario values developed by Svenska Kraftnät and projected settlement price for the futures collected from the financial trading platform Montel Online on 30th of March 2023. [71] All values used in benchmarking is summarized in Appendix C. For the purpose of the base case, the spot prices were set to the pricing of the financial derivatives sourced from Montel as a reference, as can be seen in Table 12.

Table 12. Input values for financial derivatives price parameters in the base case.

Investment year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
SE4 prices [EUR/MWh]	81.00	70.50	67.50	70.00	62.75	62.10	62.00	61.90	61.80	62.30

6.1.3. Futures contracts

The financial derivatives are defined by volume, yearly settlement prices, initial margin and risk premium compared to DA market.

For the financial derivatives, i.e., the Nordic Power Future and EPAD contracts, the parameters to be set are contracted volume, prices, and initial margins. The volume of both contracts was fixed at 10 MW. Pricing data was collected from Montel. [71] The price data was collected based on the projected settlement price for the futures at the 30th of March 2023. Each contract having the duration of one year with the first contract being entered for year 2024. The projected settlement price was available for all the year for the Nordic Power Futures since these futures may have a contract duration of 10 years. However, EPADs only have a maximum contract duration of four years meaning prices for subsequent years are not available. Therefore. Prices for EPADs for year 5 an onwards was assumed to be the same as the available projected settlement price for year 4. Furthermore, the initial margin requirement for trading the financial derivatives was set based on the initial margin values for one-year contracts on April 11th 2023, as provided by Nasdaq Listing Operations. Additionally, for the base case the risk premium compared to the day-ahead spot prices was assumed to be zero. These input values for the base case are presented in Table 13 and Table 14 below.

Table 13. Input values for financial derivatives parameters in base case.

Parameter	*Value*	*Description*
Volume	10 MW	Volume of the financial futures
Initial margin future	28.04%	Initial margin for Nasdaq Power Futures contract 11/4-2023.
Initial margin EPAD	129.93%	Initial margin for Nasdaq EPAD SE4 contract 11/4-2023.
Risk premium	0%	No risk premium between DA prices and financial contracts.

Table 14. Input values for financial derivatives price parameters in base case.

Investment year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Future prices [EUR/MWh]	67.00	55.00	47.00	45.00	44.00	43.35	43.25	43.15	43.05	43.55
EPAD prices [EUR/MWh]	14.00	15.50	20.50	25.00	25.00	25.00	25.00	25.00	25.00	25.00

6.1.4. Power purchase agreement

The construction of the model requires the following input parameters to define the simulated PPA contracts: prices and capacities for both the wind power contract and the solar power contract.

Price inputs for the PPA contracts were based on nominal H1 2022 values for on-shore wind pricing found by BloombergNEF in their 2022 *European Corporate PPA Price Survey.* The average price gap between solar and wind power PPAs of ~5.6 EUR was used to estimate the solar prices in 2022. [49] An increase in index PPA prices between 2022-2023 of 53% in the Nordics, shown by data from PexaPark, the leading analytic platform for PPAs, was used to scale up the prices from 2022. [72] [73]

The contracted capacity for the PPA contracts for the base case was calculated based on the volume of the financial derivatives and the optimal ratio between wind and solar power to achieve a baseload profile for the dataset (as presented in subsection 4.1.3. Data processing). In the base case, the average output of the PPA is set to be the same as the volume of the financial derivates, i.e., 10 MW. The total contracted capacity contracted by PPA was determined based on the average standardized output in the randomly sampled production datasets. Subsequently, this total capacity was split between solar and wind production based on the calculated optimal ratio.

Table 15. Input values for financial derivatives parameters in the base case.

Parameter	**Value**	**Unit**
Wind power PPA		
Price	52.83	EUR/MWh
Capacity	16.02	MW
Solar power PPA		
Price	61.40	EUR/MWh
Capacity	5.77	MW

Thus, the price paid in the system for each unit supplied by the simulated PPA contract in the model, will be the weighted average of the wind price and solar price based on the peak capacities.

6.1.4. Battery storage system specifications

For the battery energy storage system, the specification to be defined in the techno-economic parameters are: energy capacity (also referred to as capacity), rated power (referred to as power), duration (also described by C-rating, see 3.4.1. Technical specifications), investment cost and opportunity cost of use.

Specifications for the BESS used as input data was supplied from the company, from BESS quotations from suppliers. These values were benchmarked with external sources, see *Appendix D. Benchmarking of BESS specifications*.. In the base case, it was assumed that a 5 MW 0.5C BESS configuration was used.

Table 16. Input values for battery storage system used for input in base case.

Parameter	*Value*	*Unit*
Capacity	10.44	MWh
Power	5	MW
C-rating	0.5	No unit
Opportunity cost	10	EUR/MW
Investment cost	320 000	EUR/MWh

6.2. Sensitivity analysis

In the sensitivity analysis, a selection of input variables were varied in order to observe their effect on the systems behavior and profitability. The parameters varied are presented in Table 17 below, together with a description.

Table 17. Factors varied in the sensitivity analysis.

Factor	**Description**
Investment data	
Discount rate	Discount rate used in the discounted cash flow analysis.
Day-ahead market	
Historical price data	Year from which historical data is collected and used to simulate spot prices.
Futures contracts	
Risk premium	Assumed difference in price between future contracts and day-ahead spot prices.
Power purchase agreements	
Prices	Price levels contracted in the power purchase agreement for solar and wind power PPAs separately.
Average production volumes	Average output volume from the power purchase agreement during the modeled investment period.
Solar and wind power ratios	Share of each generation technology of the total contracted power capacity, by changing the share of wind power input parameter.
Battery energy storage systems	
BESS specifications	Technical specifications describing the BESS being used.

Opportunity cost	Potential revenue sacrificed when choosing to utilize BESS for use in the simulated strategy, rather than use for other applications i.e. ancillary services.

Each of these was varied between two cases, except for the variation of used battery energy storage system in which seven different cases were explored in addition to the base case. Therefore, the total number of simulations in the sensitivity analysis was 21.

The range for each of the factors between which the values are varied in the sensitivity analysis, i.e., the high and low case for each value, were derived based on base case values and in collaboration with supervisors in order to determine reasonable values between which these factors could vary. The actual input values are not definitive, but rather the purpose is to observe the behavior when base case values are increased or decreased.

Table 18. Values of varied parameters in sensitivity analysis.

Parameter	*Low case*	*High case*
Opportunity cost	5 EUR/MW	15 EUR/MW
Discount rate	6%	12%
Risk premium	-5%	+5%
PPA price for wind	-20% (42.26 EUR/MWh)	+20% (63.40 EUR/MWh)
PPA price for solar	-20% (49.12 EUR/MWh)	+20% 73.68 EUR/MWh
Average production PPA	8 MW	12 MW

Table 19. Values of varied parameters for BESS in sensitivity analysis.

Battery case	*10 MW 0.5C*	*1 MW 0.5C*	*5 MW 1C*	*10 MW 1C*	*1 MW 1C*
Capacity [MWh]	20.873	2.236	5.218	10.437	1.491
Power [MW]	10	1.25	5	10	1.25
Price [EUR/MWh]	310 000	370 000	395 000	370 000	450 000

Chapter 7.

Results

This chapter presents all results from the application of the simulation model on the different input parameter cases. In section 7.1. the results from the base case are presented. The results from the variation of parameters from the sensitivity analysis are compiled in the following subsections. The full table containing all result values can be found in Appendix E. All results from application of simulation model. Results presented in this chapter are analyzed in Chapter 8.
Analysis.

7.1. Base case

In this section the results from the simulation of the base case are presented for each of the categories of assessment metrics, i.e., profitability, dataset characteristics and hedging efficiency metrics.

7.1.1. Profitability metrics

Table 20. Profitability metrics results for the base case simulation.

Profitability metrics	*Mean*	*RSD*
Net present value (NPV)	6 540 000 EUR	0.64%
Internal rate of return (IRR)	46.10%	0.72%

The profitability assessment of the base case specifies that the net present value of the system over the investment period of 10 years, on average across the simulations, is estimated to be approximately 6.54 MEUR, with an average internal rate of return at 46.14%. As illustrated in Figure 23, the distribution of each metric is centered around the mean with a roughly symmetrical pattern, resembling a normal distribution. The low relative standard deviation (RSD) of 0.64% and 0.72% signifies that the value dispersion is relatively small compared to the mean value. Thus, most values in the results would cluster around the mean with a narrow range.

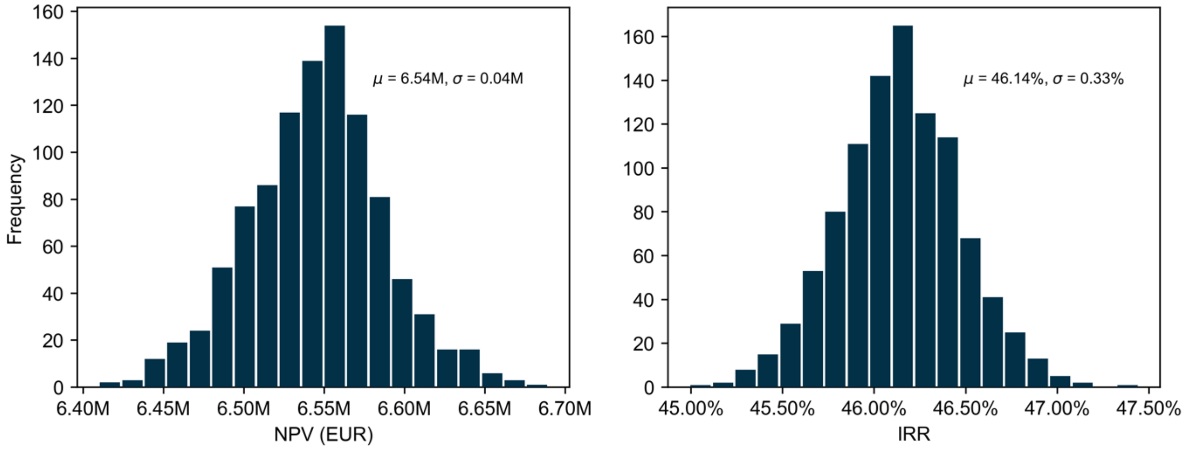

Figure 23. Distribution of profitability metric results for base case simulation.

7.1.2. Datasets characteristics metrics

The results gathered regarding the context of the system in the base case, indicate which conditions for the production outputs and the DA price datasets are impacting the simulation results.

Table 21. Dataset characteristics metrics results for the base case simulation.

Dataset characteristics metrics	Mean	RSD
Average hourly production volume from PPA	10	0.13%
Production volumes volatility	40.80%	0.18%
Average day-ahead price	69.95 EUR	0.67%
Day-ahead prices volatility	63.95%	1.26%
% hours with DA price lower than PPA price	40.70%	1.21%
% hours with DA price above future prices	41.20%	1.08%

In the base case, the average hourly production volume from the PPA was adjusted to be the same as the volume of the financial contracts across all generated production datasets, i.e., 10 MW. This average for each specific dataset varies slightly between iterations, as indicated by the relative standard deviation (RSD) of 0.13%. The volatility in production volumes indicates that, on average, the hourly production deviates by 40.80% from the mean during the period. This suggests that the volatility of the production output is relatively large compared to the mean values and is spread out over a wide range of values.

The average DA price of 69.95 EUR is the same as the set average of the yearly DA prices used as input data. This confirms that the sampled normalized DA price datasets represent the input data used from 2018-2022. The dispersion of the DA prices shows a higher amount of volatility than the production volumes, with a relative standard deviation of 62.95%.

During the simulated investment period, the DA price falls below the PPA price for PPAs during 40.70% of hours. In addition, the DA price exceeds the future price during, on average, 41.20% of hours in the investment period. An example of how prices vary across a simulated investment period is shown in Figure 24. Although, as the density graph confirms, simulated spot prices are only between the price of the PPA and the price of futures contracts around 18% of hours in the model, the majority of the time, prices tend to be either higher or lower than that range.

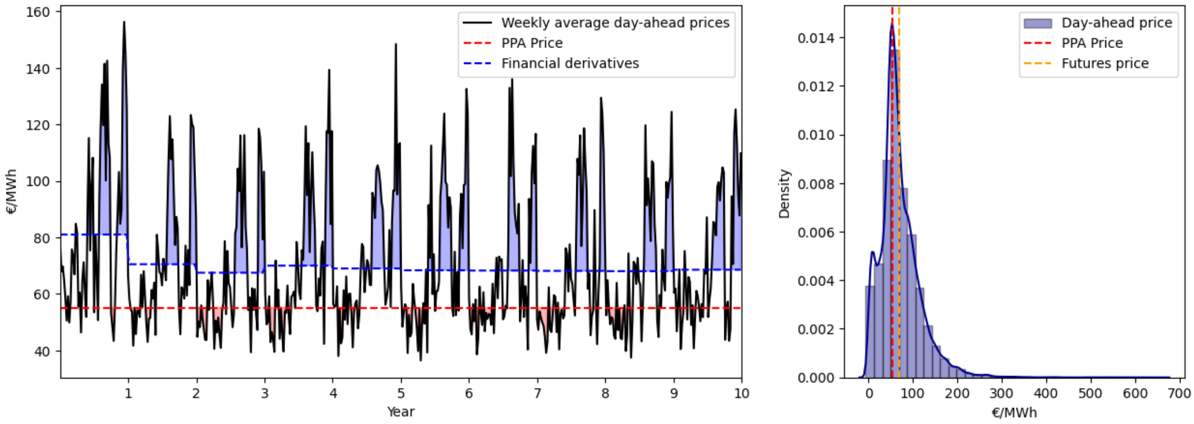

Figure 24. Simulated spot price (left) and density graph (right) for base case.

7.1.3. Hedging efficiency metrics

Table 22. Results from the base case simulation for the hedging efficiency metrics.

Hedging efficiency metrics	*Mean*	*RSD*
Share of volume deficit procured from DA as Support B	18.65%	2.25%
Share of volume deficit covered by dispatch from BESS	12.85%	1.74%
Capture factor for DA Support A	0.66	0.75%
Capture factor for DA Support B	1.73	0.71%
Capture factor for DA purchases for BESS charging	0.83	0.78%
Avoided cost factor at discharge of BESS	1.58	0.67%

Results show that in the base case, a large majority of volume deficits are not covered by DA Support B (18.65%) nor the BESS (12.85%), meaning that the rest is procured via DA Support A (68.50%). The remaining volumes were covered in 12.85% by the BESS and 18.65% on the DA market as unprofitable trades (DA Support B). Power purchased on the day-ahead market via DA Support A showed a capture factor of 0.66, indicating that the average price of electricity for these trades was significantly lower than the average spot price. Furthermore, when prices were higher and the BESS was utilized, results show that prices, on average, were 58% higher than the yearly baseload price. The capture factor for DA Support B exceeds both at 1.73, indicating the average price at which electricity is purchased to achieve balance when the spot prices are high, and the BESS cannot be utilized.

7.2. Sensitivity analysis

In the following subsections the results for each variation of the input parameters are presented in following order: discount rate, historical price data, futures contract risk premium, PPA prices, PPA average production volumes, solar and wind power ratios, battery storage system, and opportunity cost of BESS utilization. Note that only results differing from the base case are presented in this section, however all result values can be found in Appendix E. All results from application of simulation model.

Figure 25 below provides an overview of the results with the resulting net present value for each simulated case, colour coded after input parameter.

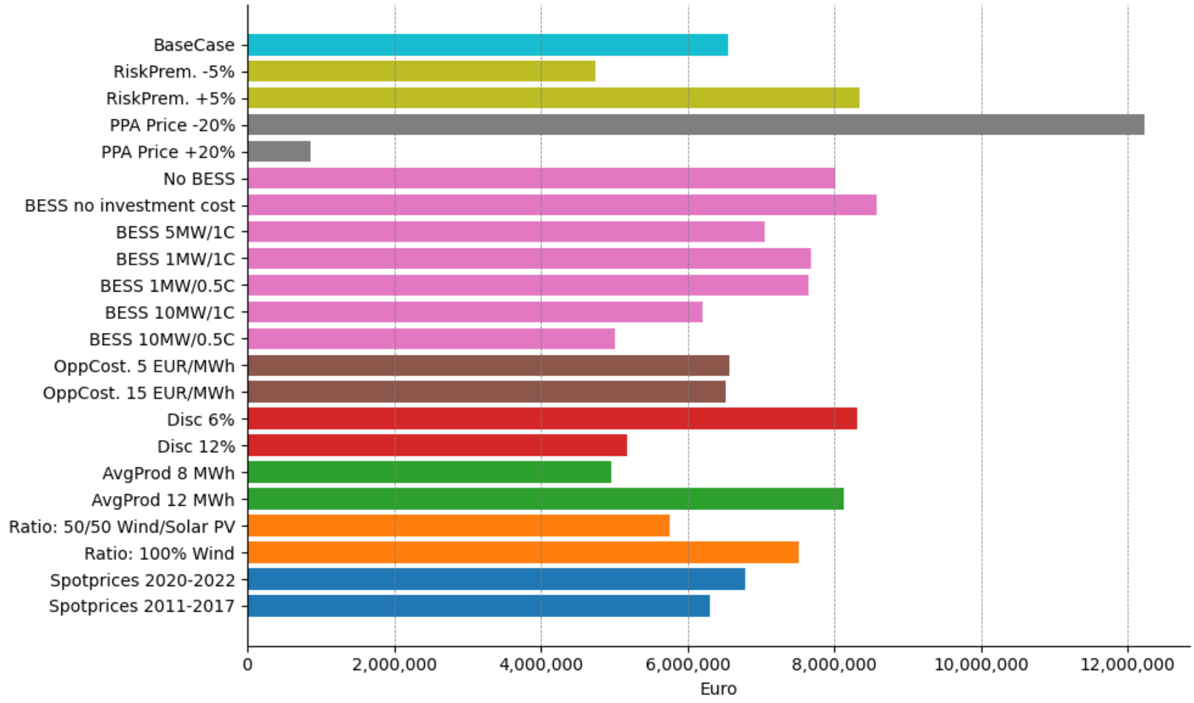

Figure 25. Resulting NPV for each case simulated in the model, color coded based on input parameter.

7.2.1. Discount rate

Table 23 Results for sensitivity analysis of changed discount rate. Differences from base case in parenthesis.

Metric	*12%*	*6%*
Net present value (NPV)	5 170 000 EUR (-21%)	8 310 000 EUR (+27%)
IRR	46.14% (0.00%)	46.14% (0.00%)

A change in discount rate only affects the NPV of the model. Specifically, an increase in the discount rate to 12% leads to a reduction in the NPV of 20.9%, while a decrease in the discount rate to 6% results in a rise in the NPV of 27%. Notably, the high IRR of 46.14% established by the base case sets the upper limit for the discount rate, beyond which the NPV would turn negative.

7.2.2. Historical price data

The second factor that varied in the sensitivity analysis was the years from which historical spot price data would be used to create the normalized hourly electricity prices datasets. Simulations included using data from 2011-2017 and 2020-2022.

Table 24. Results for sensitivity analysis simulations with historical spot price data from which normalizeed hourly datasets were created. Differences from base case in parenthesis.

Metric	**2011-2017**	**2020-2022**
Profitability metrics		
Net present value (NPV)	6 300 000 EUR (-3.78%)	6 800 000 EUR (+3.78%)
Internal rate of return (IRR)	44.75% (-3.00%)	47.52% (+3.00%)
Dataset characteristics metrics		
Day-ahead prices volatility	32.51% (-48.72%)	80.18% (+26.48)
% hours with DA price lower than PPA price	16.43% (-59.64%)	46.41% (+14.01%)
% hours with DA price above future prices	41.97% (+1.87%)	41.31% (+0.28%)
Hedging efficiency metrics		
Share of volume deficit procured from DA as Support B	7.12% (-61.80%)	18.03% (-3.33%)
Share of volume deficit covered by dispatch from BESS	10.15% (-21.01%)	15.32% (+19.27)
Capture factor – DA Support A	0.88 (+34.25%)	0.55 (-16.75%)
Capture factor – DA Support B	1.48 (-14.78%)	1.96 (+12.79%)
Capture factor for DA purchases for BESS charging	1.02 (+21.83%)	0.79 (-5.67%)
Avoided cost factor at discharge of BESS	1.43 (-9.79%)	1.66 (+4.65%)

Results demonstrates that profitability was only moderately affected by which spot price dataset was used. In the case where historical datasets from 2020-2022 were used, results show a slight increase in both NPV and IRR (+3.78% and +3.00% respectively compared to base case), and the opposite effect was found for the 2011-2017 dataset simulation (-3.78 % and -3.00%).

Dataset characteristic metrics give insight into the differences between the datasets. Using historical data from 2011-2017 showed significantly lower volatility from base case (-48.72%), and the share of hours with DA price succeeding PPA pricing reduced to 16.43% (-59.64% decrease from base case). Historical data from 2020-2022 resulted in an increase in volatility by 25.48%, and an increase in prices below PPA pricing by 14.01%.

For the 2011-2017 case, the share of volume deficit covered by DA Support B decreased to 7.12% (-61.80% compared to the base case), and the deficit covered by BESS to 10.15% (-21.01%). Therefore, 82.73% of the volume deficit is procured via the DA market when prices are relatively low (DA Support A). Simultaneously, the capture factor for DA Support B decreased by -14.78%. However, the capture factor for DA Support A and BESS charging increased by 34.25% to 0.88 and 21.83% to 1.02, respectively. Additionally, avoided cost factor at the discharge of BESS decreased by -9.79%.

In the second case, for 2020-2022 price data, DA Support B's volume share decreases slightly by -3.33%, but the deficit covered by BESS increases by 19.27%. As a result, 18.03% of the deficit is covered by DA Support B, 15.32% by BESS dispatch, and the remaining share by DA Support A. Capture factors for procurement on the DA market decreased in terms of DA Support A (-16.75% to 0.55) and increased for DA Support B (+12.79% to 1.96). For the charging of BESS, the capture factor on the DA market was -5.67% lower than the base case, at 0.79, and the avoided cost factor when dispatching the BESS resulted in 1.66, which correlates to a 4.65% increase.

7.2.3. Futures contract risk premium

Results from varying the risk premium illustrate the effect of what discrepancies between the futures price and the DA price have on the model. The case when the risk premium is increased by +5% demonstrates a more significant difference between the two prices, while the case of -5% shows the effects of a smaller gap.

Table 25. Result metrics for the sensitivity analysis of financial derivatives risk premium. Differences from base case in parenthesis.

Metric	**+5%**	**-5%**
Profitability metrics		
Net present value (NPV)	8 350 000 EUR (+27.51%)	4 740 000 EUR (-27.54%)

Internal rate of return (IRR)	56.19% (+21.81%)	35.98% (-21.99%)
Dataset characteristics metrics		
% hours with DA price lower than PPA price	40.70% (0%)	40.70% (0%)
% hours with DA prices above price for financial derivatives	37.79% (-8.27%)	44.57% (+8.19%)
Hedging efficiency metrics		
Share of volume deficit procured from DA as Support B	16.78% (-10.02%)	20.52% (+10.00%)
Share of volume deficit covered by dispatch from BESS	12.35% (-3.87%)	13.47% (+4.86%)
Capture factor for DA Support A	0.67 (+2.63%)	0.64 (-2.66%)
Capture factor for DA Support B	1.78 (+2.38%)	1.70 (-2.22%)
Capture factor for DA purchases for BESS charging	0.88 (+5.05%)	0.80 (-4.56%)
Avoided cost factor at discharge of BESS	1.63 (+3.06%)	1.53 (-3.27%)

Compared to the base case, when increasing the risk premium by 5%, NPV increases by 27.5%, and the share of hours that the DA price is above the futures price decreases by 8.27%. As a result, a lesser deficit is covered by trade on the DA Support B and the BESS, which decreases by 10% and 3.9%, respectively. The average price at which the BESS is charged also increases by 5.1%, and the average price on the DAM when the BESS is utilized increases by 3.1%. By decreasing the risk premium by 5%, NPV decreases by 27.5%, and the share of hours that the DA price is above the futures price increases by 8.19%. A more significant deficit must be covered by trade on the DA Support B and by the discharge of the BESS, which increases by 10% and 4.9%, respectively. The average price at which the BESS is charged decreases by 4.6%, and the average price on the DAM when the BESS is dispatched decreases by 3.3%.

Furthermore, by changing the risk premium, new limits are set for how the model defines DA Support A and B, which can be seen through the increase and decrease of the capture factor in DA support A and B for the two cases. With a positive risk premium, the capture factor of DA supports A and B increases by 2.63% and 2.38%, respectively. With a negative risk premium, the capture factor of DA support A and B decreases by 2.66% and 2.22%, respectively.

7.2.4. Power purchase agreement prices

Table 26. Profitability and efficiency metrics average value results for PPA price level sensitivity analysis.

Metric	**+20%**	**–20%**
Profitability metrics		
Net present value (NPV)	861 000 EUR (–86.84%)	12 200 000 EUR (+86.84%)
Internal rate of return (IRR)	14.09% (–69.45%)	76.10% (+64.94%)
Dataset characteristics metrics		
% hours with DA price lower than PPA price	54.97% (+35.05%)	24.99% (–38.61%)

The overall profitability is impacted when the power purchase agreement's price per unit power volume varies. With an increase in PPA prices by 20%, the net present value of the simulated investment results in a –86.84% decrease. In the opposite case, the NPV increases with the same percentage. Similar impacts occur on the internal rate of return in which a lower price in the PPA results in a higher IRR, i.e., higher profitability. Dataset characteristics metrics show that when the PPA price is increased by 20%, the percentage of hours throughout the investment period during which the price on the day-ahead market is lower than the PPA rises to 54.97% (an increase of 35.05% from the base case). Thus, for most of the period, the actor procures electricity with an opportunity cost.

7.2.5. Power purchase agreement average production volumes

Table 27 Results for sensitivity analysis of changed average hourly output from PPA. Differences from base case in parenthesis.

Metric	**12 MWh**	**8 MWh**
Profitability metrics		
Net present value (NPV)	8 120 000 EUR (+24.07%)	4 960 000 EUR (-24.17%)
Internal rate of return (IRR)	56.24% (+21.89%)	36.43% (-21.03%)
Hedging efficiency metrics		
Share of volume deficit procured from DA as Support B	15.80% (-15.28%)	21.86% (+17.21%)
Share of volume deficit covered by dispatch from BESS	15.67% (+21.98%)	9.91% (-22.90%)
Capture factor – DA Support A	0.657 (-0.04%)	0.659 (+0.27%)

Capture factor – DA Support B	1.74 (+0.52%)	1.73 (+0.13%)
Capture factor for DA purchases for BESS charging	0.834 (+0.09%)	0.833 (-0.08%)
Avoided cost factor at discharge of BESS	1.62 (+2.04%)	1.55 (-2.42%)

By decreasing or increasing the output from the PPA, the average hourly output will deviate from the volume contracted in the futures. A decrease to an hourly average output of 8 MWh reduces the NPV by -24.17% as well as the IRR by -21.03%. The lower output from the PPA incurs more trade on DA support B, 17.21%, and less production deficit is cover by the BESS, -22.90%. The average DA price at which the BESS is discharged is -2.42% lower than the base case. Oppositely, an increase in the hourly average output to 12 MWh increases the NPV by 24.07% as well as the IRR by 21.88%. The higher output from the PPA incurs less trade on DA support B, -15.28%, and more production deficit is cover by the BESS, 21.98%. The average DA price at which the BESS is discharge is 2.04% higher than the base case. Furthermore, neither of the cases have a greater effect on the capture factors regarding for DA Support A, DA Support B and BESS charging.

7.2.6. Solar and wind power ratios

Table 28 Results for sensitivity analysis of changed ratio between wind and solar PPA. Differences from base case in parenthesis.

Metric	**50% Wind**	**100% Wind**
Profitability metrics		
Net present value (NPV)	5 760 000 EUR (–11.92%)	7 520 000 EUR (+14.91%)
Internal rate of return (IRR)	42.00% (-9.02%)	51.36% (+11.32%)
Dataset characteristics metrics		
Production volumes volatility	44.79% (+9.77%)	44.31% (+8.61%)
% hours with DA price lower than PPA price	43.41% (+6.65%)	37.52% (–7.83%)
Hedging efficiency metrics		
Share of volume deficit procured from DA as Support B	17.91% (-3.97%)	21.28% (+14.09%)
Share of volume deficit covered by dispatch from BESS	11.55% (–10.09%)	11.98% (–6.79%)
Capture factor – DA Support A	0.65 (–1.32%)	0.66 (–0.92%)

Capture factor – DA Support B	1.75 (+1.14%)	1.72 (–6.79%)
Capture factor for DA purchases for BESS charging	0.82 (–1.20%)	0.84 (+0.44%)
Avoided cost factor at discharge of BESS	1.58 (–0.13%)	1.59 (+0.42%)

When half of the contracted peak capacity from the PPAs is from wind power and a half from solar power, the system's profitability decreases by –11.92% in NPV and –9.02% in IRR. Simultaneously, the volatility of production volumes has risen by 9.77%. The percentage of hours that the spot price is lower than the price per unit in the PPA is up by +6.65%, to 43.41% of hours. The share of volume procured via DA Support B decreased slightly to 17.91% (–3.97%), and the battery was utilized for –10.09% less of the volume compared to the base case. Capture factors for procurement on the DA market show slight changes, with a decrease of -1.32% for the purchases via DA Support A, +1.14% for DA Support B, and -1.20% for purchases to charge the BESS. Avoided cost factor during discharge of the BESS decreased by -0.13%.

When all the contracted peak capacity from the PPAs is from wind power, the profitability of the system increases by +14.91% in terms of NPV and +11.32% in terms of IRR. Simultaneously, the volatility of production volumes raised by 8.61%. The share of hours that the spot price is lower than the price per unit in the PPA is down by -7.83%, to 37.52% of hours. The volume procured via DA Support B increased to 21.28% (+14.09%), and the battery was utilized for -6.79% less of the volume compared to the base case. Capture factors for procurement on the DA market show minor changes, with a decrease of -0.92% for the purchases via DA Support A. As for DA Support B, the capture factor decreased by -6.79% and increased by +0.44% for purchase to charge the BESS. Avoided cost factor during discharge of the BESS increased by +0.42%.

7.2.7. Battery storage system

Table 29. Profitability and efficiency metrics average value results for BESS parameters sensitivity analysis.

	Profitability metrics		**Hedging efficiency metrics**		
Battery	*NPV [EUR]*	*IRR*	*% deficit covered by DA B*	*Capture Factor DA B*	*Avoided cost factor during discharge*
10 MW 0.5C	5 015 227 (-23.37%)	23.47% (-49.12%)	11.70% (-37.28%)	1.78 (+2.36%)	1.63 (+2.85%)
10 MW 1C	6 204 459 (-5.20%)	39.35% (-14.71%)	18.01% (-3.43%)	1.76 (+1.51%)	1.58 (-0.33%)
5 MW 0.5C (Base)	6 544 917 (0.00%)	46.14% (0.00%)	18.65% (0.00%)	1.73 (0.00%)	1.58 (0.00%)

5 MW 1C	7 044 251 (+7.63%)	74.05% (+60.46%)	23.58% (+26.41%)	1.73 (-0.67%)	1.54 (-2.97%)
1 MW 0.5C	7 640 625 (+16.74%)	170.74% (+270.07%)	28.19% (+51.14%)	1.69 (-2.54%)	1.53 (-3.50%)
1 MW 1C	7 688 807 (+17.48%)	207.39% (+335.08%)	29.08% (+55.93%)	1.69 (-2.63%)	1.52 (-4.21%)
Without BESS	8 013 015 (+22.43%)	678% (+1370%)	31.5% (+68.89%)	1.68 (-3.24%)	–
5 MW 0.5C Without cost	8 573 095 (+30.99%)	724% (1447.81%)	18.65% (0.00%)	1.73 (0.00%)	1.58 (0.00%)

The battery energy storage system with the highest capacity and duration (10MW 0.5C) showed the highest hedging efficiency across all metrics (as shown in Table 29). In this simulation, the volume deficit procured through DA Support B was reduced on average by -37.28% and increased the avoided cost factor by discharging to 1.63 (a 2.85% improvement from the base case). However, it also demonstrated the lowest profitability. As the power and duration of the BESS system decrease, hedging efficiency decreased while profitability increased. The system without a BESS was the second most profitable option, which had a NPV of 22.43% higher and IRR of 1371% above values from the base case. In this case, the system had a higher percentage of volume deficit procured through DA Support B (up by 68.89% compared to the base case).

When the system was simulated with the base case battery of 5MW 0.5C, but without the investment cost, the NPV was at its highest at a 30.99% increase relative to the base case. Simultaneously, the IRR ascended by 1447.81% from the base case. In this case, the hedging metrics were equal to the values of the metrics in the base case, supporting the system by avoiding prices on average 58% above the average spot price.

7.2.8. Opportunity cost of BESS utilization

Table 30. Results for sensitivity analysis of opportunity cost for utilization of BESS. Differences from base case in parenthesis.

Metric	**15 EUR/MW**	**5 EUR/MW**
Profitability metrics		
Net present value (NPV)	6 520 000 EUR (-0.38%)	6 570 000 EUR (+0.32%)
Internal rate of return (IRR)	46.00% (-0.30%)	46.25% (+0.23%)
Hedging efficiency metrics		
Share of volume deficit procured from DA as Support B	16.04% (-14.00%)	21.48% (+15.16%)
Share of volume deficit covered by dispatch from BESS	12.19%	13.67%

	(-5.14%)	(+6.37%)
Capture factor – DA Support A	0.68 (+3.63%)	0.63 (-3.85%)
Capture factor – DA Support B	1.79 (+3.42%)	1.68 (-3.31%)
Capture factor for DA purchases for BESS charging	0.89 (+6.91%)	0.78 (-6.54%)
Avoided cost factor at discharge of BESS	1.65 (+4.16%)	1.51 (-4.63%)

Varying the opportunity cost of utilizing the BESS to support the system has a minor impact on the profitability of the investment. An increase in the opportunity cost to 15 EUR/MW from 10 EUR/MW in the base case results in a -0.38% decrease in NPV and -0.30% of the IRR. Also, the percentage of deficit volume managed by dispatch of BESS decreases by -5.14% when the opportunity cost is increased, while the capture factor for DA Support B increases (+3.63%). The average price at which the BESS is discharged increased to 1.65. For a decrease in opportunity cost, the opposite occurs. Profitability is slightly increased while hedging efficiency metrics show that the BESS is utilized for a 6.37% larger share of the volume deficit, during which the average avoided cost is -4.63% lower than in the base case.

Chapter 8.

Analysis

In this chapter, the results derived from the base case simulation and the sensitivity analysis presented in Chapter 7. are reviewed and analyzed together with the findings from the pre-study.

8.1. Base case

8.1.1. Profitability metrics

Given the case conditions, the profitability metric results suggest that the hedging strategy is profitable. The positive net present value (NPV) indicates that the investment is expected to generate a profit over the specified period and is, thus, potentially a sound investment. Although favorable IRR thresholds can vary depending on the industry, risks, and investment prerequisites, the IRR results indicate that the IRR for the base case simulation is significantly higher than the estimated cost of capital (or discount rate) of the actor, further indicating profitability. The low relative standard deviation (RSD) of each metric confirms that these results are stable across the iterations in the simulation.

8.1.2. Dataset characteristics metrics

The results for dataset characteristics metrics in the base case showed high volatility in both production volumes from the PPA and day-ahead market price datasets used as input in the simulation model.

Production volumes

In the base case, the mean value of the hourly PPA production output was set to 10 MW, the same as the volume of the financial contracts. Thus, the dispersion in production output indicates that there is, on average, a difference of 40.80% between the volume from PPA and the financial derivatives (volume surplus or deficit). This result indicates that despite the baseload optimization of the wind and solar production profiles, the production from the PPA is inherently volatile due to the intermittency of these production technologies. Therefore, due to volume imbalances between production from the PPA and the financial derivatives, there will be a need in the system to, during certain hours, sell the surplus and, during others, purchase or dispatch electricity to keep the hedging system in balance.

Day-ahead prices

Since the system's profitability relies on the relation between prices, i.e., the PPA prices, DA prices, and the value of financial contracts, the volatility in DA prices will impact when profitable trades can be made during the investment period. As the PPA price, on average, is 79% of the average DA price across all years (as defined by base case PPA price input data), the high volatility of the DA price explains why on average, 40.70% of all hourly DA prices are below that of the PPA price. During these hours, if there is a volume deficit, the electricity from the PPA is purchased with an opportunity cost. However, if there is a surplus, this will be sold at a loss. Additionally, as the yearly average spot prices in the base case are set to the price levels of the financial derivatives, the high volatility in spot price causes the simulation to have a spot price above the value of these contracts at 41.20% of hours simulated. Therefore, if there is a production deficit during these hours, the volume purchased on the DA market will be unprofitable.

Results show that the spot price is within the range between the price of the two contracts during, on average, 18.10% of hours of the entire investment period. In this range, the power procured via the PPA is purchased at a discount compared to market prices, while there is a risk premium between future and market prices.

8.1.3. Hedging efficiency metrics

Hedging efficiency metrics show that most of the volume for the deficit is procured profitably via DA Support A at a price of only 66% of the average DA price of the investment period. The BESS could protect against high price levels, considering that the PPA price was 79% of the average DA price. Therefore, to a certain extent, the BESS may support the profitability. However, the capture factor for DA Support B of 1.73 suggests that when the BESS is not able to protect the system in full against high prices, e.g., the battery not being fully discharged during previous hours, or insufficient rated power, the system is exposed to costly electricity purchases in the simulated investment periods.

However, although the battery could not protect against all spikes in prices, the difference between the capture factor when the battery is charged (0.83) and the avoided cost factor for when the battery is discharged (1.58) implies a high average profit for the charge and dispatch operations of the BESS.

8.2. Sensitivity analysis

In the following sections, the findings from the sensitivity analysis will be analyzed, with reference to the base case results as well as the findings from the pre-study in order to understand the significance of the results and credibility of the results.

8.2.1. Discount rate

Based on the conducted sensitivity analysis, varying the discount rate has significant implications for the profitability assessment results. Notably, the high-case discount rate of 12% leads to a significant reduction in NPV, decreasing by 20.94%. This outcome highlights the impact of risk associated with the investment, as higher discount rate reflects a higher perceived level of risk. Oppositely, a discount rate of 6% increase NPV by 26.99%. This finding suggests that a lower discount rate reduces the perceived risk and enhances overall profitability of the investment. Nevertheless, both scenarios remain profitable, indicating that the investment system and strategy possess a certain level of resilience and viability even under increased risk conditions.

8.2.2. Historical price data years

Varying the years from which historical spot price data was used in the model to simulate future spot prices indicated that depending on the dynamics of the day-ahead market, the profitability, but especially the system's behavior, was affected.

With the 2020-2022 datasets as input to the model, results demonstrated an increase in price volatility in the simulated datasets compared to base case results (which used data from 2018-2022). Using data from 2011-2017 showed a significant decrease in price volatility. These results, expected for years from 2021 and forward, have been highly associated with extreme price behavior in terms of more fluctuating and higher electricity prices, especially in the southern parts of Sweden. [1] This was also confirmed by the findings of the data exploration of spot price datasets (see Figure 16 and Figure 18).

The findings also indicated a slight association between the level of volatility and profitability. Specifically, when volatility increased, there was a marginal increase in NPV and IRR values, whereas a decrease in volatility had the opposite effect. However, the differences observed in profitability metrics were minor, suggesting that the correlation may not be particularly strong.

Dataset characteristics metrics give insight into the system’s behavior in the simulations, which may explain the effects on cash flows and profitability. For example, in the 2011-2017 spot price case, the share of hours with DA prices below PPA prices decreased drastically, from 40.70% in the base case to 16.43%, and in the case with data from 2020-2022, this value increased to 46.41%. In both cases, the share of hours with DA prices above futures prices showed an insignificant change. However, since average price levels are the same for each case, this indicates that although the share of hours with DA prices above futures price levels did not increase, the price levels during those hours are, on average higher in the 2020-2022 simulation datasets.

This can also be seen in the CF for DA Support B for the 2020-2022 spot price data, in which the average price when electricity is purchased on the DA market with prices being relatively high, is 96% above the average spot price during simulated investment periods, compared to 48% in the 2011-2017 case. This indicates that purchases made on the DA Support B to cover deficit in the 2020-2022 dataset case are more unprofitable than in the 2011-2017 case.

Furthermore, in the 2011-2017 case, a large majority (82.73%) of deficit volume is covered by favorable procurement on the DA market via the so-called DA Support A. In the 2020-2022 case, a substantially larger share of volume is procured via DA Support B (18.03% compared to 7.12% in the 2011-2017 case). This indicates that for the 2020-2022 datasets a larger share of deficit is procured unprofitably via the DA market, at a higher price than in the 2011-2017 datasets. However, since such a large share of deficit volumes are procured via DA Support A in the 2011-2017 case, the prices at which these volumes are purchased are critical to the costs in the simulated investment cash flows. The factor measured in the 2011-2017 proved to be on average 34.25% higher than in the base case at 0.88, compared to 0.55 in the 2020-2022 case. This suggests, that although the share of unprofitable trades decreased, were less costly, and the share of profitable trades increased in the 2011-2017 datasets, the profitable trades were on average less lucrative, likely effecting the cash flows of the investment and thus the profitability.

The prices that the BESS is exposed to also differ between the cases. In the 2020-2022 case, the battery is charged at prices of an average capture factor of 0.79, while the 2011-2017 average capture factor was 1.02 of the average DA prices in the investment period. Avoided cost at dispatch for each case was 1.66 and 1.43, respectively. These results show that the difference between purchased power on the DA market and the level at which the battery was dispatched was more significant in the 2020-2022 case than in the 2011-2017 case. This indicates more favorable conditions for the profitable use of the BESS in the 2020-2022 case. Similar to the profitability of energy arbitrage, in which the price differential between charging and discharging is the basis of profit, other factors, such as round-trip-efficiency, also have an impact. [5]

8.2.3. Financial contracts risk premium

These results confirms that the price premium associated with the financial derivatives has to have a direct impact on the profitability of the system. Results show that with an increased risk premium, i.e., increasing the value of the financial derivatives in the system, the profitability of the system increases since the revenue from financial contracts is higher in comparison to the costs on the DA market and via the PPA. However, oppositely, for a lower risk premium the profitability decreases.

The greater proportion of volume acquired through Support B and the BESS on the day-ahead market, coupled with reduced prices of financial derivatives, indicates that lower prices are perceived as relatively high under the day-ahead price condition, resulting in unprofitable trades. By having higher future contracts, there is more room for day-ahead prices to fluctuate while still maintaining profitability.

These changes in the relations between the prices highlights the effects of when there is a mismatch between underlying factors to prices and actual prices of the financial derivatives at a given time, i.e., the basis risk of the system. In reality, this risk is likely very low for the proposed strategy in which the power future is combined with an EPAD. In this sense, these results also highlight the importance of the EPAD for protection of the system and mitigating the risk of reduced revenue due to discrepancies between underlying assets and future contract prices.

8.2.4. Power purchase agreement prices

The sensitivity analysis conducted in this study demonstrates a significant negative correlation between changes in PPA price levels and the profitability metrics of the system. Increasing the PPA price by 20% decreases the NPV and IRR by -86.84% and -69.45%, respectively. These results indicate the considerable influence that the pricing of the PPA contracts has on the system's profitability. This impact is attributed to the increase in the number of hours during which PPA prices exceed wholesale prices on the DAM. When DA market prices are lower than PPA contract prices, the buyer pays more for electricity than they could have on the DAM, incurring an opportunity cost. Conversely, decreasing the PPA price results in a significant increase in the system’s profitability.

These results highlight the substantial impact of price risk on buyers entering into a PPA contract, emphasizing the importance of selecting an appropriate price. At the core, the role of the pay-as-produced PPA arrangement within the context of this trading strategy is to procure electricity at a discount compared to wholesale prices and financial derivatives to sell the electricity volumes with a profit. For the off-taker, the trade-off for this price discount is bearing the risks derived from the intermittency of wind and solar power generation. [4] As the relationship between prices on the wholesale market and the power purchase agreement inevitably fluctuates over the tenor of the contract, the off-taker is constantly exposed to the price risk, which may lead to pricing not being as preferable as intended at the initiation of the contract. [41] If the price level of the PPA turns out to be excessively high over time, it undermines the original intent of entering into the PPA. Moreover, in scenarios where DA prices fall below the PPA prices, procuring electricity through the PPA becomes less advantageous.

However, procurement of electricity from the PPA may not be as profitable as intended due to changes in DA prices. In that case, the off-taker is still protected with price certainty due to the fixed pricing in the contract. Depending on the purpose of implementing this trading system, this security may be preferable as it allows for planning costs and predictability in expenses. Being exposed to the DA market may be preferable price-level-wise. However, in that case, the off-taker is entirely exposed to the market dynamics rather than partially protected via the pay-as-produced power purchase agreement. For hedging against price signals, a price fixation may be especially preferable.

Avoiding this outcome by setting a price that will be preferable throughout the entire tenor period is especially complex due to the contract's longevity, the low transparency in the PPA pricing, and the effects of the cannibalization of wholesale market prices. [41] [47] During the 10-year tenor of the simulated contract, market dynamics will inevitably shift, and the risk of fixing a high price for a long tenor will exist. However, price forecasting and other mitigation methods can be deployed. Transparency in the PPA market can exacerbate price risk by making it difficult to assess market conditions and make informed decisions. Furthermore, since the off-taker of the pay-as-produced PPA is not protected from the exposure to shape risk of intermittent power production, the peak production volumes of the PPA will likely coincide with high variable renewable production in the energy system as a whole. During these hours, cannibalization of prices causes wholesale prices to decrease, meaning that a potential surplus of volume produced from the PPA may be sold at a loss, or volumes procured may be purchased with an opportunity cost.

8.2.6. Power purchase agreement average production volumes

In the base case, the average output from the power purchase agreement (PPA) corresponds to the size of the futures and the system effectively captures the price difference between PPA and future derivatives. Results from the sensitivity analysis in which the average output from the PPA is varied illustrate that higher output leads to higher system profitability. The higher average output from the PPA results in a higher excess of power relative to the contracted futures volumes throughout the investment period. Therefore, results suggest that the increase in profitability is attributed to the volume sold in the DA market. The surplus is sold at a profit when DA prices are above PPA prices, which according to dataset characteristic metrics, is the case for 59.3% of hours. Thus, for this to have been more profitable, more surplus must have been sold at a profit.

Furthermore, results demonstrated that higher output from the PPA results in a decreased share of the volume of trades on DA Support B and a more significant share of the deficit covered by the BESS. While it may seem counterintuitive that the BESS covers a more significant share of the deficit, this is because, on average, there is less deficit compared to the base case, allowing for more of the outstanding deficit to be managed by the BESS, thus increasing its share. In addition, higher output from the PPA also increased the average DA price at which the BESS is discharged. This indicates that the BESS is utilized in higher-priced hours by increasing the output.

The second case, in which the average volume output of the PPA is lower than the volume of the financial contracts, showed a decreased profitability due to the purchases made on the DA market to procure the volume deficit. As the results indicate, an increase (+17.21%) of the share of the deficit covered by DA Support B leads to higher exposure to unfavorable spot prices. When the average output is decreased, there is a greater need to cover the deficit on the DA Support B, hence decreasing the proportion of the deficit covered by the BESS. The BESS is utilized in hours with lower prices on average, suggesting that the BESS is less cost-effective in managing the deficit when the output from the PPA is reduced.

In terms of the position of the actor implementing the trading strategy, a higher PPA output results in an on average under-hedged position for the position as off-taker in the PPA, while the futures contract position is over-hedged. Specifically, the increase in excess volume to be sold increases the exposure to the prices on the DA market. Results show that an excess in production volume allows for an increased profitability due to selling electricity at a profit on the DA market. However, this is highly dependent on the prevailing conditions on the wholesale market. Inherent relationships between spot price and production volumes in the electricity system, which have been passively embedded into the system through how datasets have been inputted into the system, lead to spot prices being generally higher when output is lower. Due to this, in reality, it is likely that during hours when excess in production from the PPA is at its highest, spot prices may be at their lowest. Due to the characteristics of the simulated system, sales on the DA market were profitable, but if prices on the DA market were to drop, this volume ratio would result in a decreased profitability.

8.2.5. Solar and wind power ratios

With a 50/50 ratio between peak capacity for solar and wind production contracted via the PPA, the system's profitability decreases both in terms of NPV and IRR. Dataset characteristics metrics showed a larger share of hours with PPA prices above the spot prices due to the difference in price levels for solar and wind PPAs. Since solar PPA prices are generally higher than wind PPA prices [49], and, therefore, higher in the input parameters for the simulation, the combined price for the two PPAs per unit is, in the 50/50 case, higher due to the larger share of solar power purchased via bilateral contracts. Therefore, a more significant percentage of the spot prices will fall below this price level, as indicated by results (+6.65% of hours). This means that, in this case, electricity purchased through the PPAs will more often be purchased with an opportunity cost, impacting the system's profitability. Dataset characteristics metrics show that the simulation based on this ratio between solar and wind results in higher volatility than the base case. Since the ratio in the base case was based on an optimization for achieving a baseload profile, increased volatility when ratio change was expected.

How electricity is obtained to handle deficit has shifted slightly in the 50/50 simulation compared to the base case. Less electricity is procured via DA Support B (-3.97%), and the volume of deficit managed by dispatching from the BESS decreased by -10.09%. The mechanisms dictating when and how production deficit is handled impacted by prices not affected by this simulation (i.e., price of financial derivatives and spot prices, see equation 3.2). This suggests that there has been a change in the amount of average volume deficit that the system includes. Either the deficit during lower spot prices has increased or the deficit during high price hours has decreased. The normalized monthly scale factors used in the generation of input datasets for the spot prices sampling model (see Table 6) show that the highest average monthly prices used in the simulation are found during the end of the year (August, September, and December) and lowest during the first half of the year (January, February, and April). This trend of the price data is confirmed by Figure 24, which illustrates an example of how spot prices vary during a simulated investment period in the base case. Solar power generation generally has a higher production during summer months and lower during winter months, as shown in data exploration (see subsection 4.1.2. Data exploration). Since solar power generation volumes are the lowest during both the highest and lowest-priced months in the simulation, the explanation for the decrease in DA Support A volumes is likely an increased deficit during low-price months in the simulation.

The second case, in which it is assumed that all of the power contracted in the PPA comes from wind power, increases profitability in terms of NPV and IRR. In contrast to the case with a 50/50 ratio of solar and wind, the price per unit of power in the PPA is lower since the PPA price is lower for wind power than solar power. This results in a reduced share of DA prices falling below the PPA's. With fewer hours of DA prices below the PPA, more profitable trades become possible, thus positively impacting profitability. Regarding the volatility of production, a 100% wind share, similar to the 50/50 ratio, increases as expected.

Furthermore, a higher share is procured through DA Support B during deficit periods than in the base case. This suggests that more periods of low production from the PPA coincides with higher DA prices. However, when examining the monthly characteristics of wind production and DA prices, there does not appear to be a correlation between high and low wind production. Instead, the increased share of deficit procured from DA Support B may be explained by the relationship between daily patterns in production volumes and spot price level (as shown in Figure 12 and Figure 20 respectively). Data exploration showed that wind production is lowest between 7 am and 10 am, which aligns with a price increase in DA prices during the same hours. Additionally, the lowest production from wind within the day generally occurs at 8 am, corresponding to the highest hourly DA price. Therefore, the hourly production patterns from wind may explain why a larger share of the deficit is procured through DA Support B. Furthermore, the BESS is utilized for a smaller portion of the deficit than the base case. This could be attributed to an increased total deficit volume, reducing the share of the BESS. However, it may also be explained by more extended periods of deficit.

With increased volatility, shape risk regarding the power supplied from the PPA also rises. When there is higher production volatility, the renewable energy project's output is subject to more significant fluctuations and deviations from expected levels. The higher the volatility in production, the more difficult it becomes to accurately forecast and plan for the renewable energy project’s output. [47] This uncertainty introduces additional risks for the off-taker, in our case the implementer of the trading strategy, as they may need to adjust and adapt to accommodate the fluctuations in electricity generation.

8.2.3. Battery storage system

The results from the sensitivity analysis in which the BESS was varied indicate that a larger capacity leads to more beneficial use of the battery, having fewer unfavorable trades on the DA Support B. Results also indicate that battery systems with longer durations are better at protecting the system from higher electricity prices, as indicated by the lower share of volume procured through DA Support B and a higher average price on the DA market when the battery is discharged. With a longer duration, the BESS can be discharged for more consecutive hours of high prices, potentially protecting against higher price spikes. These effects also seem to decrease as the power of the BESS decreases, as can be seen by comparing the differences in values for efficiency metrics for the 10 MW 0.5C and 10 MW 1C, with the difference between the less powerful battery systems of 1 MW 0.5C and 1 MW 1C. Similarly, volume shares change as the duration of BESS is changed. For instance, a slightly lower volume share procured on the DA Support B can be observed using a 1 MW 0.5C rather than a 1MW 1C. However, this difference is less prominent than in the 10 MW systems. Furthermore, the difference in the capture factor and average DA cost factor becomes negligible.

Since higher capacity and longer duration result in being able to dispatch the BESS at hours of higher spot prices, the lower profitability for the battery with large capacity and longer duration must result from the higher investment cost needed to purchase the BESS. Despite prices per MW decreasing with increased power and duration, the total investment cost increases as power increases. The total investment cost for the 10 MW 0.5C battery is approximately 6.47 MEUR, compared to the 1 MW 1 C battery cost of around 6.70 MEUR. For reference, these values correspond to 98.86% and 10.25% of the total NPV of the base case, respectively. For this reason, the case without a BESS is more profitable than all cases with a BESS, despite the lower protection. Given the circumstances modeled in the simulations (e.g., spot price levels and volatility), the BESS is not profitable enough to justify the investment costs. These results align with the findings of the pre-study, which revealed that in most European markets, the current capital costs for BESS are too high and would need to decrease, or there would need to be an increase in the need for balancing supply demand and price variability. [59] [60] However, if the expected decreases in BESS prices in the next decade transpire [61] [62], these results indicate that this would increase the profitability of the system.

The impact of the battery without CAPEX can be investigated by comparing the results from the case without a BESS and the case without any investment costs for the BESS. The difference in profit between the case with a 5 MW 0.5C battery without an upfront investment cost and the case without a battery, was indicated by the 560 080 EUR difference in NPV. Since the only difference between these two cases is the addition of the battery system, this value indicates that the cash inflows generated by the battery can provide additional revenue to the system when CAPEX is not included. This is for instance the case when the actor engaging in the trading strategy already owns the battery.

8.2.4. Opportunity cost of BESS utilization

The analysis of the impact of opportunity cost on the system's profitability reveals that profitability slightly increases with a decrease in opportunity cost and slightly decreases with an increase in opportunity cost.

For the simulation of hourly energy and cash flows in the model, the opportunity cost directly impacts when the system deems DA prices relatively low or high, i.e., when it is preferable to purchase electricity from the wholesale market. When the opportunity cost is higher, the spot prices must be higher for the system to dispatch the battery. This is confirmed by the difference in the share of times the battery was used. The BESS covered 13.67% of the volume deficit when the opportunity cost was 5 EUR/MW, and 12.19% was 15 EUR/MW. Simultaneously, the average avoided cost when dispatching the BESS is 4.16% higher with a higher opportunity cost. Despite its lower average dispatch volume during the simulated investment periods, the BESS effectively safeguards against higher prices. These results demonstrate that varying the opportunity cost within a feasible range enhances profitability by enabling greater protection against intensified price spikes.

Although the impact of this parameter is relatively small compared to others affecting the system, further increases in opportunity cost may continue to improve profitability by allowing the BESS to manage price volatility better. Nonetheless, at a certain point, the opportunity cost may be increased to an extent which may lead to the BESS being used too infrequently, ultimately reducing its contribution to system profitability.

8.3. Key takeaways

Base case

The base case demonstrates a remarkably high level of profitability. Despite employing baseload optimization techniques, the production datasets remain relatively large. This indicates that the business is operating efficiently and generating substantial profits. The prices in the day-ahead market exhibit significant volatility. This volatility affects the optimal range between Power Purchase Agreements and future contracts. Approximately only one in five hours experiences spot prices within this optimal range. The battery storage system plays a role in protecting against price spikes. However, it is important to note that it may be inadequate in safeguarding against the highest price spikes.

Sensitivity analysis

Financial contracts risk premium – Increasing the risk premium associated with financial derivatives leads to higher profitability, while a lower risk premium decreases profitability. Mismatched correlations between derivative and actual prices can introduce basis risk, impacting profitability.

Power purchase agreement prices – Increasing PPA prices negatively affect the profitability of the system, while decreasing PPA prices increase profitability. The selection of an appropriate PPA price is crucial, considering the trade-off between price certainty and exposure to market dynamics.

Battery energy storage systems – Larger capacity and longer duration of the BESS improve system profitability by reducing unfavorable trades and protecting against high electricity prices. However, the investment costs of the BESS can outweigh the benefits, making the case without a battery more profitable. Decreases in BESS costs in the future could increase system profitability.

Opportunity cost – Decreasing the opportunity cost improves profitability, enabling greater protection against price spikes. However, excessively high opportunity costs may reduce BESS's contribution to profitability by limiting its usage.

Discount rate – Varying the discount rate significantly affects profitability. Higher discount rates decrease net present value, indicating higher perceived risk, while lower discount rates increase NPV and enhance profitability.

Volume ratio – A higher average output from the PPA increases system profitability by selling excess power at a profit. It results in a decreased share of trades on the DA-market and a higher share of the deficit covered by the BESS. Conversely, lower average output from the PPA decreases profitability and increases exposure to unfavorable spot prices.

Historical price data years – The choice of historical price data affected price volatility, system behavior, and profitability. However, the impact on profitability was minor, suggesting a weak correlation. The 2020-2022 datasets showed higher volatility, more unprofitable trades during deficits, and more favorable conditions for the BESS.

Chapter 9.

Discussion

This chapter discusses the methodology applied for this thesis project and how the results were generated. After that, the writers of this thesis share their thoughts and reflections regarding the outcomes and the strategy in general. The chapter is concluded with a section highlighting areas for potential future research and a section summarizing the conclusions of this thesis concerning the research questions defined in Chapter 1.

9.1. Methodology discussion

The specific purpose and objectives of the study drove the methodology selection. However, various alternative approaches and methods could have been pursued instead. In this section, a thorough discussion of the methodology choices made is presented. This is done by evaluating the effectiveness in addressing research goals, suitability for the research context, and potential implications they may have had on the obtained results and subsequent conclusions.

9.1.1. Research design

The research questions and objectives of the project guided the chosen methodology for this master thesis. A mixed-method approach was selected to combine the strengths of qualitative and quantitative research methods to gain a more comprehensive and nuanced understanding. While a quantitative method was the natural choice for assessing the profitability of the system, the complexity of the system, its elements, and the limitations of constructing a fully accurate model posed challenges. Therefore, embedding qualitative research with quantitative research was deemed appropriate to improve the reliability and validity of the findings.

However, a challenge in implementing the embedded design approach was fully integrating qualitative findings with quantitative ones. Due to the lack of available resources on the investigated topic, applying the embedded design effectively was more difficult than expected. Additionally, using an embedded design requires careful consideration of the balance between the quantitative and qualitative components of the research so that one method does not overshadow or undermine the other. It is important to ensure that the qualitative data collected is relevant and provides useful insights into the overall research question while effectively integrating it with the quantitative component. For the purpose of this research project, the embedded design was chosen to prioritize the quantitative methods while still implementing qualitative findings. However, given more time, another type of mixed-method research could have been used in which the qualitative findings are acquired, analyzed, and integrated with quantitative results in a more structured manner.

9.1.2. Simulation of the system

This section discusses how different parts of the system were modeled. Furthermore, the choices made in the simulation of these values are discussed, including how data was collected and processed, how the model handled this data, and the potential impact on the results.

Spot price simulation

The system highly depends on spot price data for each hour in the simulated investment period. For this reason, the way in which forecasted spot prices are generated is vital for the reliability of the model and its results. The chosen method to predict spot prices is heavily simplified compared to forecasting methods used by different stakeholders in the energy industry. However, as explored in

3.2.3. Day-ahead market prices, forecasting spot prices are generally associated with high levels of uncertainty and complexity. Our model modeled spot prices based on historical monthly and hourly price trends and on forecasted yearly average spot prices.

The dependency on prior price levels, however, has limitations since it assumes that past seasonal price patterns represent those of the future. If historical price patterns do not accurately represent the patterns of coming years, there will undoubtedly be large discrepancies between real price levels and modeled ones using this method. Specifically, calculating monthly average weights to generate each hourly value in the simulation model may limit the model's generalizability, as it will only exhibit the same patterns of the years used as input data. Therefore, predictions made by the simulation model may have an inherent bias. Especially since the monthly weighted averages are used to simulate prices for each year in the investment period, which leads to each modeled year following the same underlying monthly price trend.

Findings from the data exploration and qualitative pre-study (presented in *Chapter 3. Theory and pre-study findings*) indicated that discrepancies between historical patterns and future ones might be the case. Investigation of historical prices in subsection *4.2.2. Data exploration* of spot prices indicated that price patterns in recent years differ from patterns found back in time. During the years affected by the global energy crisis, not only did price levels and volatility increase but also the monthly averages seem to deviate from monthly patterns of the past, with high prices during winter and low during summer in a more unpredictable manner (see Appendix A).

Daily price trajectories, however, were shown in the data exploration of spot prices to have a more consistent shape across data from all years, and the price range from an hour to hour within a day was larger in more recent years (2018-2022) than in years prior (2011-2017). However, in the sensitivity analysis, the impact of generated price data from different periods indicated a minor effect on the NPV and IRR of the model. The price data from 2011-2017 represents the often-attributed characteristics of spot prices following the seasons, and the price data from 2020-2022 deviates more from these common attributes. Further, external research through the pre-study concluded that spot prices in the future are expected to diverge from their seasonal predictability and instead be more affected by supply and the dynamics within the generation side of the electricity system due to the incorporation of more variable energy sources.

Accordingly, there may be more suitable methodologies to model and forecast hourly spot prices than the method chosen. This could include considering whether the model should incorporate seasonal trends or explore other dynamic price trends over the investment period, enabling a more precise simulation of price behavior over the extended timeframe. Furthermore, as explored in the pre-study section, more key drivers of the electricity prices could be incorporated as input, such as demand and weather forecasts, fuel costs, and production expectations, to capture better the influence of additional factors that affect price dynamics.

Production simulation

Production volumes entered into the system via the PPA contracts are simulated by using monthly and hourly trends in production volumes for both solar and wind based on the findings from the pre-study and the data exploration. Both investigations confirmed that wind and solar have tendencies on an hourly and monthly scale, meaning that the sampling on these time scales was appropriate for maintaining these inherent patterns.

The output values for each location were combined by applying a weighting technique that minimized the standard deviation. This approach aimed to filter out potential outlier values and reduce the impact of varying production between geographical locations to derive a more generalized output. Increasing the locations from which raw data was collected could have further minimized this effect. Additionally, incorporating data from more years would have reduced the influence of yearly variations and exceptional values. However, it was determined that the yearly differences in production had a lesser impact on production values compared to spot price data.

In addition to how the data was handled, the characteristics of the raw data itself did influence the simulations. Solar and wind data collected from Renewable.Ninja displayed distinctively high capacity factors, especially for the wind data (see Table 3), compared to the capacity factors presented in *3.1.2. Production characteristics*. The reason for these high capacity factors is that uncorrected data for production volumes was used instead of corrected values. More accurate data would have provided lower capacity factors for the two production technologies. However, it can be argued that the effect of higher capacity factors does not greatly affect the outcome of the simulated model. A higher capacity factor results in a higher output per MW. However, data is scaled up in the model by the input parameters for contract capacity, which were determined based on achieving a certain average output. Therefore, the contracted capacities set as input would likely be higher if data with lower capacity factors were used. However, the average output in the model would have been the same. The capacity factors do, however, impact the optimized ratio between wind and solar for baseload profile by use of equation (3.5). As the capacity factor for the wind was higher in relation to its explored value, compared to the difference for solar, the use of corrected and more realistic data would have resulted in a greater share of wind in the optimized ratio. As sensitivity analysis results showed, this would have decreased the average price of power contracted via the power purchase agreement. In turn, the results likely would likely show higher profitability.

Hourly mechanisms of the system

The hourly flows model was built using defined conditions to simulate using the battery storage system effectively and trading on the DA market. However, the way the hourly flow model was constructed, and the simplifications made may have impacted the accuracy of the results.

The cash flows are simulated hourly, including revenue from future contracts and costs for electricity procurement via PPA. However, the settlements for these contracts are, in reality, not necessarily on an hourly basis. The futures explored in this study, traded via Nasdaq, have a daily mark-to-market settlement, and the settlement for the PPAs may vary depending on contract specifications. However, the generalizations to hourly settlement capture the true value of each trade and enable the construction of a system that acts on an hourly basis. Furthermore, simulated production output from the PPA was always assumed to be correct, meaning there was no need for the system to act on markets closer to delivery since its projections were accurate. However, their intermittency is a significant factor in the production technologies of the PPAs. Projected output bided on the DA market may deviate from the actual output the day after, resulting in a need to trade in balance. How this might affect the model does fall to the specifications of the PPAs. Depending on the terms of the contract, balancing responsibility might fall on the seller of the PPA or the off-taker. However, simulating these probable imbalances in output was deemed to be outside the scope of this report, which solely focused on the DA market.

Moreover, as indicated by the results, integrating a BESS provided additional value to the system. However, the considerable investment cost of the BESS offset this added value. Nonetheless, it is worth noting that the modeling of the battery's utilization could potentially have been improved to enhance the overall added value. For instance, the input data regarding investment prices and the simulated conditions on the spot market depend on how the mechanisms defined by the BESS were utilized. In the modeling of the system, the use of the battery was not optimized. Instead, it followed a predefined condition as to when it is put in use based on the price of financial contracts and the opportunity cost of the battery (see section *5.2.5. Hourly flows model*). The system is modeled to use the BESS once the threshold for relatively high spot prices is surpassed. Consequently, during an increase in DA price spanning across multiple hours, the BESS may only be able to mitigate the impact of the beginning of a price jump (the exact number of hours depending on the duration and available capacity) when the DA price still is increasing and still have not peaked. Therefore, had the use of the battery been simulated more efficiently, the system's profitability may increase. However, in the variation of opportunity cost in the sensitivity analysis, the threshold for when the BESS was put into use was effectively shifted. In this way, the increasing opportunity cost acted as a quasi-optimization of the BESS within the model, allowing the battery to be used more effectively. As indicated by the results, the higher opportunity cost contributed to increased profitability, however, only slightly. The results indicate how further optimizing the battery's use may affect the system's profitability. Hence, when implementing this usage case for a BESS, in addition to others, such as ancillary services, the effective use of the battery is vital to maximizing its value.

Furthermore, the model simplified the battery utilization, assuming no degradation and no decreased round-trip efficiency. These factors likely impacted the battery's performance. With added degradation, the battery would experience a gradual loss of capacity and efficiency over time. This reduction in capacity affects the amount of energy that can be stored and subsequently released during a charging and discharging cycle, thus influencing the round-trip efficiency. As noted in the findings from the pre-study, studies have shown that these factors may significantly impact the economics of battery storage systems. Had these factors not been omitted from the model, the battery's profitability and ability to protect against unpreferable purchases on the DA market would likely have been lower.

Assessment of simulations

The assessment model aimed to give insight into the profitability of each iteration within each simulation case and provide insights about system behavior and mechanisms. Discounted cash flow and the profitability metrics NPV and IRR were chosen as they complement each other to achieve a comprehensive framework for the financial analysis of the system. However, these profitability evaluation methods rely on the certainty of the simulated cash flows and the inputs into the model. They are also heavily dependent on the estimation of the discount rate, as it reflects the risks associated with the investment. Other methods of evaluating profitability, such as payback period and return on investment (ROI), could have also been suitable choices. Nevertheless, with regards to long-term investment objectives, discounted cash flow analysis with NPV, complemented with IRR, was considered suitable as it takes into consideration the time-value of money, permits risk adjustment through the utilization of discount rates, and provides a comprehensive overview of cash flows throughout the investment period.

The metrics used to investigate the characteristics of the inputted datasets as well as the hedging efficiency, were developed with the aim to obtain a greater understanding of what occurs within the simulated system, beyond the financial perspective. These were useful in understanding why certain changes to systems inputs effects profitability results. However, these metrics could have been defined differently. For instance, volatility in production and spot price datasets was quantified by use of relative standard deviation (RSD) due to its simplicity and interpretability. Other methods for measuring these dynamics might have been more accurate or indicated other results. Furthermore, in order to gain an even greater and more in-depth understanding, other metrics could have been incorporated into the assessment of the system. For instance, share of hours or volume throughout the simulated investment period during which the system experiences a production deficit between PPA output compared to volume of financial contracts, could give insight into how often electricity needs to be procured in another way.

9.1.3. Application of the model

To generate results, the model was applied on multiple scenarios in which input parameters were first determined for a base case and then varied according to the one-factor-at-a-time (OFAT) sensitivity analysis method. This method allowed for identification of individual effects on the model's output by systematically varying each input parameter. The analysis of the base case assumed that the cash flow estimations were correct, disregarding the possibility of potential inaccuracies. Therefore, conducting a sensitivity analysis was crucial to identify the inputs that have the most significant impact on the profitability of the system and assess how robust the results are to variations of those inputs.

Sensitivity analysis method

The OFAT method was chosen as it minimized the number of simulations to be run, since the model required long run-times for the completion of one simulation. However, one of the limitations of the OFAT method is that it does not consider the interdependencies and interactions between parameters. By varying one parameter at a time while keeping others fixed, it fails to capture the combined effects of multiple factors. This approach may not fully reflect the behavior of the system, as variations in multiple parameters can lead to interactions and synergy effects that may be overlooked in an OFAT analysis. Other sensitivity analysis techniques could offer complementing and additional benefits. For instance, multivariate sensitivity analysis, in which multiple input parameters are varied simultaneously, would allow for catch the interactions between parameters in the results

The results are also heavily influenced by the values each parameter is varied by. Therefore, it is essential to ensure that the chosen values are based on reliable information and realistic assumptions. This helps to maintain the integrity and credibility of the analysis. Although values were based on existing data and consulted with supervisors at the company as well as with the university supervisor there is risk for inherent bias and incorrect assumptions. This probable bias, stemming from the definition of the values could be mitigated using stochastic methods such as Monte Carlo simulation. However, the time limit as well as computational inefficiency of the model limited the possibility of implementing these methods in this thesis.

9.2. Reflections

9.2.1. Profitability results

The results from the simulation model demonstrated that the proposed trading strategy would yield high profitability, both for the presented base case and across all the outcomes generated through the sensitivity analysis. However, the results assume that the simulation of the cash flows are correct, and that the assumptions made as well as the inputted data, accurately represent the system. The difference in price levels between PPA and futures contracts, as defined by input variables, had an innate impact on the high profitability throughout the results.

Therefore, due to the inherent bias, the actual values of results for profitability metrics should be viewed with discretion rather than absolute certainty. However, changes observed in the sensitivity analysis serve as indicators of the system's behavior and its most impactful factors.

Multiple factors and decisions in the execution of the model and generation of results may explain these high values. Some of the assumptions made to simplify the construction of the model could have contributed to an overestimation of profitability compared to actual implementation of the trading strategy. Notably, the neglect of certain costs, such as transaction costs associated with financial trading, operational and management costs for the battery storage system, administrative expenses involved with setting up the PPAs, as well potential imbalance costs that may arise. Additionally, the exclusion of degradation and round-trip-efficiency, results in the battery being used more efficiently in the model compared to in real life.

9.3.2. Purpose of the system

The system investigated in this thesis is in essence a combination of different trading and hedging mechanisms, commonly used to protect against price risks by various actors. The cornerstone of the system is the trade of power via financial contracts and making a profit doing so without own production of electricity rather operating in the electricity markets to be able to do so. The power purchase agreement and battery energy storage systems are in this sense two elements which are employed to protect against and minimize the risk of this position.

The purpose of each element, and the approach by which an actor can implement this type of strategy and how results should be interpreted, will therefore depend on the overall aim and role of the actor. As discussed previously, there are various risks associated with this system. Depending on the purpose of implementing this strategy, the risk appetite of the actor may vary. Specifically, the actor can take a speculative role, meaning the actor is more willing to accept the potential for both substantial gains and losses, or choose to minimize risks and take a position in which they are hedged to a greater extent. In this sense, the strategy could be seen as a risk management technique, utilizing multiple methods to protect against potential financial losses. Therefore, in reality, neither the power purchase agreement nor the battery storage system is indispensable for the purpose of revenue generation. An actor can approach each choice in designing this trading strategy to determine their approach.

To exemplify, the incorporation of a battery energy storage systems did negatively affect the profitability of the strategy due to its capital expenditure, although the results indicated that the usage of such a system did contribute to improve profitability of some trades and to some regard protect against price spikes. Therefore, our results do not motivate the investment of battery systems for the sole purpose of using them for this type of strategy. However, depending on the context and the intentions of the owner of the battery system, the use of a battery system for this purpose may not require complete financing of the battery. As previously explored, installed storage capacity in Sweden will be needed in the implementation of more variable renewable sources. In this transition, revenue generation and bankability of BESS will be imperative and although the current rise in installed capacity primarily been driven by use on ancillary markets, use on other markets and varying business models for BESS will likely be a part of the future energy system. Although implementing BESS on day-ahead markets may not currently be as lucrative as ancillary service markets, our research indicates that utilization on the DA market still holds value. This approach could potentially enhance generation of multiple revenue streams and services through value stacking to maximize the economic benefits and overall value derived from a battery storage installation. Consequently, instead of relying solely on a single application or market, value stacking enables BESS to simultaneously participate in and provide multiple grid services. Furthermore, value stacking offers a degree of protection against decreases in profitability of a specific revenue stream or market. For instance, as more participants enter the ancillary market seeking similar returns, saturation of the market becomes a possibility. By diversifying revenue streams, value stacking mitigates the impact of a decline in one market. This strategy is particularly relevant for actors like Flower, who aim to generate profitability by leveraging multiple markets and business models with existing battery systems rather than relying solely on one market, especially considering profitability in the long-term.

Furthermore, the role of the power purchase agreements can also be questioned and changed depending on the intentions of the actor. Our findings show that due to the large price premium of financial derivatives compared to current power purchase agreement prices, considerable profitability can be found in using power purchase agreements to partially supply necessary electricity to trade the financial derivatives. However, it would be possible for the actor to exclude the PPAs from the system and depend entirely on procurement from the day-ahead market. For instance, this could be motivated by the expected decrease of DA prices due to cannibalization. Conversely, the actor could actively choose to assume an asymmetric position in terms of volume procured by PPAs and sold in futures contracts, in which they would deliberately expose themselves to a higher level of price risk, in order to potentially generate higher profits based on their anticipated future price levels. Since the output from the PPA is variable, the actor is always to a certain extent exposed to this risk, however, they can choose to minimize it or capitalize on it. Implementing this will be a process of defining which risks the actor is both willing and able to take.

Chapter 10.

Conclusions

In this final chapter, the conclusions from this thesis are summarized, specifically regarding the research questions and the main conclusions drawn from the study. In addition, it suggests promising directions for further exploration of the topic.

10.1. Answering the research questions

This master thesis aimed to answer two research questions; if the proposed trading strategy could be profitable and how the characteristics of the elements within the system would affect the profitability. These questions were addressed by constructing a mathematical model to simulate the strategy as a system for a 10-year investment period and estimate cash flows. The model was applied to a base case scenario and further analyzed through sensitivity analysis, where individual parameters were systematically varied and evaluated.

What is the level of financial feasibility for the proposed strategy in terms of profitability?

To address this research question, a base case scenario was defined, which involved the application of input parameters anticipated for implementation in the near future. The results from both the base case and sensitivity analysis consistently revealed a substantial level of profitability, as evidenced by the assessed profitability metrics. These findings strongly indicate that the trading strategy has the potential to generate favorable returns.

However, it was acknowledged that the profitability results found are highly dependent on the input parameters entered into the simulation model. Although these parameters were considered feasible based on pre-study findings and were determined in part in collaboration with domain experts and supervisors, they may contain inherent biases and uncertainties. Therefore, although the thesis provides strong evidence that the trading strategy is profitable, it emphasizes the need to carefully choose and fine-tune the input parameters for reliable and consistent results. Future research should conduct tests with a broader range of parameter values to improve our understanding and confidence in the strategy's profitability.

How do the individual components and their respective characteristics impact the profitability of the proposed strategy?

This question was explored through sensitivity analysis, where input parameters varied. Findings showed that the most impactful parameters were the price levels of the power purchase agreement and futures contracts, and investment costs for the battery storage system.

The analysis highlights the crucial role of the price discrepancy between procured electricity through Power Purchase Agreements (PPAs) and future contracts in ensuring the system's profitability. The current price discount compared to day-ahead prices of power purchase agreements and the risk premium associated with futures contracts are, therefore, essential to the profitability of this system. Any shifts in the relationship between these prices, driven by market dynamics, could potentially undermine the viability of implementing this strategy.

Additionally, while incorporating Battery Energy Storage Systems (BESS) offered some protection against price spikes, the research findings revealed that the system was more profitable without a BESS due to its significant investment costs. Therefore, based on the findings, investing solely in a storage system is not advisable unless there is a significant decrease in costs in the future. However, incorporating a storage system could serve as an additional revenue stream for an existing system. Also, without the BESS, the actor is more exposed to the price dynamics and variability of the day-ahead market.

The analysis revealed that other factors also influenced profitability. Importantly, procuring a larger volume through power purchase agreements than the volume sold on financial markets resulted in higher profitability, mainly due to the price relationship between PPAs and the day-ahead (DA) market. Additionally, a slight correlation between volatility and profitability was observed, indicating that Battery Energy Storage Systems (BESS) had more favorable opportunities during periods of increased volatility. However, it is essential to note that these results heavily depend on the price dynamics incorporated into the model through input parameters and datasets.

10.2. Future research

This thesis has provided valuable insights into the proposed trading strategy and has shed light on several important aspects. However, there are still avenues for further research that would enhance our understanding and contribute to advancing knowledge regarding this strategy and its components. In the list below, we outline potential directions for future investigations that can build upon the findings of this study.

- *Further explore the interrelations within the system* – The sensitivity analysis used an OFAT method, hence only exploring case by case. Therefore, further efforts can be made to explore the interactions between the input parameters. Moreover, additional effort can be made in optimizing the utilization of the BESS, both regarding identifying hours with the most significant price spreads and considering the state of the BESS, its degradation, and its cycle life.
- *Further, explore the profitability of the BESS* – The study primarily investigates the holistic profitability of the system. By isolating the profitability of the BESS in the system, more conclusions of periods when the BESS is more profitable, may be drawn. This could include additional factors impacting BESS performance which were omitted in this study, such as degradation and round-trip-efficiency. Moreover, it would be interesting to incorporate the BESS against other markets, such as the intraday market,

to compare with the results from this thesis and to consider and evaluate other BESS-use cases.

- *Further, explore market behaviors* – Spot price volatility is expected to keep increasing coming years. Therefore, efforts can be made by exploring how an increasing spot price volatility affects the systems' profitability. Furthermore, the emerging cannibalization effect is not considered in the model. This field is of increasing interest to market actors affected by the phenomenon. Hence, the incorporation of the cannibalization effect in the model could be done to see how this affects the profitability of the system as well as the business case for the BESS.

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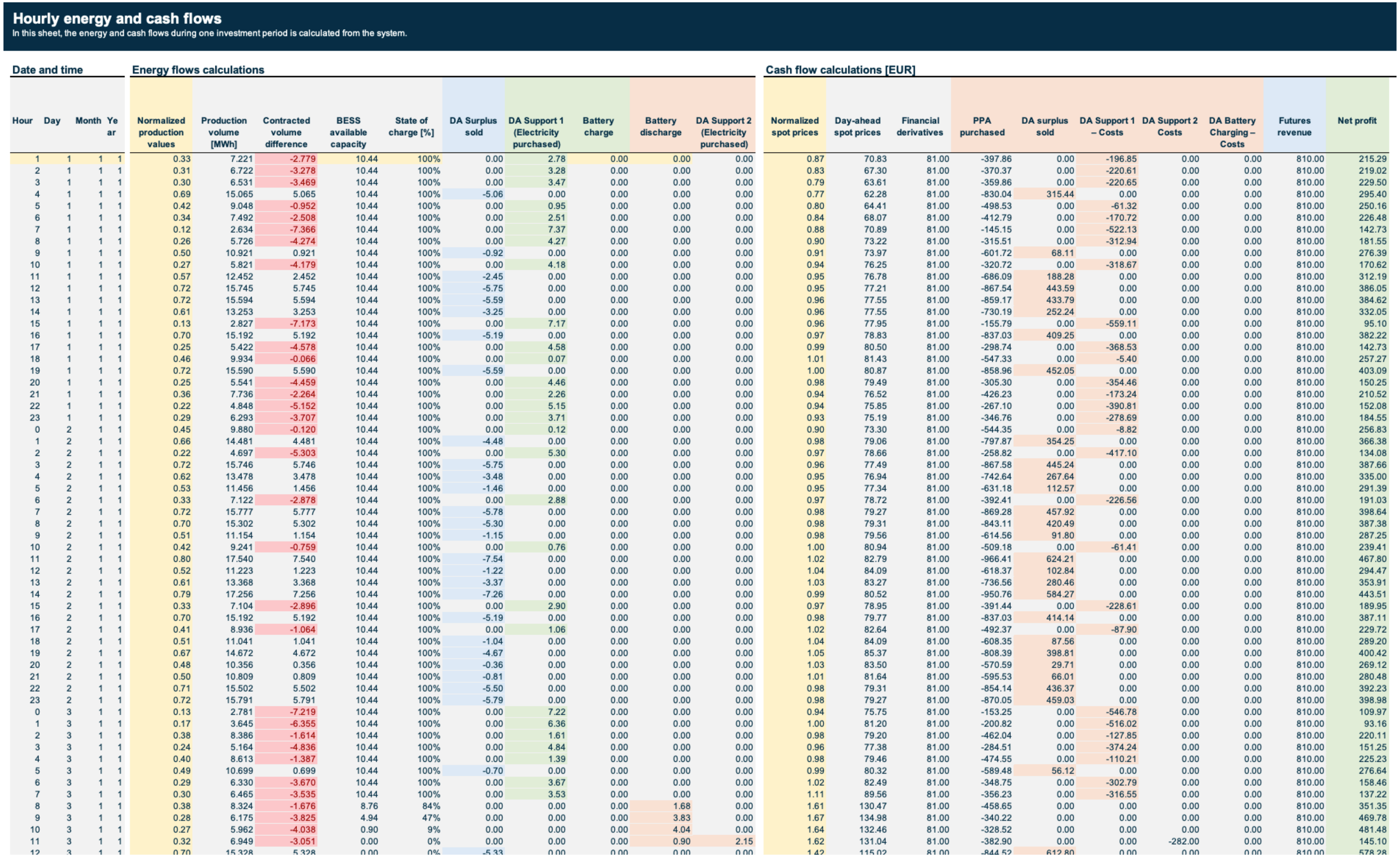
Appendix A. Normalized monthly average spot prices per year 2011-2022.

Months	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
2011	1.438	1.331	1.305	1.106	1.123	1.001	0.821	0.869	0.662	0.63	1.029	0.71
2012	1.118	1.542	0.869	0.988	0.935	1.031	0.564	0.814	0.878	1.016	0.987	1.289
2013	1.057	0.99	1.113	1.102	0.925	0.862	0.876	1.011	1.15	1.06	1.003	0.852
2014	1.044	0.981	0.856	0.852	1.1	1.015	0.935	1.085	1.146	0.981	0.965	1.036
2015	1.33	1.359	1.158	1.123	1.018	0.879	0.401	0.729	0.96	1.081	1.14	0.861
2016	1.049	0.673	0.756	0.751	0.803	1.143	0.983	1.033	1.003	1.241	1.392	1.161
2017	1.056	1.062	0.95	0.91	0.923	0.87	0.96	1.054	1.148	1.001	1.075	0.996
2018	0.709	0.878	0.97	0.84	0.771	1.005	1.148	1.205	1.088	1.105	1.163	1.11
2019	1.38	1.158	0.993	1.003	0.905	0.696	0.938	0.971	0.918	1.058	1.063	0.922
2020	1.02	0.718	0.617	0.531	0.542	0.936	0.884	1.563	1.378	1.017	1.338	1.443
2021	0.618	0.669	0.56	0.527	0.593	0.907	0.845	1.039	1.498	1.072	1.386	2.263
2022	0.695	0.523	0.957	0.724	0.873	1.117	0.759	1.902	1.476	0.488	0.813	1.631
2018-2022	0.783	0.69	0.845	0.712	0.773	0.991	0.862	1.474	1.357	0.813	1.063	1.613

Appendix B. Hourly flows model in Excel



Hourly energy and cash flows

In this sheet, the energy and cash flows during one investment period is calculated from the system.

Date and time				Energy flows calculations										Cash flow calculations [EUR]									
Hour	Day	Month	Year	Normalized production values	Production volume [MWh]	Contracted volume difference	BESS available capacity	State of charge [%]	DA Surplus sold	DA Support 1 (Electricity purchased)	Battery charge	Battery discharge	DA Support 2 (Electricity purchased)	Normalized spot prices	Day-ahead spot prices	Financial derivatives	PPA purchased	DA surplus sold	DA Support 1 – Costs	DA Support 2 Costs	DA Battery Charging – Costs	Futures revenue	Net profit
1	1	1	1	0.33	7.221	-2.779	10.44	100%	0.00	2.78	0.00	0.00	0.00	0.87	70.83	81.00	-397.86	0.00	-196.85	0.00	0.00	810.00	215.29
2	1	1	1	0.31	6.722	-3.278	10.44	100%	0.00	3.28	0.00	0.00	0.00	0.83	67.30	81.00	-370.37	0.00	-220.61	0.00	0.00	810.00	219.02
3	1	1	1	0.30	6.531	-3.469	10.44	100%	0.00	3.47	0.00	0.00	0.00	0.79	63.61	81.00	-359.86	0.00	-220.65	0.00	0.00	810.00	229.50
4	1	1	1	0.69	15.065	5.065	10.44	100%	-5.06	0.00	0.00	0.00	0.00	0.77	62.28	81.00	-830.04	315.44	0.00	0.00	0.00	810.00	295.40
5	1	1	1	0.42	9.048	-0.952	10.44	100%	0.00	0.95	0.00	0.00	0.00	0.80	64.41	81.00	-498.53	0.00	-61.32	0.00	0.00	810.00	250.16
6	1	1	1	0.34	7.492	-2.508	10.44	100%	0.00	2.51	0.00	0.00	0.00	0.84	68.07	81.00	-412.79	0.00	-170.72	0.00	0.00	810.00	226.48
7	1	1	1	0.12	2.634	-7.366	10.44	100%	0.00	7.37	0.00	0.00	0.00	0.88	70.89	81.00	-145.15	0.00	-522.13	0.00	0.00	810.00	142.73
8	1	1	1	0.26	5.726	-4.274	10.44	100%	0.00	4.27	0.00	0.00	0.00	0.90	73.22	81.00	-315.51	0.00	-312.94	0.00	0.00	810.00	181.55
9	1	1	1	0.50	10.921	0.921	10.44	100%	-0.92	0.00	0.00	0.00	0.00	0.91	73.97	81.00	-601.72	68.11	0.00	0.00	0.00	810.00	276.39
10	1	1	1	0.27	5.821	-4.179	10.44	100%	0.00	4.18	0.00	0.00	0.00	0.94	76.25	81.00	-320.72	0.00	-318.67	0.00	0.00	810.00	170.62
11	1	1	1	0.57	12.452	2.452	10.44	100%	-2.45	0.00	0.00	0.00	0.00	0.95	76.78	81.00	-686.09	188.28	0.00	0.00	0.00	810.00	312.19
12	1	1	1	0.72	15.745	5.745	10.44	100%	-5.75	0.00	0.00	0.00	0.00	0.95	77.21	81.00	-867.54	443.59	0.00	0.00	0.00	810.00	386.05
13	1	1	1	0.72	15.594	5.594	10.44	100%	-5.59	0.00	0.00	0.00	0.00	0.96	77.55	81.00	-859.17	433.79	0.00	0.00	0.00	810.00	384.62
14	1	1	1	0.61	13.253	3.253	10.44	100%	-3.25	0.00	0.00	0.00	0.00	0.96	77.55	81.00	-730.19	252.24	0.00	0.00	0.00	810.00	332.05
15	1	1	1	0.13	2.827	-7.173	10.44	100%	0.00	7.17	0.00	0.00	0.00	0.96	77.95	81.00	-155.79	0.00	-559.11	0.00	0.00	810.00	95.10
16	1	1	1	0.70	15.192	5.192	10.44	100%	-5.19	0.00	0.00	0.00	0.00	0.97	78.83	81.00	-837.03	409.25	0.00	0.00	0.00	810.00	382.22
17	1	1	1	0.25	5.422	-4.578	10.44	100%	0.00	4.58	0.00	0.00	0.00	0.99	80.50	81.00	-298.74	0.00	-368.53	0.00	0.00	810.00	142.73
18	1	1	1	0.46	9.934	-0.066	10.44	100%	0.00	0.07	0.00	0.00	0.00	1.01	81.43	81.00	-547.33	0.00	-5.40	0.00	0.00	810.00	257.27
19	1	1	1	0.72	15.590	5.590	10.44	100%	-5.59	0.00	0.00	0.00	0.00	1.00	80.87	81.00	-858.96	452.05	0.00	0.00	0.00	810.00	403.09
20	1	1	1	0.25	5.541	-4.459	10.44	100%	0.00	4.46	0.00	0.00	0.00	0.98	79.49	81.00	-305.30	0.00	-354.46	0.00	0.00	810.00	150.25
21	1	1	1	0.36	7.736	-2.264	10.44	100%	0.00	2.26	0.00	0.00	0.00	0.94	76.52	81.00	-426.23	0.00	-173.24	0.00	0.00	810.00	210.52
22	1	1	1	0.22	4.848	-5.152	10.44	100%	0.00	5.15	0.00	0.00	0.00	0.94	75.85	81.00	-267.10	0.00	-390.81	0.00	0.00	810.00	152.08
23	1	1	1	0.29	6.293	-3.707	10.44	100%	0.00	3.71	0.00	0.00	0.00	0.93	75.19	81.00	-346.76	0.00	-278.69	0.00	0.00	810.00	184.55
0	2	1	1	0.45	9.880	-0.120	10.44	100%	0.00	0.12	0.00	0.00	0.00	0.90	73.30	81.00	-544.35	0.00	-8.82	0.00	0.00	810.00	256.83
1	2	1	1	0.66	14.481	4.481	10.44	100%	-4.48	0.00	0.00	0.00	0.00	0.98	79.06	81.00	-797.87	354.25	0.00	0.00	0.00	810.00	366.38
2	2	1	1	0.22	4.697	-5.303	10.44	100%	0.00	5.30	0.00	0.00	0.00	0.97	78.66	81.00	-258.82	0.00	-417.10	0.00	0.00	810.00	134.08
3	2	1	1	0.72	15.746	5.746	10.44	100%	-5.75	0.00	0.00	0.00	0.00	0.96	77.49	81.00	-867.58	445.24	0.00	0.00	0.00	810.00	387.66
4	2	1	1	0.62	13.478	3.478	10.44	100%	-3.48	0.00	0.00	0.00	0.00	0.95	76.94	81.00	-742.64	267.64	0.00	0.00	0.00	810.00	335.00
5	2	1	1	0.53	11.456	1.456	10.44	100%	-1.46	0.00	0.00	0.00	0.00	0.95	77.34	81.00	-631.18	112.57	0.00	0.00	0.00	810.00	291.39
6	2	1	1	0.33	7.122	-2.878	10.44	100%	0.00	2.88	0.00	0.00	0.00	0.97	78.72	81.00	-392.41	0.00	-226.56	0.00	0.00	810.00	191.03
7	2	1	1	0.72	15.777	5.777	10.44	100%	-5.78	0.00	0.00	0.00	0.00	0.98	79.27	81.00	-869.28	457.92	0.00	0.00	0.00	810.00	398.64
8	2	1	1	0.70	15.302	5.302	10.44	100%	-5.30	0.00	0.00	0.00	0.00	0.98	79.31	81.00	-843.11	420.49	0.00	0.00	0.00	810.00	387.38
9	2	1	1	0.51	11.154	1.154	10.44	100%	-1.15	0.00	0.00	0.00	0.00	0.98	79.56	81.00	-614.56	91.80	0.00	0.00	0.00	810.00	287.25
10	2	1	1	0.42	9.241	-0.759	10.44	100%	0.00	0.76	0.00	0.00	0.00	1.00	80.94	81.00	-509.18	0.00	-61.41	0.00	0.00	810.00	239.41
11	2	1	1	0.80	17.540	7.540	10.44	100%	-7.54	0.00	0.00	0.00	0.00	1.02	82.79	81.00	-966.41	624.21	0.00	0.00	0.00	810.00	467.80
12	2	1	1	0.52	11.223	1.223	10.44	100%	-1.22	0.00	0.00	0.00	0.00	1.04	84.09	81.00	-618.37	102.84	0.00	0.00	0.00	810.00	294.47
13	2	1	1	0.61	13.368	3.368	10.44	100%	-3.37	0.00	0.00	0.00	0.00	1.03	83.27	81.00	-736.56	280.46	0.00	0.00	0.00	810.00	353.91
14	2	1	1	0.79	17.256	7.256	10.44	100%	-7.26	0.00	0.00	0.00	0.00	0.99	80.52	81.00	-950.76	584.27	0.00	0.00	0.00	810.00	443.51
15	2	1	1	0.33	7.104	-2.896	10.44	100%	0.00	2.90	0.00	0.00	0.00	0.97	78.95	81.00	-391.44	0.00	-228.61	0.00	0.00	810.00	189.95
16	2	1	1	0.70	15.192	5.192	10.44	100%	-5.19	0.00	0.00	0.00	0.00	0.98	79.77	81.00	-837.03	414.14	0.00	0.00	0.00	810.00	387.11
17	2	1	1	0.41	8.936	-1.064	10.44	100%	0.00	1.06	0.00	0.00	0.00	1.02	82.64	81.00	-492.37	0.00	-87.90	0.00	0.00	810.00	229.72
18	2	1	1	0.51	11.041	1.041	10.44	100%	-1.04	0.00	0.00	0.00	0.00	1.04	84.09	81.00	-608.35	87.56	0.00	0.00	0.00	810.00	289.20
19	2	1	1	0.67	14.672	4.672	10.44	100%	-4.67	0.00	0.00	0.00	0.00	1.05	85.37	81.00	-808.39	398.81	0.00	0.00	0.00	810.00	400.42
20	2	1	1	0.48	10.356	0.356	10.44	100%	-0.36	0.00	0.00	0.00	0.00	1.03	83.50	81.00	-570.59	29.71	0.00	0.00	0.00	810.00	269.12
21	2	1	1	0.50	10.809	0.809	10.44	100%	-0.81	0.00	0.00	0.00	0.00	1.01	81.64	81.00	-595.53	66.01	0.00	0.00	0.00	810.00	280.48
22	2	1	1	0.71	15.502	5.502	10.44	100%	-5.50	0.00	0.00	0.00	0.00	0.98	79.31	81.00	-854.14	436.37	0.00	0.00	0.00	810.00	392.23
23	2	1	1	0.72	15.791	5.791	10.44	100%	-5.79	0.00	0.00	0.00	0.00	0.98	79.27	81.00	-870.05	459.03	0.00	0.00	0.00	810.00	398.98
0	3	1	1	0.13	2.781	-7.219	10.44	100%	0.00	7.22	0.00	0.00	0.00	0.94	75.75	81.00	-153.25	0.00	-546.78	0.00	0.00	810.00	109.97
1	3	1	1	0.17	3.645	-6.355	10.44	100%	0.00	6.36	0.00	0.00	0.00	1.00	81.20	81.00	-200.82	0.00	-516.02	0.00	0.00	810.00	93.16
2	3	1	1	0.38	8.386	-1.614	10.44	100%	0.00	1.61	0.00	0.00	0.00	0.98	79.20	81.00	-462.04	0.00	-127.85	0.00	0.00	810.00	220.11
3	3	1	1	0.24	5.164	-4.836	10.44	100%	0.00	4.84	0.00	0.00	0.00	0.96	77.38	81.00	-284.51	0.00	-374.24	0.00	0.00	810.00	151.25
4	3	1	1	0.40	8.613	-1.387	10.44	100%	0.00	1.39	0.00	0.00	0.00	0.98	79.46	81.00	-474.55	0.00	-110.21	0.00	0.00	810.00	225.23
5	3	1	1	0.49	10.699	0.699	10.44	100%	-0.70	0.00	0.00	0.00	0.00	0.99	80.32	81.00	-589.48	56.12	0.00	0.00	0.00	810.00	276.64
6	3	1	1	0.29	6.330	-3.670	10.44	100%	0.00	3.67	0.00	0.00	0.00	1.02	82.49	81.00	-348.75	0.00	-302.79	0.00	0.00	810.00	158.46
7	3	1	1	0.30	6.465	-3.535	10.44	100%	0.00	3.53	0.00	0.00	0.00	1.11	89.56	81.00	-356.23	0.00	-316.55	0.00	0.00	810.00	137.22
8	3	1	1	0.38	8.324	-1.676	8.76	84%	0.00	0.00	0.00	1.68	0.00	1.61	130.47	81.00	-458.65	0.00	0.00	0.00	0.00	810.00	351.35
9	3	1	1	0.28	6.175	-3.825	4.94	47%	0.00	0.00	0.00	3.83	0.00	1.67	134.98	81.00	-340.22	0.00	0.00	0.00	0.00	810.00	469.78
10	3	1	1	0.27	5.962	-4.038	0.90	9%	0.00	0.00	0.00	4.04	0.00	1.64	132.46	81.00	-328.52	0.00	0.00	0.00	0.00	810.00	481.48
11	3	1	1	0.32	6.949	-3.051	0.00	0%	0.00	0.00	0.00	0.90	2.15	1.62	131.04	81.00	-382.90	0.00	0.00	-282.00	0.00	810.00	145.10
12	3	1	1	0.70	15.328	5.328	0.00	0%	-5.33	0.00	0.00	0.00	0.00	1.42	115.02	81.00	-844.52	612.80	0.00	0.00	0.00	810.00	578.28

Appendix C. Benchmarking of long-term price forecasts

All price values in EUR.

	Bixia **Long-term forecasts**		**Svenska Kraftnät** **Electrificaton**		**Nord Pool** **Future derivatives prices**	
Price estimation source	*System price*	*Bidding Zone price SE4*	*SVK Electrification renewables scenario SE4*	*SVK Electrification dispatchable scenario SE4*	*Nordic Power Futures BL (2023-03-30)*	*SE4 EPAD (2023-03-30)*
2023	90	9				
2024					67	14
2025			33	33	55	15.5
2026		7			47	20.5
2027	50				45	25
2028	50				44	
2029	50	1-1.5			43.35	
2030	50	1-1.5			43.35	
2031	50				43.35	
2032	50				43.35	
2033	50				43.35	
2034	50					
2035	50		30	41		
2036	50					
2037	50					
2038	50					
2039	50					
2040	50					
2041						
2042						
2043						
2044						
2045			29	29		

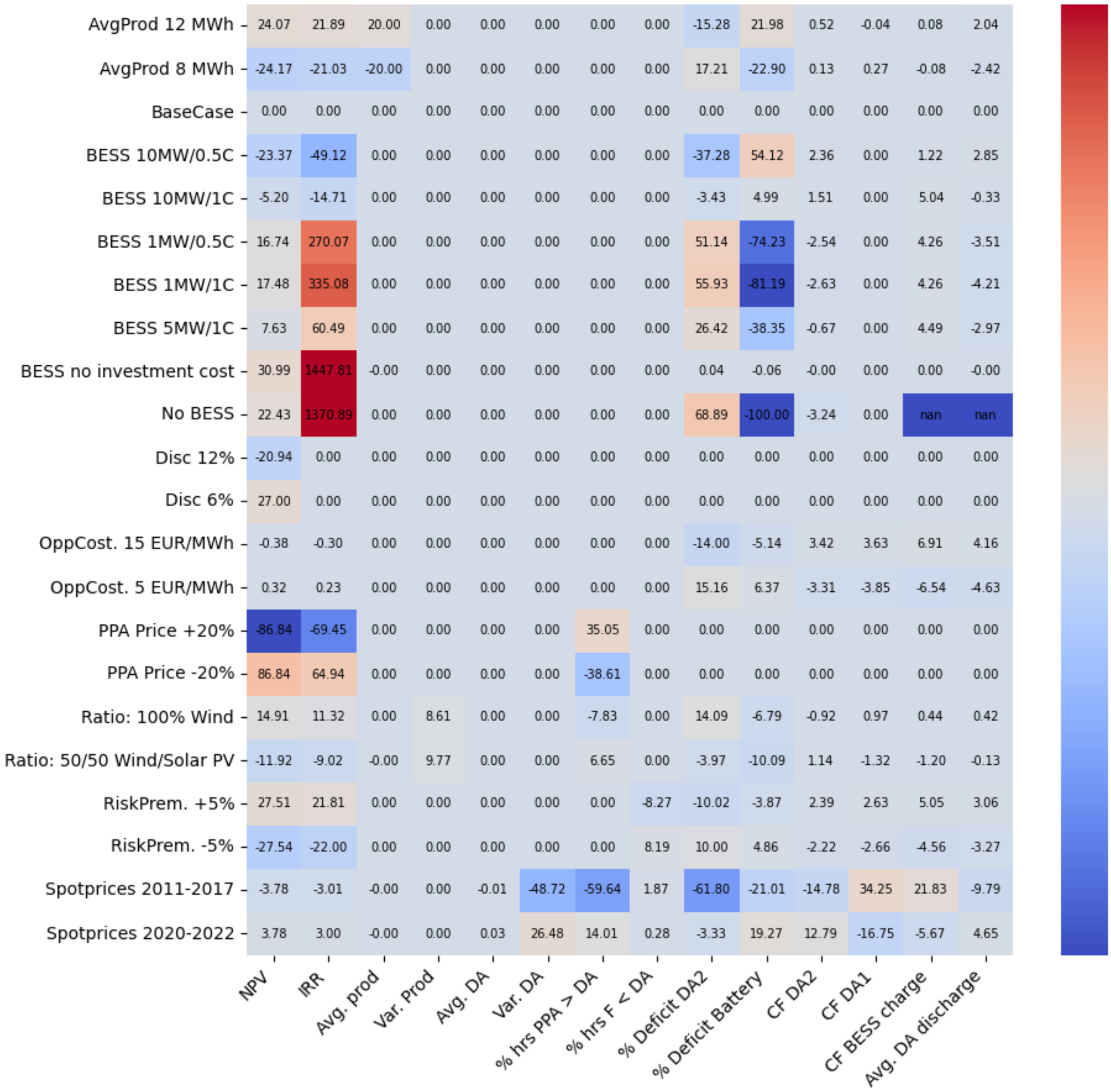
Appendix D. Benchmarking of BESS specifications.

Table 1 below illustrates the cost as estimated by NREL in $/kWh of a 60MW lithium-ion BESS with different duration times. [74]

Battery case #	**1**	**2**	**3**	**4**	**5**
Capacity	60 MW	60 MW	60 MW	60 MW	60 MW
Duration	2 hours	4 hours	6 hours	8 hours	2 hours
Energy	120 MWh	240 MWh	360 MWh	480 MWh	120 MWh
Cost	428 $/kWh	369 $/kWh	349 $/kWh	339 $/kWh	428 $/kWh

Appendix E. All results from application of simulation model.

AVG. DA ISCHARG E	CF BESS CHARGE	CF DA1	CF DA2	% DEFICIT BATTERY	% DEFICIT DA2	% HRS F < DA	HRS PPA > DA	VAR. DA	AVG. DA	VAR. PROD	IRR	NPV	
1.616156	0.833955	0.657208	1.743604	0.156734	0.158015	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.562374	8.120564 e+0	**AVGPROD_ 12MW**
1.545461	0.832612	0.659261	1.736821	0.099072	0.218605	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.364346	4.962769 e+0	**AVGPROD_ 8**
1.583834	0.833250	0.657502	1.734609	0.128491	0.186513	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.461380	6.544917 e+0	**BASECASE**
NaN	NaN	0.657502	1.678452	0.000000	0.315004	0.412021	0.407048	0.633976	69.94809 3	0.40802	6.786410	8.013015 e+0	**BESS_0**
1.628929	0.843382	0.657502	1.775628	0.198026	0.116978	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.234751	5.015227 e+0	**BESS_10M W_0.5**
1.578541	0.875273	0.657502	1.760838	0.134897	0.180107	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.393524	6.204459 e+0	**BESS_10M W_1C**
1.528263	0.868729	0.657502	1.690485	0.033110	0.281894	0.412021	0.407048	0.633976	69.94809 3	0.40802	1.707426	7.640625 e+0	**BESS_1MW 0.5C**
1.517154	0.868753	0.657502	1.688928	0.024167	0.290838	0.412021	0.407048	0.633976	69.94809 3	0.40802	2.007391	7.688807 e+0	**BESS_1MW 1C**
1.536777	0.870654	0.657502	1.722923	0.079218	0.235786	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.740450	7.044251 e+0	**BESS_5MW 1C**
1.583834	0.833250	0.657502	1.734609	0.128491	0.186513	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.461380	5.174144 e+0	**DISC_12**
1.583834	0.833250	0.657502	1.734609	0.128491	0.186513	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.461380	8.311974 e+0	**DISC_6**
1.649667	0.890862	0.681381	1.793970	0.121885	0.160410	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.459976	6.520238 e+0	**OPPCOST_ 15**
1.510443	0.778785	0.632206	1.677257	0.136682	0.214788	0.412021	0.407048	0.633976	69.94809 3	0.40802	0.462461	6.565977 e+0	**OPPCOST_ 5**
1.583834	0.833250	0.657502	1.734609	0.128491	0.186513	0.412021	0.549723	0.633976	69.94809 3	0.40802	0.140933	8.613880 e+0	**PPAPRICE_ +20**
1.583834	0.833250	0.657502	1.734609	0.128491	0.186513	0.412021	0.249906	0.633976	69.94809 3	0.40802	0.761021	1.222845 e+0	**PPAPRICE_ -20**
1.632291	0.875356	0.674817	1.776041	0.123513	0.167828	0.377941	0.407048	0.633976	69.94809 3	0.40802	0.561990	8.345531 e+06	**RISKPREM _+5**
1.532120	0.795241	0.639999	1.696086	0.134736	0.205171	0.445778	0.407048	0.633976	69.94809 3	0.40802	0.359878	4.742343 e+06	**RISKPREM _-5**



	NPV	IRR	Avg. prod	Var. Prod	Avg. DA	Var. DA	% hrs PPA > DA	% hrs F < DA	% Deficit DA2	% Deficit Battery	CF DA2	CF DA1	CF BESS charge	Avg. DA discharge
AvgProd 12 MWh	24.07	21.89	20.00	0.00	0.00	0.00	0.00	0.00	-15.28	21.98	0.52	-0.04	0.08	2.04
AvgProd 8 MWh	-24.17	-21.03	-20.00	0.00	0.00	0.00	0.00	0.00	17.21	-22.90	0.13	0.27	-0.08	-2.42
BaseCase	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BESS 10MW/0.5C	-23.37	-49.12	0.00	0.00	0.00	0.00	0.00	0.00	-37.28	54.12	2.36	0.00	1.22	2.85
BESS 10MW/1C	-5.20	-14.71	0.00	0.00	0.00	0.00	0.00	0.00	-3.43	4.99	1.51	0.00	5.04	-0.33
BESS 1MW/0.5C	16.74	270.07	0.00	0.00	0.00	0.00	0.00	0.00	51.14	-74.23	-2.54	0.00	4.26	-3.51
BESS 1MW/1C	17.48	335.08	0.00	0.00	0.00	0.00	0.00	0.00	55.93	-81.19	-2.63	0.00	4.26	-4.21
BESS 5MW/1C	7.63	60.49	0.00	0.00	0.00	0.00	0.00	0.00	26.42	-38.35	-0.67	0.00	4.49	-2.97
BESS no investment cost	30.99	1447.81	-0.00	0.00	0.00	0.00	0.00	0.00	0.04	-0.06	-0.00	0.00	0.00	-0.00
No BESS	22.43	1370.89	0.00	0.00	0.00	0.00	0.00	0.00	68.89	-100.00	-3.24	0.00	nan	nan
Disc 12%	-20.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Disc 6%	27.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OppCost. 15 EUR/MWh	-0.38	-0.30	0.00	0.00	0.00	0.00	0.00	0.00	-14.00	-5.14	3.42	3.63	6.91	4.16
OppCost. 5 EUR/MWh	0.32	0.23	0.00	0.00	0.00	0.00	0.00	0.00	15.16	6.37	-3.31	-3.85	-6.54	-4.63
PPA Price +20%	-86.84	-69.45	0.00	0.00	0.00	0.00	35.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PPA Price -20%	86.84	64.94	0.00	0.00	0.00	0.00	-38.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ratio: 100% Wind	14.91	11.32	0.00	8.61	0.00	0.00	-7.83	0.00	14.09	-6.79	-0.92	0.97	0.44	0.42
Ratio: 50/50 Wind/Solar PV	-11.92	-9.02	-0.00	9.77	0.00	0.00	6.65	0.00	-3.97	-10.09	1.14	-1.32	-1.20	-0.13
RiskPrem. +5%	27.51	21.81	0.00	0.00	0.00	0.00	0.00	-8.27	-10.02	-3.87	2.39	2.63	5.05	3.06
RiskPrem. -5%	-27.54	-22.00	0.00	0.00	0.00	0.00	0.00	8.19	10.00	4.86	-2.22	-2.66	-4.56	-3.27
Spotprices 2011-2017	-3.78	-3.01	-0.00	0.00	-0.01	-48.72	-59.64	1.87	-61.80	-21.01	-14.78	34.25	21.83	-9.79
Spotprices 2020-2022	3.78	3.00	-0.00	0.00	0.03	26.48	14.01	0.28	-3.33	19.27	12.79	-16.75	-5.67	4.65