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Short-term energy market effects from icing on wind turbines

Intraday and regulating market price dynamics in northern Sweden and Finland during icing-influenced wind power production

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Abstract

This thesis investigates how wind power production deviations caused by icing affect price levels, regulation direction and volatility in the intraday and balancing markets. It also includes a temporal analysis of price signals during the onset and recovery phases of icing events. The analysis focuses on SE2 in Sweden and the Finnish power system, using market and production data from October to April over the years 2021–2024. Icing events are identified based on deviations from expected wind power output. Market data during these events are compared to a reference period to analyze price dynamics relative to the day-ahead market. The hypothesis is that sudden production losses due to icing lead to increased up-regulation needs, higher imbalance costs and potential for rising intraday prices, while the recovery phase is expected to show down-regulation and falling prices. The results show that average intraday and imbalance prices during icing events are above the spot price in both SE2 and Finland. In SE2, down-regulation remains the most common, with only a slight shift toward up-regulation, while Finland shows a significant increase in up-regulation hours. Imbalance price spreads become more volatile during icing, with distributions shifting toward more extreme values, both higher up-regulation prices and more negative down-regulation prices. Temporal patterns suggest a tendency for early up-regulation followed by delayed intraday price increases, although this appears to be driven by outliers. No clear trend is observed at the end of events. Overall, the findings indicate that icing can lead to notable shifts in market behavior and that market responses vary, both over time and between regions. These insights may support improved forecasting and risk-aware trading under uncertain production conditions.

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Populärvetenskaplig sammanfattning

Vindkraft har blivit en central del av den nordiska elmixen. Men eftersom elproduktionen är helt beroende av väderförhållanden är den också känslig för vissa klimatfenomen, bland annat isbildning. När is bildas på rotorbladen försämras vindkraftverkens förmåga att producera el, vilket kan leda till plötsliga och oförutsedda produktionsbortfall. Dessa händelser är svåra att prognostisera och kan skapa utmaningar för både elproducenter och systemoperatörer som ansvarar för att hålla elsystemet i balans.

Den här studien identifierar sådana ishändelser och undersöker hur dessa påverkar elmarknaden, med särskilt fokus på intradagsmarknaden (för handel upp till en timme innan leverans) och balansmarknaden (där elproduktion regleras i realtid). Dessa två marknader är avgörande för att hantera snabba förändringar i elproduktionen. Analysen bygger på data från elområde SE2 i Sverige och hela det finska kraftsystemet, FI, under perioden oktober till april 2021–2024. Isbildningshändelser har identifierats genom att jämföra verklig elproduktion med beräknad förväntad produktion, och dessa har jämförts med en referensperiod utan isbildning.

Hypotesen är att isbildning leder till behov av mer uppreglering och högre elpriser i början av händelserna, och att detta sedan vänder till nedreglering och sjunkande priser när produktionen återhämtar sig. Resultaten visar att de genomsnittliga priserna på både intradags- och balansmarknaden är högre än spotpriset under isbildning, i både SE2 och Finland. I SE2 är det dock fortfarande vanligast med nedreglering, vilket skulle kunna tyda på att andra aktörer i systemet kompenserar för bortfallen eller att produktionen återhämtar sig snabbt. I Finland däremot ökar andelen uppreglering tydligt, vilket kan tyda på ett mer känsligt system med högre beroende av vindkraft.

Studien visar också att den genomsnittliga prisspridningen, det vill säga hur mycket priserna varierar jämfört med spotpriset ökar under isbildning. Det sker fler extrema prisutfall, både mycket höga uppregleringspriser och mycket negativa nedregleringspriser, vilket tyder på en ökad marknadsosäkerhet. En mer detaljerad analys av början och slutet av isbildningshändelser visar att prisreaktioner i balansmarknaden i vissa fall kommer snabbt, medan intradagspriser reagerar med viss fördröjning. Däremot syns ingen tydlig indikation på nedreglering i slutet av händelserna, vilket delvis motsäger hypotesen.

En viktig slutsats är att det är svårt att dra generella slutsatser om marknadens beteende, eftersom isbildningseffekterna varierar mellan olika händelser. Resultaten påverkas också av enstaka extrema prisutfall. Trots det ger studien viktiga insikter i hur marknaden kan reagera vid produktionsbortfall orsakade av isbildning, vilket i sin tur kan tillföra viktiga insikter för att förbättra prognosmodeller, handelsstrategier och styrning av elsystemet. Detta är särskilt relevant i takt med att andelen väderberoende elproduktion ökar i Norden och behovet av flexibilitet och förutsägbarhet blir allt viktigare.

Acknowledgements

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As I reach the end of my studies at Uppsala University, I want to thank all those who have stood by me throughout this journey. I'm excited to put my knowledge into practice and do my part in building a more sustainable world.

Alva Wesslén
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Glossary of Terms and Abbreviations

RES **Renewable Energy Sources** – Energy sources that are replenished naturally, such as wind, solar, and hydro power.

NOIS **Nordic Operational Information System** – A platform used by Nordic TSOs to share real-time operational information relevant to electricity balancing and grid stability.

IEA Wind TCP **International Energy Agency Wind Technology Collaboration Programme** – An international collaboration to advance wind energy research and share knowledge across member countries.

DA / DAM **Day-Ahead/Day-Ahead Market** – The electricity market where hourly bids are submitted and matched one day before delivery.

ID / IDM **Intraday/Intraday Market** – A continuously traded electricity market closer to real time, used to manage updated forecasts and imbalances.

ID3 **ID3 Price Index** – The volume-weighted average price of all intraday trades conducted within the last three hours before delivery.

TSO **Transmission System Operator** – An entity responsible for operating, maintaining, and developing the high-voltage electricity transmission system in a given area. TSOs also maintain system balance by activating resources in the balancing market. In the Nordic countries, examples include Svenska kraftnät (SE) and Fingrid (FI).

Balancing Market The market used by the transmission system operator (TSO) to ensure real-time balance between supply and demand, typically through up- and down-regulation after gate closure in the day-ahead and intraday markets.

Up-regulation A balancing action taken to increase electricity supply or reduce consumption when there is a system shortage.

Down-regulation A balancing action taken to reduce electricity supply or increase consumption when there is a system surplus.

Imbalance Price The price applied to deviations between scheduled and actual generation or consumption, based on the cost of activated balancing energy.

Spread The price difference between two market prices, such as the imbalance price and the spot price, or ID3 and spot price. Spread is always used as the price difference relative spot price in this thesis.

Icing Event A period when wind turbine output is significantly reduced due to ice accumulation on the blades.

Icing Factor A proxy metric representing actual wind power output relative to expected output, used to identify potential icing-related underperformance.

1 Introduction

The global transition to renewable energy has positioned wind power as a cornerstone of sustainable electricity generation. In Sweden and Finland, wind power currently accounts for approximately 20% of the electricity mix [1][2], a number that is expected to grow as new wind farms are deployed. However, this expansion faces challenges, particularly since many on-shore wind farms are located in remote areas due to societal resistance to placing turbines near residential zones. In northern Sweden and Finland, this often means operating in regions with cold winter climates, where icing on wind turbine blades is a recurrent issue [3].

Wind power, as an intermittent energy source, introduces important challenges for electricity market operations, as its production depends on weather conditions and can fluctuate significantly over short timeframes. Unlike flexible generation sources, such as hydro or nuclear power, wind power cannot be dispatched on demand, which makes its integration into the power system more complex [4]. As a result, the unpredictability of wind power leads to higher volatility in electricity prices, particularly in short-term markets such as the intraday and balancing markets [5][6]. These markets play a crucial role in handling last-minute imbalances and ensuring grid stability [7][8].

Among the many factors that contribute to wind power variability, icing presents a particularly severe challenge. Ice accumulation on turbine blades can cause sudden and substantial production losses, disrupting both forecasting models and market dynamics. Unlike standard variations in wind speed, icing-related losses are harder to predict and can lead to rapid and unexpected deviations from projected power output [9].

As the Nordic energy system grows increasingly reliant on weather-dependent renewable energy production, these challenges are becoming more pronounced. This has changed how different electricity markets interact and how important they are. Markets that operate closer to the time of delivery, like the intraday and regulating markets, are playing a bigger role in trading and setting prices. Understanding these changes is crucial because, until now, the day-ahead market has been the most important. It has influenced new electricity investments, real-time pricing, risk management and has been used as a reference price in capacity markets [10].

While extensive research has been conducted on technical solutions to mitigate icing, such as heating systems and mechanical de-icing methods and on performance studies related to climate and temperature conditions [11, 12, 13], the market implications of icing remain largely unexplored. Previous studies have analysed how increasing shares of variable renewable energy sources (RES) impact electricity price formation, grid stability and market efficiency [14, 15, 16], yet little attention has been given to how icing-specific events influence short-term price dynamics and the need for balancing power. This thesis addresses this gap by investigating how icing impacts price dynamics in intraday and regulating markets.

By providing a data-driven analysis of past icing events, this study aims to offer insights for market participants, such as traders, system operators and wind power producers, in anticipating and managing icing-related risks more effectively. These insights could serve as a background for improving prediction models, refining trading strategies and optimizing system balancing measures to mitigate the financial and operational risks associated with icing events.

1.1 The energy market participant Vattenfall

Vattenfall is one of the largest producers of renewable energy in Europe, operating 1 300 wind farms with a total installed capacity of 6.1 gigawatts (GW) across five European countries. This generation supplies electricity to around five million households annually [17].

As a large wind power producer, Vattenfall actively engages in multiple electricity markets to manage variability in generation. Participation in the intraday market enables short-term adjustments based on updated forecasts, while the balancing (regulating) market provides opportunities to offer flexibility services and respond to system needs close to real time [18].

For a market actor like Vattenfall, understanding the impact of adverse weather conditions, such as icing events in cold-climate regions, is crucial both operationally and economically. Icing can cause sudden and severe production curtailments, with implications for market positioning, imbalance costs and reserve activation. While mitigation technologies such as de-icing systems can reduce some of the risks [19], gaining insight into how the intraday and balancing markets behave during icing events is key to improving operational strategies and minimizing financial exposure [20].

1.2 Project scope

This thesis investigates the impact of icing events on wind turbines in northern Sweden (SE2) and Finland (FI) on electricity market outcomes, focusing particularly on the intraday and balancing markets. As wind power constitutes a growing share of the Nordic energy mix, understanding operational disruptions caused by icing is essential. By identifying historical icing events through production data and analysing their correlation with market variables, such as ID3 price, imbalance prices and regulating directions, this study aims to quantify the market impacts of reduced wind output due to icing in both SE2 and FI.

1.2.1 Research questions

To fulfill this aim, the thesis addresses the following research questions:

- How do production losses caused by icing affect price levels, regulating direction and volatility in the intraday and balancing markets?
- How do price signals in the intraday and balancing markets respond at the onset of icing events and what does this reveal about market sensitivity to forecasted production losses?

- How do price signals in the intraday and balancing markets evolve towards the end of icing events and what does this indicate about market expectations during the recovery phase of wind production?

By addressing these questions, this thesis aims to fill a gap in the existing literature on the market implications of icing in wind power production. The findings are intended to guide market participants, including traders, system operators and wind power producers, in anticipating and managing the risks associated with icing, thereby improving operational risk management and contributing to greater market stability during periods of production uncertainty.

1.2.2 Delimitations

This study is limited to the price areas SE2 and FI, as these regions belong to climate zones where icing events are relevant. The analysis is based on data from October to April during the years 2021 to 2024, since these months represent the typical icing season in northern Europe.

The market focus is restricted to the intraday and balancing markets in SE2 and FI. Other markets, such as the day-ahead market and capacity market, are excluded from the scope of this thesis. To analyse price dynamics, the study uses price spreads as a central metric.

Certain data are excluded due to limited availability or quality issues. Data when wind power production is curtailed due to low spot prices are also excluded from the study. These simplifications were made to ensure a feasible and consistent analysis.

2 Background

This chapter provides the necessary background to understand the interplay between wind power production in cold climates and its impact on short-term electricity markets. It begins by describing the role of wind power in the Nordic electricity system by highlighting its growing importance and the unique difficulties associated with operating wind turbines in cold climates. Then it explores the phenomenon of icing in greater detail, including meteorological causes, physical effects on turbines and current strategies for detection, forecasting and mitigation.

Subsequently, the structure of the Nordic electricity market is introduced, with a particular focus on the ID and balancing markets in SE2 and FI. These short-term markets play a critical role in balancing supply and demand in real time and are especially sensitive to sudden production losses caused by icing events. The chapter concludes by discussing the importance of forecast accuracy in cold-climate regions and the challenges that icing poses to maintaining system reliability and market efficiency.

2.1 Wind power production in the Nordic energy system

The Nordic countries are rapidly expanding wind power as part of their transition to carbon neutral energy systems. Ambitious targets for example, Finland aims for carbon-neutrality by 2035, have driven large investments in RES [3]. Wind power capacity in the Nordics has grown fast in recent years, with Sweden reaching 16.4 GW of installed wind by the end of 2023 and expected to supply over 25 % of the country's electricity by 2026 [21]. Finland is seeing a similar boom; Wind electricity could equal twice Finland's domestic demand by 2022 by the late 2030s according to current development plans [3]. Many of these new installations are located in cold and exposed areas just as northern Sweden's SE2 region and various parts of Finland. In these areas the wind resources are abundant but the winter conditions are harsh. In effect, a significant share of Nordic wind farms can be classified as *cold climate* sites, defined by the IEA Wind TCP as areas with frequent atmospheric icing or very low temperatures beyond standard turbine limits [21][3].

As the Nordic power system increasingly relies on weather-dependent wind generation, operational reliability and forecast accuracy have become critical. Wind power is variable and the Nordics' high penetration of wind power has introduced greater short-term supply fluctuations. Sudden, unexpected drops in wind production, for example due to turbine icing or extreme weather, are a system-wide concern today. Accurate forecasting is difficult in such a climate-dependent system, so unpredicted wind outages can lead to grid balancing issues and price volatility [22]. In the worst cases, an abrupt loss of wind output in one region can tighten the power supply and spike electricity prices across the Nordic market.

2.2 Icing on wind turbines and wind power losses

Atmospheric icing on wind turbines is one of the key causes of sudden wind production losses in the Nordic region. A large share of wind power in northern Sweden and Finland is located in cold and remote areas where winter conditions often lead to ice accretion on turbine blades [23]. Icing occurs when supercooled water droplets freeze on exposed surfaces, typically during cold and humid weather. There are different variations of ice that can form on turbine blades and all types of ice accretion can lead to production losses by degrading blade performance or causing operational shutdowns [24].

Ice accretion changes the aerodynamics, reduces efficiency and may trigger vibrations or emergency stops. In severe cases, icing can cause large instantaneous production drops and in high-risk areas the annual energy losses can be up to 20 % [25]. Nonetheless, detection and forecasting technologies have improved, short-term prediction of icing remains difficult due to complex local weather patterns [21][26]. Mitigation strategies such as blade heating and surface coatings are used to reduce the icing impact. However, these solutions have both technical and economic limitations [24]. As a result, icing remains a key challenge for reliable wind power operation in cold climates. This underscores the importance of flexible power markets capable of handling both unexpected production losses and rapid production returns.

2.3 Electricity market structure in SE2 and FI

In the Nordic power system, energy trading is structured around specific time frames to ensure a balance between supply and demand. It is organized into different markets, each with different objectives and the primary platforms facilitating this are the day-ahead market (DAM) and the intraday market (IDM). The DAM serves as the main electricity trading platform, where buyers' and sellers' orders are matched to establish hourly prices for the upcoming 24-hour period, known as spot prices [18]. This auction is closed at noon (12:00 CET) the day before delivery [27].

Since unexpected changes in production or consumption can arise after the day-ahead closure, due to weather shifts, outages, or forecast errors, market participants can use the IDM to adjust their positions. The IDM operates continuously and allows trading up to one hour before delivery in most Nordic bidding zones and in Finland as late as 30 minutes before delivery begins [7]. Until March 2025, the IDM in the Nordics supported hourly and half-hourly products; this study is based on data from that period and therefore does not cover the more recent transition to 15-minute trading [28].

The balancing (regulating) market also plays an important role by activating flexibility close to real time. Its design influences how power producers and consumers are incentivized to provide up- or down-regulation in response to sudden deviations, such as those caused by icing events [29][30].

In addition to the DAM, IDM and balancing market, the electricity system also includes price hedging instruments and an imbalance settlement mechanism [29]. However, this report focuses primarily on the DAM, IDM and balancing markets in the periods before, during and immediately after icing events [30].

2.3.1 The intraday market

The IDM plays a critical role in sustaining short-term balance in the Nordic electricity system. It is a continuous, pay-as-bid market that allows participants to adjust their trading positions after the closure of the DAM, operating up until one hour before the actual delivery hour. Trading opens at 14:00 CET the day before delivery and enables participants to react to improved forecasts and unforeseen deviations in both production and consumption [31, 27, 10].

Unlike the DAM, which is cleared once per day using a uniform price auction, the IDM operates continuously. In the IDM, trades are made in real time through a system called continuous double auction where buy and sell orders are matched immediately based on price and time of submission, much like in stock markets. A key feature of the intraday market is that trades and available cross-border transmission capacity are matched at the same time. This means that each local market only shows orders that can actually be fulfilled given the current grid constraints [31][32].

Due to the volatile nature of RES generation and particularly wind power, which constitutes a growing share of the Nordic electricity mix, the production levels forecast in the DAM often deviate from actual outcomes. This results in imbalances that must be corrected closer to real time [10, 22, 32]. For example, lower-than-forecasted wind speeds may lead to underproduction and negative imbalances, while unexpectedly high wind speeds can result in more generation than expected, requiring down-regulation.

The IDM allows for continuous cross-border electricity trading across much of Europe. In the Nordic region, Nord Pool facilitates this trading, with market orders potentially being matched with participants from other interconnected European markets. [33]. Participants can trade on hourly, half-hourly and, more recently, 15-minute contracts. These shorter contract durations are particularly beneficial for wind power producers, as they enable more flexible and responsive trading in light of frequent and rapid changes in production forecasts [34][32]. This thesis is based on data from a period when only hourly and half-hourly trading was possible on the IDM, therefore the introduction of 15-minute products is not covered by this study [28].

In terms of unforeseen production deviations that can be caused by icing events, the IDM serves as an essential tool for minimizing system imbalances and reducing reliance on more expensive balancing resources.

2.3.2 The balancing market

To maintain the real-time balance of the Nordic electricity system, national Transmission System Operators (TSOs) are responsible for continuously matching electricity supply and demand. This is achieved through the procurement and activation of ancillary services, which ensure grid stability both during normal operations and as a response to disturbances [29]. Ancillary services include a range of balancing products that allow upward or downward regulations in production or consumption. These services can be provided by power plants, industrial loads, energy storage systems, or aggregators [35].

The balancing market is the main mechanism for balancing the system during the operating hour. TSOs in the Nordic region operate this market together through the Nordic Operational Information System (NOIS), which coordinates bids across different bidding areas. Market participants submit up- or down-regulation bids with defined capacity and price. The accepted bids are activated by TSOs according to the real-time system needs, up to 45 minutes before delivery [36].

Each delivery hour is classified as up-regulation, down-regulation, or no-regulation depending on the net activated volume. For up-regulation, the TSO purchases energy (requests increased production or reduced consumption), while in down-regulation, the TSO sells energy (reduces production or increases consumption). The imbalance price is determined by the marginal activated bid and can be the same across bidding areas unless bottlenecks limits cross-border exchanges [36].

There are notable differences in how the balancing market functions in Sweden compared to Finland. While both countries participate in the common Nordic balancing market, Finland tends to rely more frequently on national resources and congestion often limit price harmonization between Finland and Sweden [10]. This leads to differences in market outcomes, such as imbalance spreads and volume of activated bids. Also, the availability and participation of industrial demand-side resources vary, influencing how flexible each national market can respond to real-time imbalances that occur [10][36].

2.3.3 The role of short-term electricity markets

The intraday and balancing markets are particularly sensitive to deviations from forecasted electricity production and consumption. Since prices on the DAM is based on forecasted values, any unexpected changes such as technical faults, sudden demand fluctuations, or rapid shifts in wind generation require corrective measures closer to the delivery hour. Forecast errors are therefore a key driver of short-term market volatility [10].

In the Nordic power system, characterized by a growing share of weather-dependent RES, these challenges are especially pronounced. As described by [18], the intraday market plays an increasingly critical role in handling such imbalances. In cold climate regions such as SE2 and FI, icing events introduce a form of production loss that is particularly difficult to predict. Even advanced weather and power forecasting models struggle to anticipate the start, duration and severity of icing-related reductions. [26, 21, 23].

These unplanned production changes can lead to substantial deviations from expected and scheduled output. This often requires intensified intraday trading and the activation of balancing reserves to restore system balance. In the context of icing-related limitations, typically both sudden and highly localised, understanding how the market responds to such forecast errors is crucial for both operational reliability and effective market design [10, 22, 32].

Intraday trading serves as a critical tool for market participants to reduce potential imbalance exposure [18][10]. When forecasted production suddenly drops due to icing, producers aim to adjust their positions by purchasing power on the intraday market, thereby avoiding being penalised through imbalance settlement. From a financial perspective, the goal is to trade at a price that is more favorable than the potential cost of imbalance regulation. If a participant fails to match their position and remains imbalanced, they are settled at the imbalance price, which can be either significantly higher (in case of up-regulation) or lower (in case of down-regulation) than the spot price. In cases where no regulation is activated, the settlement is based on the day-ahead spot price [22].

This creates a strong incentive for proactive intraday trading, especially under uncertainty, to manage risk. A positive spread between the intraday price and the spot price can be interpreted as a risk premium, where actors are willing to pay more than spot to avoid the potentially higher cost of up-regulation. Conversely, if the intraday price is below spot, it may reflect expectations of down-regulation, or an attempt to reduce excess volume at a lower cost. The interplay between these markets is therefore central to understanding market reactions to events such as icing, where sudden losses in wind power trigger strategic adjustments in trading behavior [32, 10].

3 Method

This chapter outlines the methodological framework used to investigate the effects of wind turbine icing on intraday and regulating electricity markets in northern Sweden (SE2) and Finland (FI). The study focuses on the winter months (October to April) from 2021 to 2024. The primary objective is to identify icing events and analyse their influence on market dynamics.

The underlying **hypothesis** is that icing events will impact the intraday and balancing markets through increased price levels and a shift in regulation patterns, but that these effects will vary over the course of the event. At the start of an icing event, sudden and unplanned production losses are expected to cause upward regulation and increased prices compared to the spot price, as the market responds to the shortfall. Toward the end of the event, as production begins to recover, prices are expected to normalise and potentially shift toward downward regulation. ID prices are assumed to follow a similar pattern, though with a delay, due to gate closure one hour before delivery, which limits immediate trading responses to real-time information. These assumptions are based on the idea that unexpected variations in wind production require rapid market adjustments, particularly in regions where wind constitutes a significant share of the electricity mix.

These assumptions form the basis of the analytical approach described below. The methodology focuses on three main components:

- **Icing event identification**: Detecting periods of icing-related power production losses. In this context, an icing event is defined as any period where the observed production falls to 40% or less of expected output, based on the assumed icing factor.
- **Market impact analysis**: Quantitatively analysing how identified icing events affect ID price spreads and regulation price spreads.
- **Data processing and validation**: Filtering, validating, structuring and aggregating data. The three central data sets are wind speed and production data for each wind farm, power curve data for each wind farm and trading data for the all of the identified icing events.

3.1 Identification of Icing Events

The first step of this study was to identify icing events of interest for further analysis. A key assumption throughout the thesis is that a wind farm producing 40 % or less of its theoretical output is experiencing an icing-related production loss. This threshold was chosen as a reasonable criterion for detecting significant performance reductions associated with to icing.

To identify such periods, actual wind power output was compared to theoretical values derived from wind speed and turbine power curves. These data were retrieved for each wind farm and subsequently aggregated to obtain the total theoretical and actual power output across all wind farms in the respective regions (SE2 and FI). An *icing factor*, defined as the ratio between actual and theoretical power output, was then calculated for each hourly observation. Hours with an icing factor of 40 % or less were filtered and classified as icing events. These periods then served as the basis for further analysis of how the intraday and balancing markets responded during and around icing events.

3.1.1 Theoretical power output calculation

The theoretical power output at each wind speed was estimated using power curve data from each wind farm. A power curve represents the relationship between wind speed and a wind turbine's power output, typically provided as discrete data points. These curves are derived from standardised testing and reflect the expected electrical output under normal operating conditions. They usually follow a characteristic S-shape: at low wind speeds, the turbine generates little or no electricity. As the wind speed increases, the power output rises quickly until it reaches the turbine's maximum (rated) capacity. If the wind becomes too strong, the turbine shuts down to avoid damage and the power output drops to zero [37].

To obtain continuous theoretical output values, linear interpolation was applied between the available discrete data points in each farm's power curve. This enabled estimation of expected power production $P(v)$ for any observed wind speed v during the analysis period.

The interpolation process involved identifying two bounding points from the power curve dataset $\mathcal{P}$, where:

- (v_{low}, P_{low}) is the highest wind speed in the dataset less than or equal to v,
- (v_{high}, P_{high}) is the lowest wind speed greater than v.

The slope k and intercept m of the linear segment between these points were then computed:

$$k = \frac{P_{high} - P_{low}}{v_{high} - v_{low}}, \quad m = P_{low} - k \cdot v_{low} \tag{1}$$

The expected power output at wind speed v is then given by:

$$P(v) = k \cdot v + m \tag{2}$$

For each timestamp in the dataset, the interpolated expected output was compared to the actual measured output using the following ratio:

$$\text{Icing Factor} = 100 \cdot \frac{P_{actual}}{P_{expected}} \tag{3}$$

The analysis focused on aggregated power data from multiple wind farms, as this was considered the most robust basis for identifying icing-related production losses at the system level. Accordingly, the icing factor was calculated using the total power output from all wind farms in SE2 and FI, respectively, over the entire study period. An illustration

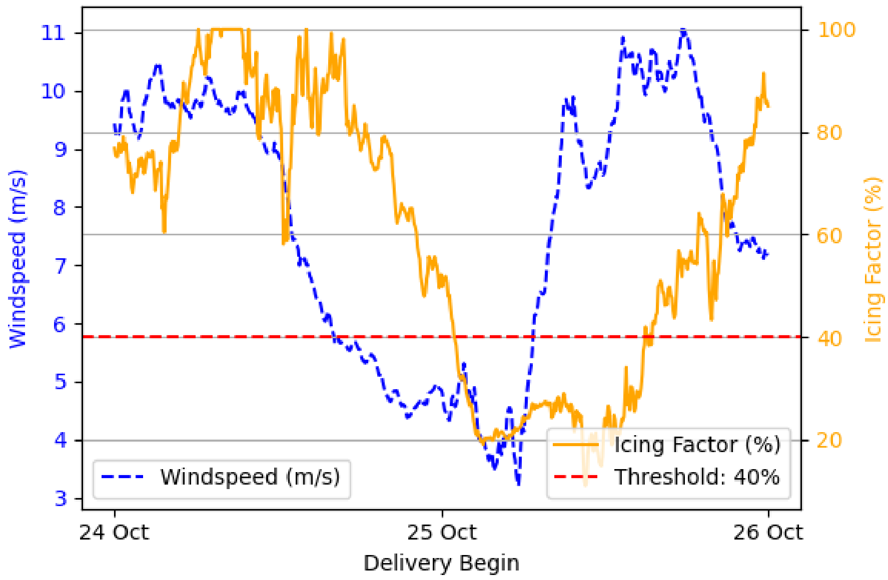


Figure 1: Illustration of how icing factor and wind speed change during a period of time SE2. The red line indicates the 40 % threshold used to identify icing events.

of how the icing factor and wind speed varied over a selected period is shown in Figure 1. The figure highlights periods where the icing factor falls below the 40 % threshold, which was used to classify the icing events.

The icing factor quantifies the deviation between actual and theoretical power production. A value near 100 % indicates normal operation, while significantly lower values suggest underperformance due to icing. In this study, any period of time with an icing factor of 40 % or less for two hours or longer, was classified as an *icing event*.

3.2 Market Impact Analysis

This section describes the methodology used to analyse the intraday and balancing market reaction to icing events. Two main datasets were used: one containing only the hours identified as icing events and another including these icing periods along with a buffer of three hours before and three hours after each event. Both datasets included hourly data on wind speed, the icing factor, spot prices, imbalance prices and the ID3 price index (which is further explained below) for the SE2 and FI regions, respectively.

The analysis began with aggregated statistical calculations based on all identified icing events. This was followed by hourly-based analyses that examined how the average spread between imbalance prices or ID3 prices and the spot price evolved around the start and end of each icing event. These analyses were intended to identify trends and patterns in how the intraday and balancing markets responded to icing-related production deviations.

To provide a basis for comparison, a reference dataset was constructed using all hours from the studied winter periods (October–April, 2021–2024). Importantly, this dataset includes all hours, also those affected by icing events or other potential extreme conditions, rather than excluding them. This decision was made to reflect a more realistic representation of a general market behavior during the winter months, where various types of forecast deviations and production challenges, not only icing, may influence prices and regulation. Consequently, the reference period served as a baseline for "average market conditions" rather than an idealised, disturbance-free state. However, it is important to note that defining a universal "normal" state of the electricity market is inherently difficult, as market dynamics are influenced by a wide range of unpredictable factors including weather variability, fuel prices, consumption patterns and regulatory changes.

3.2.1 Intraday price index ID3

The intraday market (IDM) allows continuous trading of electricity products up until shortly before delivery. As trades occur at varying prices throughout the trading window, a single hourly price is not always representative of the overall market behavior. Market operators publish price indices based on volume-weighted averages to address this. One of such indexes used in this study, is called the *ID3 index* (ID3).

The ID3 reflects the volume-weighted average price of all trades executed during the three hours prior to the delivery of a specific hourly product [38]. It is calculated as the average of transaction prices, where each price is weighted by the volume of trades at that price. This means that prices with higher traded volumes have a greater impact on the final ID3 value than those with lower volumes [39].

The index is calculated using the following formula:

$$\text{ID3} = \frac{\sum_{i \in T_h^3} V_i P_i}{\sum_{i \in T_h^3} V_i} \tag{4}$$

where P_i and V_i denote the price and volume of trade i, respectively and T_h^3 represents the set of all trades executed in the three hours prior to delivery hour h [39].

This pricing method captures the most recent market expectations and is particularly valuable for balancing forecasts with real-time developments in systems with large shares of variable renewable generation. Since wind production forecasts may change rapidly in response to weather uncertainty (such as icing events), the ID3 index can be a more accurate reflection of the real time market value than the spot price alone.

3.2.2 Analysis of market indicators

The first part of the analysis focused on summarising the price situation during identified icing events compared to the reference period. For each region (SE2 and FI), descriptive statistics which included mean and standard deviation and median, were calculated for key market variables such as spot price and imbalance price, ID3 were only calculated for the hours during each icing event. Additionally, the price difference between ID3 prices and spot prices (ID3 spread), as well as between imbalance prices and spot prices (imbalance spread), was calculated to assess deviations from the baseline market value. The DA spot price represents the expected value of electricity based on forecasts and market conditions available the day before delivery. In contrast, intraday and imbalance prices reflect real-time supply and demand conditions and the market expectations of it. Therefore, analysing spreads relative to the spot price provided an indication of how the market adjusts its valuation of electricity as new information becomes available, such as unexpected production losses due to icing.

Furthermore, the share of hours under up-regulation, down-regulation, or no regulation was analysed to explore how the need for system balancing varied during icing periods. These proportions were then compared to those during the reference period.

To further investigate the relationship between forecast deviations and intraday price dynamics, a correlation analysis was conducted between the ID3 index and the calculated icing factor. This aimed to examine whether greater losses in wind power output due to icing correlated with increasing prices on the IDM.

Lastly, the distributions of imbalance price spreads were analysed. These distribution plots provided additional insights into how pricing behavior shifted during icing events compared to more generalised reference conditions.

3.2.3 Temporal analysis of market spreads during icing events

To assess how the intraday and balancing markets responded to icing-related production losses and recoveries, a temporal spread analysis was conducted. The aim was to determine whether and to what extent the price signals in these markets changed in the hours surrounding the icing events.

For each identified icing event, two fixed analysis windows were defined. The first spanned from three hours before the start of the event to eight hours after its onset. The second covered the period from eight hours before the end of the event to three hours after its final hour. Within these time frames, three key variables were extracted for each hour:

- The **ID3 spread**, defined as the difference between the ID3 and the spot price.
- The **imbalance spread**, defined as the difference between the imbalance price and the spot price.
- The **icing factor**, used to track the degree of production loss due to icing.

For each relative hour in the analysis window (three hours before, during and three hours after each icing event), data from all events were aggregated to calculate the average spread values. A 95 % confidence interval was also calculated for each hourly average using a bootstrap method in Python, to illustrate the uncertainty around the mean estimates.

Using spreads relative to the spot price allowed for a standardised comparison of price behavior regardless of underlying price levels. This was particularly important given the volatility in electricity markets during winter months. Analysing both the start and end of icing events provided a more complete picture of market dynamics in response to sudden forecast deviations.

3.3 Description of data

This study is based on multiple datasets used in different stages of the analysis: identifying icing events and evaluating how the intraday and balancing markets respond to such events. The data used for identifying icing events cover the period from October to April, for the years 2021 to 2024, and are restricted to wind farms located in SE2 and FI. The imbalance prices and spot prices are based on the reference period including the icing events. IDM data cover the hours during and surrounding the identified icing events.

Wind production data and actual power output were retrieved at an average five-minute resolution based on data from SCADA (Supervisory Control and Data Acquisition) systems from each wind farm. These were aggregated to hourly resolution and used to calculate the icing factor for the wind farms in the region. Curtailment data, also retrieved from SCADA system, were used to exclude hours with scheduled production stops not related to weather conditions. To estimate theoretical power output, power curve data were collected for each wind farm from Windfor [40]. These curves represent the relationship between wind speed and expected power output under normal operating conditions where each data point specifies the power output at a given wind speed.

The electricity market data was retrieved from Nord Pool [41]. These include:

- DA spot prices (EUR/MWh) (hourly)
- ID trading data: price, volume, trading direction (buy/sell), timestamp for trade and contract hour (data for each transaction made within the studied time period)
- Imbalance prices (EUR/MWh)(hourly)

The spot prices and imbalance prices were used for calculating price spreads and evaluating market signals during icing events. The ID trading data were used to construct the ID3 index for each relevant hour, enabling comparison with spot prices and analysis of IDM dynamics.

3.3.1 Data processing

To prepare the data for analysis, a structured preprocessing workflow was applied to ensure consistency, accuracy and alignment across datasets. The steps included filtering for relevant regions and time periods, aggregating time series data, estimating expected power production and identifying periods of production loss due to icing.

The analysis focused on wind farms located in SE2 and FI, where icing conditions are common. All production and wind speed data were originally recorded at 5-minute intervals and were aggregated to hourly resolution to align with the temporal granularity of the market data.

To ensure consistency across all sources, only hourly observations with complete data coverage for wind speed, actual power output and relevant market indicators were retained. Furthermore, curtailment plans were used to filter out hours when production was reduced due to non-weather-related operational decisions.

3.4 Discussion of methodological considerations

This section outlines some methodological considerations and limitations associated with the approach used in this thesis. While the methods applied enable a structured analysis of how the electricity market responds to production losses caused by icing events, certain assumptions and simplifications have been necessary.

This discussion of these aspects has two main purposes. First, it promotes transparency by clarifying the boundaries within which the results should be interpreted. Second, it helps to critically evaluate the findings, particularly in light of the complex and dynamic nature of both wind power production and electricity market behavior.

3.4.1 The icing event threshold and its limitations

The first part of this thesis, involving the identification of icing events, is based on a fixed threshold assumption: a wind farm is considered to experience an icing event when its actual production falls below 40 % of the expected theoretical output. While this simplification allows for a consistent and practical identification method across regions and time, it also introduces certain limitations that should be acknowledged.

Importantly, this threshold does not account for other potential causes of production losses, such as technical faults, control system inefficiencies, or temporary curtailments not captured in the data. Furthermore, it may not correspond precisely to the level at which icing begins to influence market behavior. Instead, it serves as a pragmatic proxy for identifying periods likely to involve significant icing-related impacts. As such, the results derived from this method should be interpreted with an understanding of its simplifying assumptions.

3.4.2 Data limitations and quality considerations

While the datasets used in this study were carefully selected and preprocessed to ensure consistency and completeness, certain limitations remain. The SCADA-based wind production data are subject to measurement errors and may vary in precision between wind farms. Additionally, power curve data provided by manufacturers represent idealised conditions and may not fully capture site-specific variations such as terrain effects or turbine degradation.

The identification of icing events relies on an approach based on a threshold using the calculated icing factor, which may not distinguish between all causes of production loss. Moreover, the market data can be influenced by external factors unrelated to icing, such as demand spikes, unexpected outages, or cross-border effects. As such, while efforts were made to isolate the impact of icing, other variables may still affect the observed market responses.

These limitations should be kept in mind when interpreting the results, especially with regard to generalising the findings beyond the specific regions and time period studied.

3.4.3 The complexity of intraday market dynamics

Analysing the IDM in relation to icing events is challenging due to the many external factors that can influence market behavior during the same time periods. The IDM reflects a continuous and dynamic trading environment where prices and volumes are affected not only by wind forecast deviations but also by other unforeseen events such as unplanned outages, system imbalances in neighboring regions or countries, or demand changes.

This complexity makes it difficult to isolate the market response specifically attributable to icing-related production deviations. As a result, observed price signals during icing events may partly reflect other overlapping market conditions. While the aggregated approach used in this study helps to highlight general trends, it is important to interpret the findings with awareness of this limitation.

3.4.4 Considerations about the ID3 Index

The ID3 index is widely used as a benchmark for short-term electricity price developments in the continuous IDM. It reflects the volume-weighted average price of all trades conducted during the last three hours before delivery and thereby captures the most recent market expectations.

However, it is important to acknowledge that the ID3 index may not fully capture the true price dynamics in regions with relatively low intraday liquidity, which can be tha case in SE2 and FI. In these areas, fewer trades may occur in the last hours before delivery, which can make the index more sensitive to individual transactions or less representative of broader market sentiment. This is in contrast to countries with higher trading volumes, where the index is based on a more robust set of transactions and can thus be seen as a more reliable price signal.

Despite these limitations, the ID3 index was chosen in this study as it remains one of the most standardised and comparable indicators available for analysing IDM behavior across time and regions. While it could be argued that a custom-designed price index might better reflect Nordic trading conditions, for example, by adjusting the time window before delivery or filtering for minimum trading volumes, this would require new assumptions and reduce the ability to compare results with other studies. The choice to use the standardised ID3 index therefore represents a trade-off between achieving regional accuracy and maintaining methodological consistency.

4 Results

This chapter is divided into two main sections, with the results presented separately for the two different areas, SE2 and FI. The structure is consistent and the same types of analyses are used in both sections. Each section begins with a statistical summary of the identified icing events. In total, 121 icing events are studied in SE2 and 91 in FI, ranging from 2 to 202 hours. The events are identified within the colder months ranging from October to April, over the years 2021 to 2024. This period is used consistently as the reference period throughout some parts of the results.

The first part of each section presents aggregated statistical results based on all identified icing events. This is followed by hourly-based analyses, illustrating how the average spread between imbalance or ID3 prices and the spot price evolves around the start and end of the icing events. Together, these statistics and illustrations aim to provide insight on how icing influences both intraday and balancing market outcomes.

4.1 Price development and dynamics during icing events in SE2

Table 1 summarises the mean, median, standard deviation and spread for imbalance prices and spot prices during icing events and during the reference period. Data for the ID3 price is included only for the icing events due to limited data availability. The spread is defined as the difference between the icing event values and the corresponding values during the reference period.

Table 1: Overview of hourly average, median and standard deviation values for prices and spreads relative to the spot price in SE2 during icing events and the reference period.

Metric	Type	Mean (spread)	Std	Median (spread)
Imbalance Price	Icing Events	72.96 (+5.49)	198.96	41.75 (+2.20)
Spot Price	Icing Events	67.47	90.51	39.55
ID3 Index	Icing Events	100.72 (+33.25)	89.54	69.80 (+30.25)
Imbalance Price	Reference Period	46.19 (–3.47)	100.61	27.00 (–7.18)
Spot Price	Reference Period	49.66	59.75	34.18

Imbalance prices were noticeably higher during icing events compared to the reference period. Both the average and median imbalance prices increased, with the average price rising by over 25 EUR/MWh. While the spread relative to the spot price was slightly positive during icing, it was negative in the reference period.

Spot prices also increased during icing events, with both average and median values being moderately higher than in the reference period. However, the change in spot price was less pronounced than for imbalance prices.

The ID3 index, available only during icing periods, showed a substantially higher average than the corresponding spot price, with a spread exceeding 30 EUR/MWh. The median ID3 value was also considerably higher than the median spot price.

4.1.1 Correlation between ID3 and icing factor

Figure 2 illustrates the relationship between the icing factor and the ID3 price. The regression line in the scatter plot has a negative gradient of -1.03, indicating that lower icing factors (i.e., greater production loss due to icing) are associated with higher ID3 price. The data points are widely scattered around the regression line.

The dataset includes all hours during identified icing events as well as a buffer of three hours before and after each event, which results in a higher density of data points at lower icing factor levels (≤ 40%).

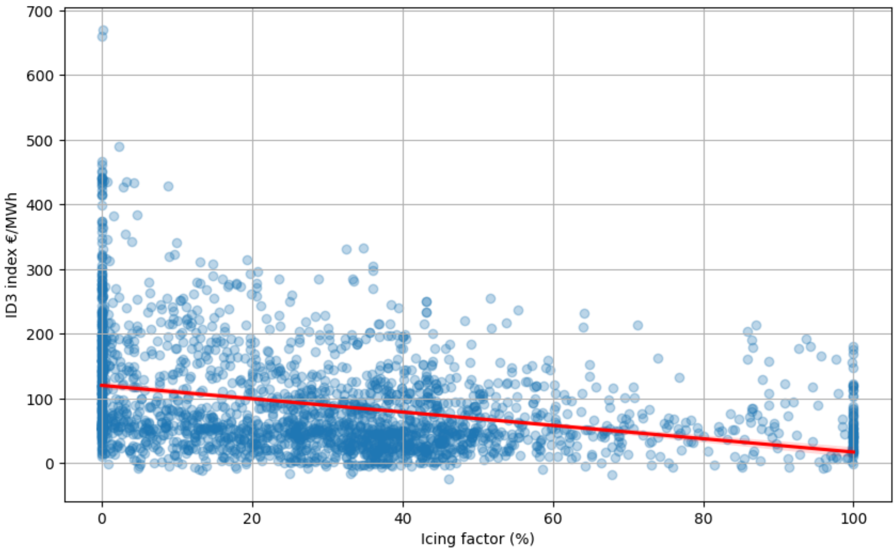
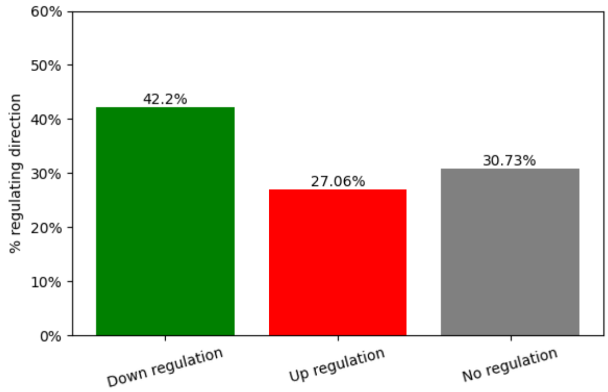


Figure 2: Correlation between ID3 price and icing factor for icing events in SE2.

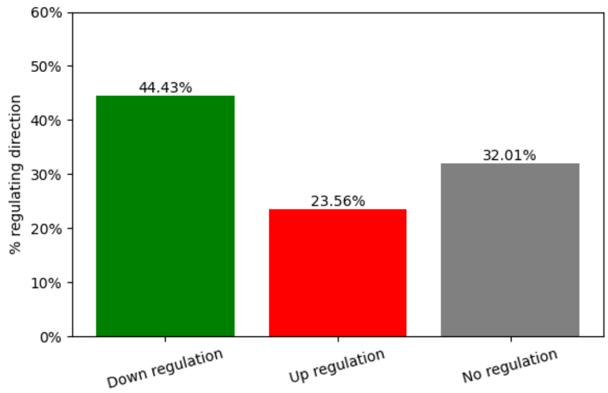
4.1.2 Regulating direction

The figures 3a and 3b show the distribution of regulating power direction during icing events and during the reference period in SE2. In both cases, hours with down-regulation occurs more frequently than up-regulation and about one third of the hours show no regulation at all.

Compared to the reference period, the share of down-regulated hours is slightly lower during icing events, whereas the share of up-regulated hours is somewhat higher. The number of unregulated hours also appears to decrease during icing events.



(a) Up-, down- and unregulated hours (icing events)



(b) Up-, down- and unregulated hours (reference period)

Figure 3: Distribution of up-, down- and unregulated hours in SE2 during icing events (a) and during the reference period (b)

4.1.3 Distribution of imbalance price spreads

Figure 4 shows how the imbalance price spreads relative to the spot price differ during icing events compared to the reference period. To improve readability, data above the 95th percentile and below the 5th percentile have been excluded, along with all data points where the imbalance spread equals zero. This filtering explains the unusual shape at spread zero in the figure. The distribution shifts towards larger absolute price spreads during icing events, with both more pronounced negative and positive deviations. In addition, the density of down-regulation hours is lower during icing periods.

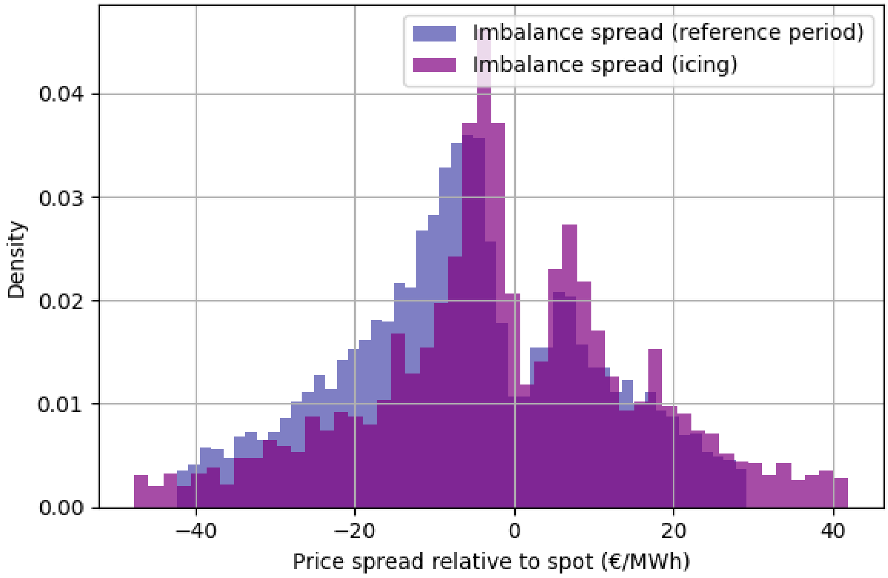
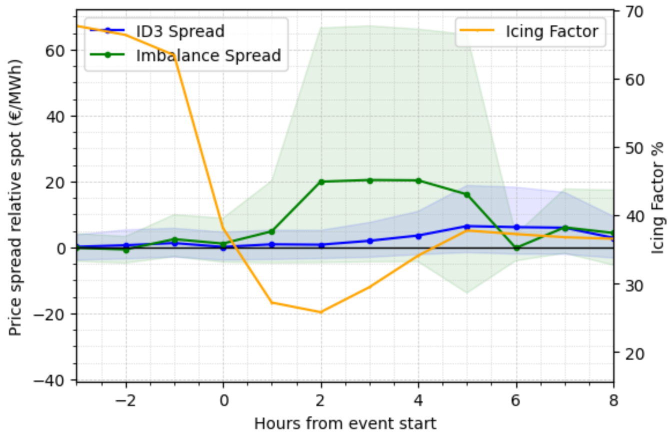


Figure 4: Distribution of imbalance spreads in SE2 for icing events and during the reference period, excluding outlier values (within the lower 5th and higher 95th percentile).

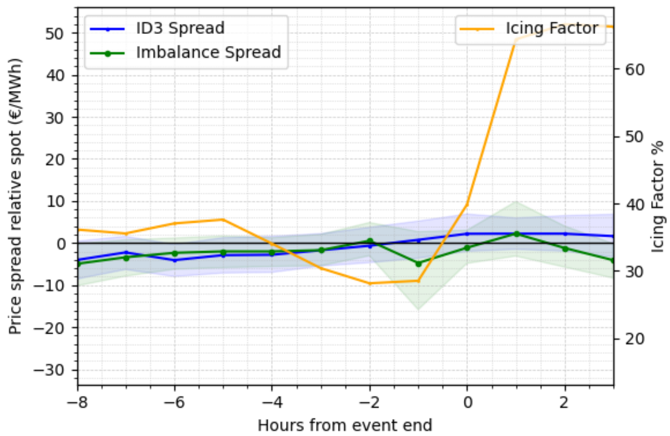
4.1.4 Temporal price spread patterns around icing events

An illustration of how the average ID3 spread and imbalance spread develop over time in relation to icing factor is provided in figures 5 and 6. These figures offer insights into how the ID3 and imbalance prices change over time by presenting average spreads before, during and after icing events.

Figure 5 shows the average price spreads in relation to the changing icing factor in SE2 aligned to the start of all identified icing events and the bottom graph aligned to their end. Time zero marks the start or end hour of each event.



(a) Price spreads at the start of icing events.



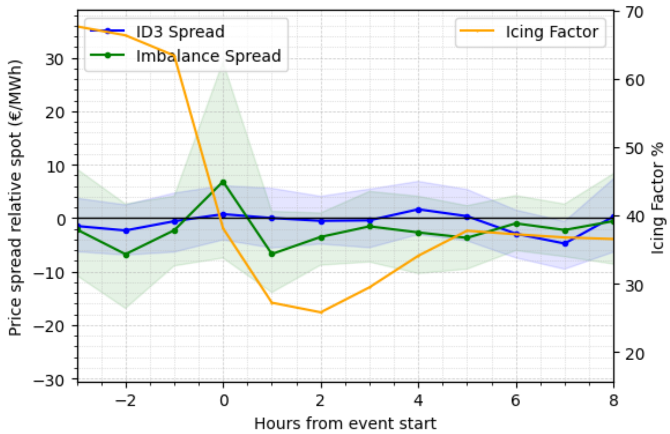
(b) Price spreads at the end of icing events.

Figure 5: Average ID3 and imbalance price spreads relative to spot price during icing events in SE2. This is showed in relation to the changing icing factor during start and end of the icing events. Shaded areas indicate 95% confidence intervals.

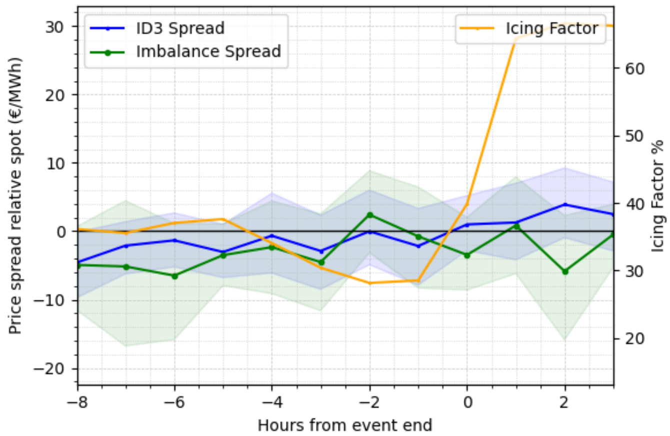
From three hours before the start of the icing events, the icing factor drops sharply from 70 %, marking the significant loss in wind power production ($\leq$ 40 %) and continues to decrease until its lowest output at hour two. This decline in output is followed by a clear increase in the imbalance spread, which peaks about one hour after the event begins. The ID3 spread also rises, but more gradually. An upward trend becomes noticeable around hour two. While the imbalance spread decreases again and returns to values close to the spot price by hour six, the ID3 spread remains positive. The shaded areas (green for imbalance spread and blue for ID3 spread) represent 95 % confidence intervals. These intervals are wide for several hours of the event, indicating considerable variation in the underlying data.

Figure 5b shows no clear trend in price spreads around the end of the icing events. Both the ID3 and imbalance spread are close to zero and largely mirror each other until two hours before the end of the event. During the final hours, the ID3 spread displays a small positive deviation and going from negative ID3 spread to a positive value. The imbalance spread alternates between positive and negative values towards the end, with a greater share of negative spread observations. The icing factor, which indicates wind power output relative to normal levels, gradually increases after the end of the icing events. From values below 40 %, it recovers to approximately 70 % three hours after the event has ended.

Figure 6 presents the same average spreads for start and end of icing events as Figure 5 above, but excludes the 5th and 95th percentiles of the dataset to reduce the influence of extreme values. In this case, the previously observed trend in imbalance spread following the start of icing events is no longer visible. Both the imbalance spread and ID3 spread changes around zero in figure 6a. While the imbalance spread appears to be negative across almost the entire graph, it does show a positive value at hour 0, with a large confidence interval. In Figure 6b the ID3 spread seems to be increasing throughout the last hours of the event and around hour 0, it shifts from negative to positive values.



(a) Price spreads during start of icing events



(b) Price spreads during end of icing events

Figure 6: ID3 spread and imbalance price spread relative spot with a shaded area of a 95% confidence interval, excluding values in 5th and 95 percentile. Second y-axis shows the change of icing factor over time.

4.2 Price development and dynamics during icing events in FI

The following sections present a statistical overview of the prices and distribution of prices during identified icing events in Finland. The results include the same types of results as for SE2, such as bar charts comparing regulating market prices during icing events and during the reference period (Oct-Apr, 2021-2024), distribution plots of ID3 spread values and average hourly spreads between imbalance or ID3 prices and spot prices before, during and after the icing events. The spreads refer to price differences from spot prices and the reference period used is consistent with what applied in the SE2 analysis.

Table 2 summarises the mean, median, standard deviation and spread for imbalance prices and spot prices during icing events and during the reference period. Data for the ID3 price is included only for the icing events due to limited data availability. Values in parentheses represent the average hourly spread between the imbalance or ID3 price and the corresponding spot price.

Table 2: Overview of hourly average, median and standard deviation values for prices and spreads relative to the spot price in FI during icing events and the reference period.

Metric	Type	Mean (Spread)	Std	Median (Spread)
Imbalance Price	Icing Events	202.53 (+30.67)	228.15	140.19 (+5.32)
Spot Price	Icing Events	171.87	228.15	134.87
ID3 Index	Icing Events	186.18 (+14.32)	159.77	129.28 (–5.59)
Imbalance Price	Reference Period	97.50 (+9.09)	157.04	77.07 (+12.06)
Spot Price	Reference Period	88.41	97.11	65.01

During icing events, both the imbalance and spot prices are considerably higher than during the reference period. The average imbalance price more than doubles and the spot price shows a similarly large increase. The average spread between imbalance and spot price is more than three times larger during icing events compared to the reference period.

The median imbalance price during icing events is also notably higher and the median spread is slightly positive, in contrast to a higher median spread in the reference period. The standard deviation of the imbalance price is substantially higher during icing events, indicating that prices vary more across hours.

The ID3 index, which is only retrieved and calculated for the hours of the icing events, has a higher average value than the corresponding spot price. However, its median value is lower than the median spot price, resulting in a negative median spread.

4.2.1 Correlation between ID3 and icing factor

Figure 7 shows signs of a negative correlation between icing factor and ID3 price. However, the downward slope is not steep, with a gradient of –0.87. This indicates a correlation between reduced wind production due to icing losses and an increase in ID3 price. The data points are widely scattered around the regression line, indicating a weak correlation.

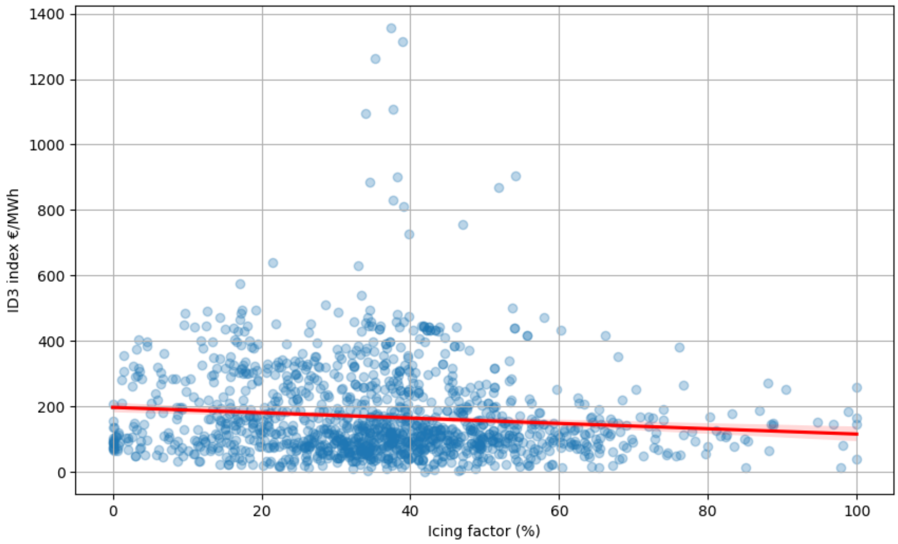
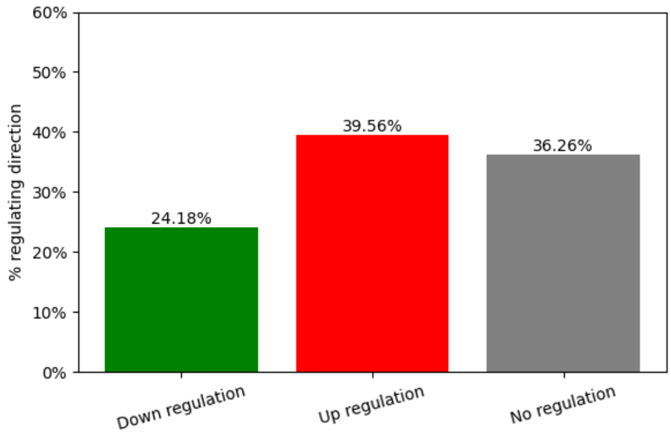


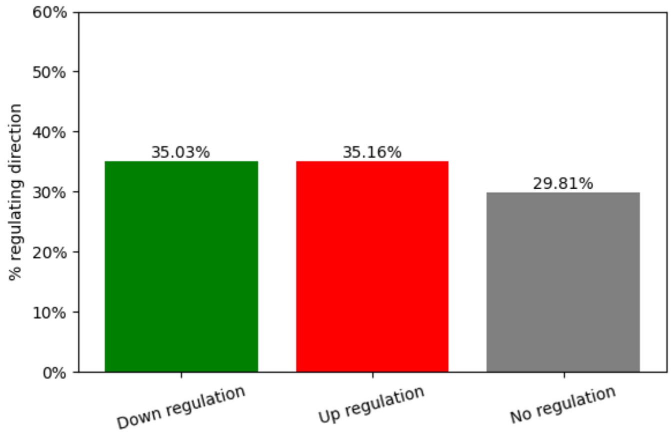
Figure 7: Correlation between ID3 price index and icing factor for icing events.

4.2.2 Regulating direction

Figure 8 presents the share of up-regulated, down-regulated and un-regulated hours during icing events (8a) and during the reference period (8b). The majority of hours during icing events are either up-regulated or unregulated, with up-regulation being most frequent followed by unregulated hours. Down-regulated hours are less common, occurring 24 % of the time. The distribution during the reference period is more balanced, with nearly equal shares of up- and down-regulation. The share of unregulated hours are about 30 %.



(a) Up-, down- and unregulated hours (icing events).



(b) Up-, down- and unregulated hours (reference period).

Figure 8: Distribution of up-, down- and unregulated hours in FI during icing events (a) and during the reference period (b).

4.2.3 Distribution of imbalance spreads

Figure 9 illustrates how the distribution of imbalance spreads shifts between icing events and the reference period. The most frequently occurring spread in both periods is zero, but values equal to zero, along with those below the 5th and above the 95th percentile, have been excluded to enhance readability. This filtering explains the apparent dip in density at spread zero in the figure.

The spreads during icing events display a wide range of values, with events that extend towards values exceeding negative 110 EUR/MWh and positive 190 EUR/MWh. The distribution appears flatter and more dispersed in relation to the reference period, with a higher density across a broader interval.

For the reference period, the distribution is more concentrated around zero, with most spreads ranging between negative 100 EUR/MWh and positive 100 EUR/MWh. The values are also generally more on the negative side, with spreads

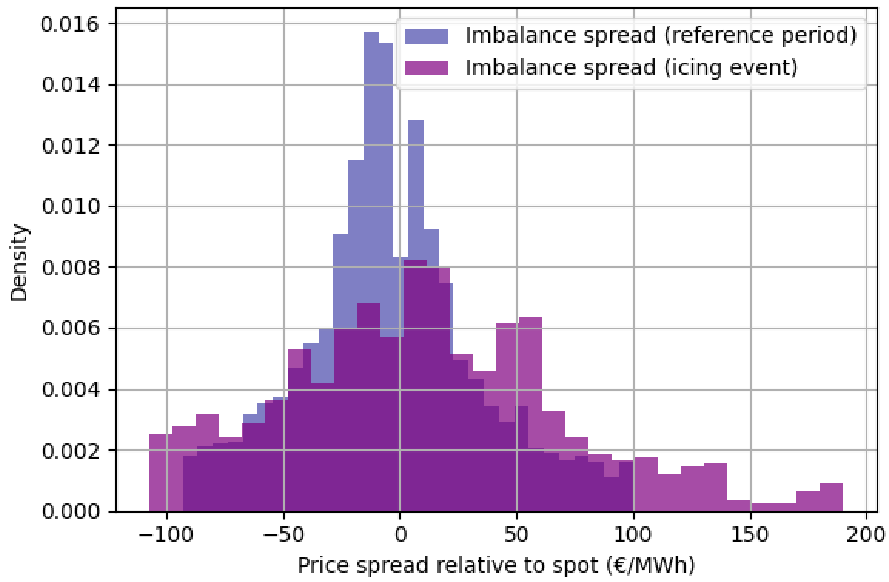
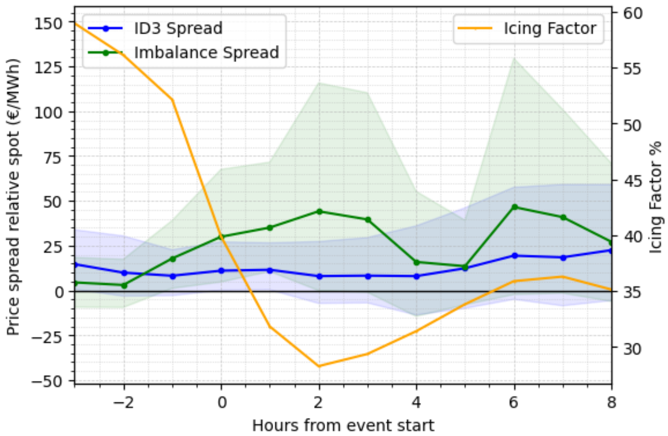


Figure 9: Distribution of imbalance spreads spreads in FI for the icing events, excluding outlier values (within the lower 5th and higher 95th percentile).

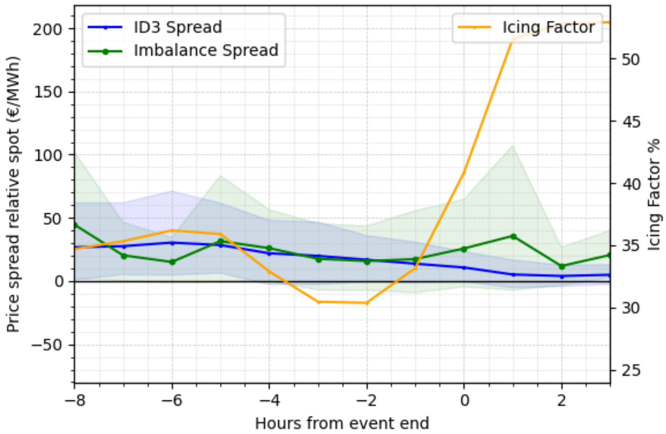
4.2.4 Temporal price spread patterns around icing events

Figure 10 presents how average ID3 and imbalance price spreads evolve during the hours before and after the start and end of identified icing events in FI. The aim is to capture market behavior in relation to the production deviations caused by icing.

At the start of the events (Figure 10a), the icing factor, shown as an orange line, drops from around 60 % to 30 %, reflecting a significant decline in wind power output. Toward the end of the events (Figure 10b), the icing factor gradually recovers, reaching approximately 55 % three hours after the events end, indicating partial restoration of production capacity.



(a) Price spreads at the start of icing events



(b) Price spreads at the end of icing events

Figure 10: Average ID3 and imbalance price spreads relative to spot price during icing events in FI. This is showed in relation to the changing icing factor during start and end of the icing events Shaded areas indicate 95% confidence intervals.

In both figures, the ID3 and imbalance spreads remain positive during all hours, indicating that the average prices on the intraday and regulating markets are more expensive than the spot price within these time frames of the icing events. The hourly development of these spreads differs between the start and end of the events.

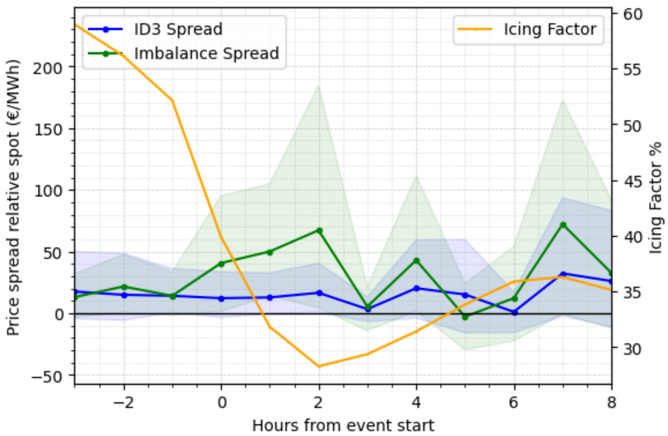
In Figure 10a, the imbalance spread increases notably about one two hours before the event begins, while the ID3 spread remains relatively stable initially but begins a gradual upward trend around hour 4. Figure 10b shows a downward trend in the ID3 spread beginning approximately five hours before the end of the event, whereas the imbalance spread fluctuates without a clear directional pattern.

The shaded green and blue areas represent 95 % confidence intervals, which indicate the variability in hourly average price spreads. Notably, in Figure 10a, the imbalance spread confidence intervals widen between hours 2 and 6, where the peaks are.

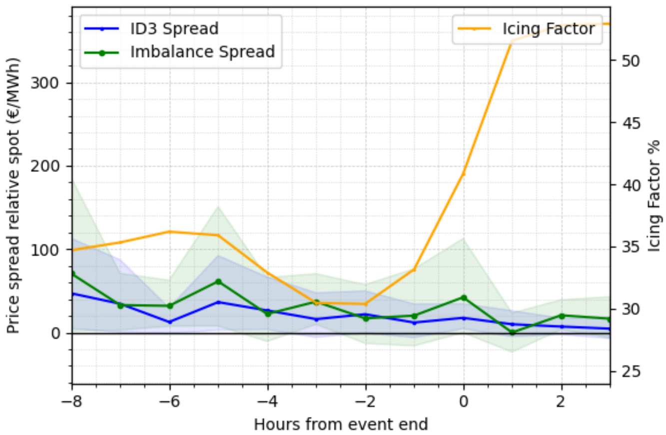
Figure 11 shows the same analysis as in Figure 10, but with the most extreme values excluded to reduce the influence of outliers. Most of the spreads, both for ID3 and imbalance prices, remain positive throughout the event windows. This means that during most hours around icing events, intraday and balancing market prices lie above the corresponding spot prices.

In Figure 11a, the imbalance spread increases during the initial hours of the event, peaking approximately two hours after the start. In Figure 11b, both the ID3 spread and the imbalance spread show a gradual downward trend toward the end of the event and continue to decline in the three hours following.

The confidence intervals vary in width across the time window and are particularly wide around certain peaks in the imbalance spread. This marks greater uncertainty in these hourly averages, likely reflecting variation in market responses across different icing events.



(a) Price spreads during start of icing events



(b) Price spreads during end of icing events

Figure 11: ID3 and imbalance price spreads relative to spot price with a 95% confidence interval, excluding values in the 5th and 95th percentiles. Second y-axis shows the change of icing factor over time.

5 Analysis and Discussion

This chapter analyses the results presented in the previous section in relation to the research questions. The discussion is structured around three research questions, followed by a comparative analysis between SE2 and FI, limitations of the study and concludes with reflections on future work. The first research question explores how wind power production losses due to icing impacts price levels, regulation direction and market volatility. The second examines how price spreads relative to the spot price develop at the onset of icing events, while the third focuses on their evolution toward the end of these events.

The results are presented and discussed with regard to observable trends in the IDM and balancing markets and how these may be linked to system conditions during and around the icing events. Where relevant, the findings are also connected to previous research and information regarding market behavior under extreme weather conditions. The chapter ends with limitations of the study and suggestions for future research directions.

5.1 Icing effects on prices, regulation and volatility in SE2

The need to restore balance during icing events in SE2 seems to correlate with increased average costs on the short-term electricity markets. Both the average ID3 price and the imbalance price exceed the spot price during the average hour of an identified icing event. The median values follow the same pattern, suggesting that the results are not necessarily solely driven by a few extreme observations. The elevated ID3 prices indicate increased market tension and a perceived risk of higher imbalance costs, which reflects a willingness among market participants to secure positions at higher ID prices in anticipation of production losses.

This interpretation is further supported by the correlation between the ID3 price and the icing factor. The analysis shows a weak negative relationship, which means that as the icing factor decreases, indicating more severe production losses, the ID3 price tends to rise. While the correlation is weak, the trend aligns with the idea that anticipated production losses lead to increased intraday market pressure. The scattered pattern, however, suggests that other factors also influence pricing, reinforcing the notion of uncertainty and varied market responses during these events.

Notably, the average ID3 spread is larger than the average imbalance spread, implying that market participants may overestimate the actual system imbalance risk. The fact that ID3 prices, on average, increase more than imbalance prices suggests that producers and traders act proactively to avoid the uncertainty associated with imbalance settlement, even if it means accepting a premium. This behavior may reflect not only a perceived risk of up-regulation during icing events, but also a lack of confidence in short-term wind forecasts. However, it is also possible that this premium is primarily concentrated at the beginning of the icing events, when the production loss is sudden and uncertainty is at its highest. As the event progresses and the system adapts the gap between ID3 and imbalance prices may narrow. Therefore, the observed average ID3 premium may not reflect a persistent overestimation throughout the entire duration of the events.

The large standard deviations observed for both ID3 and imbalance prices introduces an uncertainty, highlighting that market responses during icing conditions are highly variable and not easily generalised. Such variability underscores the complexity of system balancing under rapidly changing conditions. It also means that while averages provide useful insights, they may conceal important event-level dynamics.

While the average imbalance price increases during icing events in SE2 compared to the reference period, a larger share of hours still requires down-regulation rather than up-regulation. This indicates that factors beyond production deviations, such as system flexibility, forecast conservatism, or overcompensation by market participants, may also influence the direction of regulation. System flexibility refers to how easily the power system can respond to imbalances, while forecast conservatism implies that actors may underestimate expected production to avoid imbalance costs. Overcompensation can occur when several actors adjust in the same direction, creating a new imbalance in the opposite direction. Compared to the reference period, the distribution of regulation hours shifts slightly, with fewer down- and unregulated hours and a slight increase in up-regulation.

Notably, although down-regulation remains more frequent in terms of hours, the mean imbalance price still exceeds the spot price, suggesting that the financial impact of fewer but more expensive up-regulated hours outweighs the effect of more frequent down-regulation. This implies that the average cost of up-regulation during icing events is significantly higher than the costs from down-regulation, indicating an asymmetry in price risk. This interpretation is supported by the distribution plots, which show that the spread between imbalance and spot prices becomes both wider and more right-skewed during icing periods. High positive imbalance spreads that indicate costly up-regulation are more frequent, reflecting increased price volatility and elevated market stress.

The comparison of imbalance price spreads during icing events and the reference period further supports the hypothesis that icing events are associated with increased up-regulation risk. While the average imbalance spread is negative during the reference period, indicating more frequent or more costly down-regulation, it turns positive during icing events. Even though down-regulation remains more common in terms of hours, the financial impact of fewer but more expensive up-regulated hours appears to dominate. This reinforces the conclusion that the market's response to icing is shaped not only by actual physical imbalances, but also by perceived risk and uncertainty in short-term system conditions.

In addition to these shifts in average price levels, icing events are also associated with greater price volatility. This is evident in the standard deviation of imbalance prices, which is nearly twice as high during icing events compared to the reference period. Similar variability is observed in spot and ID3 prices as well, indicating that short-term price signals can become more unpredictable under icing conditions, further highlighting the challenge of managing risk during such events.

While these findings point to heightened market volatility, the large standard deviations also reflect substantial heterogeneity in the data. This variability introduces uncertainty into the analysis, suggesting that the observed trends are not consistently present across all events. Nevertheless, the results offer valuable insights into market behaviors and risk patterns that have occurred under icing conditions.

These findings partially support the hypothesis, showing increased prices and volatility during icing, although the persistent down-regulation indicates more complex system responses than initially expected.

5.2 Icing effects on prices, regulation and volatility in FI

Icing events in FI are associated with shifts in short-term market behavior compared to the DAM. Both average imbalance and ID3 prices tend to be higher than the spot price during these events, indicating that market participants anticipate higher balancing costs and act accordingly while trading on the IDM. Despite these elevated average prices, the median values are notably lower, particularly for ID3, where the spread to median spot price is negative, suggesting that a few extreme hours heavily influence the mean. This discrepancy highlights the heterogeneous nature of market responses to icing and underscores the need to analyse both average and distributional patterns, as well as analysing the specific events in more depth to understand the differences in the data.

The positive spread between average ID3 and spot price, and between imbalance and spot prices, indicate that market participants are willing to pay extra in the IDM to avoid the risk of expensive imbalance costs. This could reflect a fear of costly up-regulation and uncertainty about short-term forecasts during icing events. During these events, imbalance price spreads show greater variation, with both high and low values occurring more frequently. This is reflected in a wider and more uneven distribution, where particularly the large positive imbalance spreads associated with expensive up-regulation compared to spot stand out.

The distribution of regulating direction also changes during icing. The share of up-regulated hours increases substantially compared to the reference period, indicating that actual system imbalances due to production losses are more pronounced in FI than in SE2. This could potentially be due to less system flexibility or a higher dependence on wind power. Less system flexibility means the power system has limited ability to quickly respond to sudden changes in energy production, making price impacts from icing more pronounced. Together, the increased up-regulation and the rise in imbalance prices above spot support the idea that icing events cause more strain on the electricity system and make balancing more expensive.

The distribution of regulating direction also changes during icing. The share of up-regulated hours increases substantially compared to the reference period, suggesting that actual system imbalances caused by production losses are more pronounced in FI than in SE2. This could be attributed to a combination of lower system flexibility and a higher relative dependence on wind power in FI. Finland's generation mix offers limited short-term flexibility. As a result, FI frequently relies on imported flexibility from neighboring countries, particularly Sweden. However, when export capacity from Sweden is fully utilized, such as during cold, high-demand periods, the Finnish system may face constraints in securing external balancing support. In these situations, the domestic system must compensate, often leading to increased up-regulation and higher imbalance prices. Together, the increase in up-regulation hours and the observed rise in imbalance prices above spot prices support the view that icing events place additional strain on the electricity system, increasing the cost and complexity of maintaining real-time balance.

At the same time, the divergence between mean and median values, together with high standard deviations, points to a wide variation in the magnitude of market effects across different icing events. Some events trigger severe price reactions, while others appear to have a more limited impact. This indicates that icing events do not result in consistent market reactions, but instead add uncertainty that market participants need to handle.

The observed correlation between lower icing factors and higher ID3 prices, although weak, supports the interpretation that traders respond proactively to signs of production shortfall. This could indicate a risk-aware behavior that may overestimate actual imbalances, leading to more aggressive pricing in the IDM.

Icing events in Finland result in increased average price levels on both IDM and imbalance market, heightened volatility and a stronger shift toward up-regulation. While the exact outcomes vary, the overall pattern aligns with the hypothesis that production losses from icing materially affect short-term electricity markets, both through the level and distribution of imbalance prices and through risk perceptions among market actors on the IDM.

5.3 Market response to the onset of icing events

From the temporal analysis of the start and end of icing events, several trends and market dynamics are identified. The observed pattern suggests that the balancing market responds rapidly to unexpected production losses caused by icing in SE2, as indicated by the sharp increase in the imbalance spread shortly after the event begins. This reflects an immediate need for up-regulation to offset the sudden decline in wind power generation.

In contrast, the more gradual increase in the ID3 spread suggests that IDM participants react with a slight delay, likely due to the time required for updated forecasts and trading decisions to be reflected in market prices. This delay may be influenced by the gate closure times, one hour before delivery in SE2 and thirty minutes in FI, which limit the ability to act on the most recent information. The rising ID3 spread indicates increased trading activity and a greater willingness to secure positions above the spot price in response to production uncertainty.

Notably, the ID3 spread remains elevated even after the imbalance spread returns to near-zero levels, indicating that market participants continue to anticipate potential system imbalances or costly regulation. This sustained spread could be interpreted as a risk premium on the IDM, driven by the uncertainty surrounding the duration and extent of the reduction of turbine efficiency during icing events. In this context, IDM traders seem to maintain expectations of further up-regulation, resulting in persistently higher price spreads relative to the spot market.

At the start of icing events in FI (Figure 10a), the first notable observation is that the average spreads in both the balancing market and the IDM are positive throughout the analysed time period. This indicates that average up-regulation prices exceed the average spot price during the initial phase of these events, reflecting increased system stress due to the sudden decline in wind power production.

Notably, the imbalance spread begins to rise approximately two hours before the assumed start of the event. This suggests that the balancing market reacts earlier to the production loss, possibly because the system is more sensitive and have a greater need for up-regulation at earlier stages of the icing event. This pattern may indicate that the actual onset of icing, and the associated production loss, occurs earlier than what is captured by the defined icing factor threshold.

In contrast, the ID3 spread remains relatively stable during the hours leading up to the event but begins to increase gradually around hour 4. This delayed upward trend may reflect the slower response of IDM participants as they adjust to confirmed operational conditions and forecast updates. The increase implies a growing willingness to trade above spot price under uncertain production circumstances, indicating a perceived risk of costly regulation or sustained supply shortage.

The elevated imbalance spreads highlight the general up-regulation need triggered by reduced wind power output during icing events. Meanwhile, the positive spreads in the IDM support the interpretation that traders price in a risk premium in response to the uncertainty associated with icing-related production losses.

Furthermore, the wide confidence interval for both price spreads underline the variability in market reactions, suggesting that while the overall trend is upward, the scale of price responses differs across events. This implies that an average price situation during the onset of an icing event is difficult to identify and generalise only based on a production loss factor. In some cases, price movements could be immediate and pronounced, while in others they are delayed or muted, possibly depending on system conditions, event severity, or other market expectations. As such, the observed patterns should be interpreted as indicative tendencies rather than predictive rules. Future research could help clarify under which conditions the start of an icing event triggers strong market responses and when the impact remains limited.

These findings suggest that the onset of icing events in both SE2 and FI can, in some cases, trigger rapid and anticipatory responses in the balancing market, while the intraday market reacts more gradually, which is consistent with the hypothesis of this study.

5.4 Market behavior during recovery from icing events

During the final hours and the three hours following the end of the icing events in SE2, trends are less pronounced compared to the onset of the events. Both the imbalance and ID3 spreads fluctuate around zero, with the ID3 spread showing a slight positive deviation. This suggests that as wind power production begins to recover, the need for balancing varies. The hypothesis that a sudden return of wind generation could lead to excess supply and trigger down-regulation does not appear to be supported by the data in this study.

In Finland, the average ID3 spread begins to decline approximately five hours before the end of icing events but remains positive throughout, indicating continued market expectations of up-regulation needs. In contrast, imbalance spreads fluctuate without a clear trend, although the average imbalance price remains above the spot price. These observations suggest that the recovery from icing events could be more gradual, resulting in less distinct price movements in the balancing market. This interpretation is supported by the development of the icing factor, which reaches only about 55 % three hours after the end of the events, indicating that wind power output has only recovered to roughly half of its normal capacity until the end of the studied time period.

5.5 Price signal sensitivity to extreme icing events

Building on the previous analyses of general market patterns and dynamics observed at the start and end of icing events, it is valuable to note that much of the observed market response appears to be driven by a limited number of extreme cases. When the most extreme observations are excluded, by removing the 5th and 95th percentiles, the temporal analysis results become noticeably less distinct. Many of the previously observed price trends around icing events flatten or disappear entirely.

This suggests that icing does not lead to uniform market responses. Instead, the high variability across events implies that icing introduces uncertainty rather than a predictable outcome. The clearest market signals seem to be associated with the most severe events, reinforcing the event-specific nature of these impacts.

While this supports the conclusion that icing can cause significant price effects, it also highlights the importance of context, such as system conditions, event severity and timing. Rather than capturing a uniform pattern, the results reflect an average shaped by both mild and extreme cases. Generalisations should therefore be made with caution and the observed tendencies interpreted as indicative rather than deterministic.

5.6 Regional differences in market reactions to icing events

While the analyses were conducted using a consistent methodology across both SE2 and Finland, the results differ in several aspects as shown in the results. These differences may reflect the distinct market structures, generation mixes and transmission constraints in each bidding zone. As such, the findings should be interpreted within the context of each area rather than as universal conclusions about icing effects in the Nordic electricity market.

While both SE2 and Finland experience higher prices and increased volatility during icing events, several key differences emerge. In Finland, market responses were generally stronger: average spreads and standard deviations are higher and the balancing market tends to react earlier, often before wind output has dropped below 40 %. This suggests greater sensitivity to production losses and possibly tighter system conditions between supply and demand.

The direction of regulation also differs notably. In SE2, down-regulation remains more common even during icing, which could indicate higher system flexibility or the presence of offsetting deviations. In FI, however, icing events coincide with a clear shift toward up-regulation, reflecting a more strained market. This may be due to a higher dependence on wind power and limited access to flexible regulating hydropower compared to SE2.

Overall, the findings imply that icing has a more pronounced and consistent impact on the Finnish ID and balancing market. While large variations exist in both regions, some patterns, such as the frequent occurrence of positive ID3 spreads in FI, may still offer helpful guidance. For instance, these signals could support more confident trading above the spot price when icing is observed, although decisions should always account for case-by-case variability.

5.7 Discussion of observed effects

This thesis demonstrates that icing events can cause substantial price impacts in both the IDM and balancing markets. The findings confirm previous research linking turbine underperformance during icing to increased system stress and add new knowledge by illustrating how markets respond dynamically during the start and end phases of such events.

Short-term price spikes and sustained ID risk premiums suggest that market participants react not only to actual production losses, but also to the anticipation of future imbalances. For traders, this highlights the potential value of incorporating real-time or forecast-based indicators of icing into trading strategies. Being able to anticipate when production drops below certain thresholds, such as the 40 % level used in this study, could provide a helpful basis for decision-making under icing conditions and help mitigate imbalance costs more effectively.

Understanding how icing impacts prices and balancing outcomes is important for both market oversight and operational strategy. For TSOs and regulatory authorities, insights into the effects of icing on price volatility and system imbalances can inform evaluations of market efficiency, reliability and incentive structures, potentially pointing to the need for improved forecasting tools, risk management practices, or adaptations in market design to strengthen system resilience in winter. For wind producers, the findings highlight the value of proactive icing management through de-icing technologies, predictive maintenance, or strategic bidding adjustments during high-risk periods.

However, generalising the effects of icing events is difficult, as the results vary considerably between individual cases. The large differences in average ID3 and imbalance prices across events suggest that other factors, such as system conditions, forecast accuracy, or the severity and duration of icing, may also play a crucial role. Without further investigation into these contextual variables and the relation between them and the market outcome of the specific icing event, it is difficult to establish a consistent pattern.

Nevertheless, the observed average price levels in the intraday and balancing markets during identified icing events could serve as a reference point when designing trading strategies. For market participants with access to short-term forecasts indicating potential icing, using historical average prices as guidance may be a useful approach when making trading decisions. Understanding the potential magnitude and direction of these effects is important for both risk assessment and strategic positioning under uncertain production conditions. While this approach is not definitive, it could be evaluated over time to assess how well the expected outcomes align with actual market behavior.

5.8 Limitations of the study

Despite these insights, several limitations should be considered. The analysis is based on data from Vattenfall's wind farms, which do not represent total wind power deviations in each bidding zone. The event detection method also relies on a fixed threshold, production dropping below 40 % of expected output, which is a simplification for the analysis. Conducting a sensitivity analysis using different thresholds could improve the robustness of the findings and clarify whether certain effects only occur under more severe conditions.

It is also important to note that electricity prices are influenced by many interacting factors. While this study focuses on icing, other elements such as transmission constraints, outages, or concurrent weather phenomena can strongly affect price dynamics. Although a broad reference period is used to contextualise the results, it remains difficult to fully isolate icing effects from the overall market environment.

Moreover, mean spreads between market prices and the spot price provide valuable insight into expected profitability. As discussed in the analysis, average price levels observed during icing events can be used as a reference point when designing trading strategies; for instance, a positive average spread implies that trading above the spot price on the intraday market could, on average, yield a more favorable outcome than being settled at the imbalance price. However, this approach also has limitations, as averaging tends to mask important aspects of price risk, such as the asymmetry and volatility of regulation prices. While extreme values are less frequent, they often carry significant financial implications. Therefore, relying solely on average values may underestimate the uncertainty faced by market participants.

5.9 Future work

Future research could further develop this analysis in several directions. A natural next step would be to investigate each identified icing event individually to determine whether large price movements coincide with other system factors such as congestion, generation outages, or unusually high demand. This would help distinguish the specific role of icing from other causes of market stress.

Another important extension would be to perform a sensitivity analysis of the 40 % threshold used to define icing events. Testing alternative values, such as 30 % or 50 %, could clarify how the severity of production loss influences price responses and whether certain threshold levels better capture market sensitivity to icing-related production deviations.

In addition, the recent shift to 15-minute resolution in the Nordic IDM and balancing markets has fundamentally changed how imbalances are priced and resolved. This reform allows trading and balancing much closer to delivery, which could improve the system's ability to react to sudden production losses, such as those caused by icing. A comparison of icing events before and after this market design change could provide insights into whether it has helped mitigate the operational and financial effects of production uncertainty.

6 Conclusions

This thesis examined how icing-induced wind power losses affect short-term electricity markets in SE2 and FI. The study identified 121 icing events in SE2 and 91 in FI and the results show that the studied events tend to be associated with higher average prices and increased volatility in both the intraday and balancing markets. In both areas, average ID3 and imbalance prices exceed the spot price. Up-regulation costs appear to outweigh down-regulation costs in both SE2 and FI, pointing to asymmetric price risk, where upward imbalances tend to be more costly than downward ones due to higher regulation prices.

Regional differences are observed where SE2 tends to show more down-regulation during both icing events and the reference period. In contrast, FI shows a stronger shift toward up-regulation during icing events compared to the reference period. Elevated price volatility and wider spreads were observed in both regions, but these effects were more pronounced in FI.

The analysis of price signals around the start and end of icing events suggests that the balancing market can react early and strongly to anticipated production losses, while the intraday market adjusts more gradually, consistent with the study's hypothesis. However, these effects are not uniformly observed across all events. Toward the end of icing periods, market signals are less distinct, likely reflecting the gradual and uncertain recovery of wind output. In FI, average prices in both the IDM and balancing market remain above the spot price during both the onset and recovery phases. Overall, the results point to indicative but context-dependent market responses, highlighting the importance of case-specific factors such as event severity, timing and system conditions.

These findings point to the need for a better understanding of what characterizes high-impact icing events, whether it is severity, duration, or system context. Such insights could help operators, traders and producers refine forecasts and risk mitigation strategies. As the system grows more weather-sensitive, this becomes increasingly important.

While the results broadly support the initial hypothesis that icing increases prices, regulation needs and volatility, the effects vary across events and regions. The conclusions should therefore be viewed as exploratory: they suggest that icing influences market dynamics, but also underscore the complexity and context-dependence of these effects. As such, they offer a foundation for further research rather than firm generalisations.

References

[1] Finnish Wind Power Association. Wind power in 2023 in finland, 2023. Accessed: 2023-10-01.

[2] Svenska kraftnät. Om olika energikällor, 2023. Accessed: 2023-10-01.

[3] Tomas Wallenius and Ville Lehtomäki. Overview of cold climate wind energy: challenges, solutions, and future needs. *Wiley Interdisciplinary Reviews: Energy and Environment*, 5(2):128–135, 2016.

[4] Olivier Parent and Adrian Ilinca. Anti-icing and de-icing techniques for wind turbines: Critical review. *Cold regions science and technology*, 65(1):88–96, 2011.

[5] Energimarknadsinspektionen. Utvärdering av kostnader och nyttor av smarta elnät. Technical Report Ei R2021:06, Energimarknadsinspektionen (Ei), 2021. Accessed: 2025-03-18.

[6] Sveriges Riksdag. De svenska energimarknaderna – en samhällsekonomisk analys, 2024.

[7] Nord Pool. Intraday market, 2024. Accessed: 2025-02-27.

[8] Klaus Skytte. The regulating power market on the nordic power exchange nord pool: an econometric analysis. *Energy Economics*, 21(4):295–308, 1999.

[9] Fayçal Lamraoui, Guy Fortin, Robert Benoit, Jean Perron, and Christian Masson. Atmospheric icing impact on wind turbine production. *Cold Regions Science and Technology*, 100:36–49, 2014.

[10] Petr Spodniak, Kimmo Ollikka, and Samuli Honkapuro. The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The nordic case. *Applied Energy*, 283:116063, 2021.

[11] H. Ganander and G. Ronsten. Design load aspects due to ice loading on wind turbines: A preliminary study based on sourva measurements, as part of the new ice tools project wp3. In *Boreas VI*, 2003.

[12] Henry Seifert, Annette Westerhellweg, and Jürgen Kröning. Risk analysis of ice throw from wind turbines. *Boreas*, 6(9):2006–01, 2003.

[13] Göran Ronsten. Swedish experiences of wind power in cold climate: icing, ice throw and deicing; svenska erfarenheter av vindkraft i kallt klimat: nedisning, iskast och avisning, Jun 2004.

[14] D. Justus. Wind power integration into electricity systems, case study 5 to the oecd/iea report on international energy technology collaboration and climate change mitigation. Technical report, OECD/IEA, 2005. Accessed: 2025-03-18.

[15] P. Norgard, G. Giebel, H. Holttinen, L. Söder, and A. Petterteig. Fluctuations and predictability of wind and hydropower. Technical report, EU Project: Wind Power Integration in Liberalised Electricity Markets, Roskilde, Denmark, 2004. Accessed: 2025-02-13.

[16] H. Auer, M. Stadler, G. Resch, C. Huber, T. Schuster, H. Taus, L. H. Nielsen, J. Twidell, and D. J. Swider. Cost and technical constraints of res-e grid integration, 2004.

[17] Vattenfall. Hållbar produktion, 2025. Accessed: 2025-02-28.

[18] Magnus Brolin, Camille Hamon, and Sofia Nyström. En generell beskrivning av intradagmarknadens funktion, 2021.

[19] He Shen, Fupeng Zhang, Wenfeng Guo, Zhi Xu, and Yan Li. An experimental study on surface de-icing of glass fiber-reinforced plastic plate by electrothermal and ultrasonic coupling method. *Applied Thermal Engineering*, 265:125570, 2025.

[20] Khaled Alshehri, Subhonmesh Bose, and Tamer Başar. Centralized volatility reduction for electricity markets. *International Journal of Electrical Power & Energy Systems*, 133:107101, 2021.

[21] J. Aho, R. Cattin, M. Durstewitz, T. Wallenius, et al. Ice detection guidelines for wind energy applications. Technical Report IEA Wind Task 19 Report, IEA Wind TCP Task 19, 2022. Accessed: 2025-05-15.

[22] Sara Fogelberg and Ewa Lazarczyk. Wind power volatility and its impact on production failures in the nordic electricity market. *Renewable Energy*, 105:96–105, 2017.

[23] Marie Cecilie Pedersen, Tobias Ahsbahs, Wiebke Langreder, and Morten Lybech Thøgersen. On the modelling chain for production loss assessment for wind turbines in cold climates. *Cold Regions Science and Technology*, 216:103989, 2023.

[24] Zhijin Zhang, Hang Zhang, Xu Zhang, Qin Hu, and Xingliang Jiang. A review of wind turbine icing and anti/de-icing technologies. *Energies*, 17(12):2805, 2024.

[25] Linyue Gao, Yongqian Liu, Linyue Ma, and Hui Hu. A field study of ice accretion and its effects on the power production of utility-scale wind turbines. *Renewable Energy*, 167:1042–1051, 2021.

[26] Sirui Lyu, Yuhan Wang, Zixiao Tian, Yiwei Ma, Zhicheng Liu, Xin Li, Yingchen Zhang, and Zhe Wang. Data-driven approaches for icing loss prediction in wind power generation: A review. *Renewable and Sustainable Energy Reviews*, 187:112418, 2024.

[27] Econstor. The relevance of wholesale electricity market places: the nordic case. Research report, Econstor, 2020. Accessed: 2025-04-11.

[28] Nord Pool. Transition to 15-minute market time unit (mtu), 2025. Accessed: 2025-05-20.

[29] Nordic TSOs. Nordic balancing model: Balancing energy market design. Technical report, Fingrid, Energinet, Statnett, Svenska kraftnät, 2020. Accessed: 2025-04-11.

[30] CE Delft and Microeconomix. Refining short-term electricity markets to enhance flexibility: Stocktaking as well as options for reform in the pentalateral energy forum region. Technical report, Agora Energiewende, Berlin, Germany, 2016. Study commissioned by Agora Energiewende, Report number 099/02-S-2016/EN.

[31] Richard Scharff and Mikael Amelin. Trading behaviour on the continuous intraday market elbas. *Energy Policy*, 88:544–557, 2016.

[32] Karsten Neuhoff, Nils Ritter, Anselm Salah-Abou-El-Enien, and Periklis Vassilopoulos. Intraday markets for power: Discretizing the continuous trading. *Energy Economics*, 64:364–378, 2017.

[33] ENTSO-E. Single intraday coupling (sidc), 2025. Accessed: 2025-05-20.

[34] Arthur Henriot. Economic curtailment of intermittent renewable energy sources. *Energy Policy*, 49:663–672, 2012.

[35] Svenska kraftnät. Balansansvar och reglerkraft, 2022. Accessed: 2025-04-11.

[36] Nordic balancing philosophy. Technical report, Nordic Operations Development Group, 2021. Updated 2021-11-10.

[37] Yih-Huei Wan, Erik Ela, and Kirsten Orwig. Development of an equivalent wind plant power-curve. In *WindPower 2010*. National Renewable Energy Laboratory (NREL), 2010.

[38] EPEX SPOT. The power of indices: What purpose do price signals have?, February 2024. Accessed: 2024-03-01.

[39] Michal Narajewski and Florian Ziel. Econometric modelling and forecasting of intraday electricity prices. *arXiv preprint arXiv:1812.09081*, 2019.

[40] ENFOR. Wind power forecasting software windfor™, 2025. Accessed: 2025-05-20.

[41] Nord Pool. Day-ahead prices, 2025. Accessed: 2025-04-20.

A Additional results in SE2

Distribution of imbalance spreads and ID3 spreads

Figure 12 shows the distribution of imbalance spreads and ID3 spreads relative to the spot price for all hours during icing events. Imbalance spreads equal to zero are excluded, as their high frequency would otherwise dominate the graph and hinder interpretation.

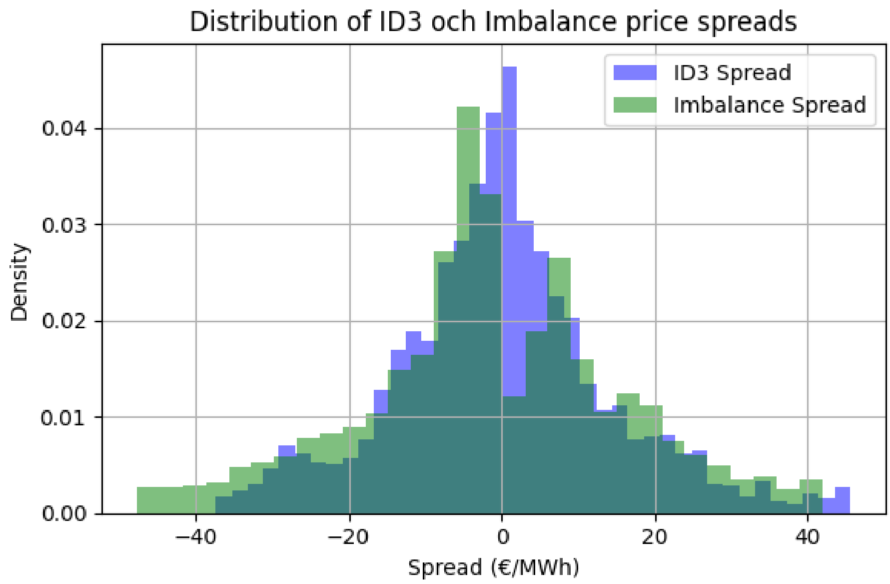


Figure 12: Distribution of ID3 spread and imbalance spread from spot price in SE2 during the icing events

Price spreads during start and end of icing events for different spot intervals

The following figures illustrate the same ID3 spread and imbalance spread over time as shown in the results section, however, these are divided into different spot price intervals and wind speed intervals.

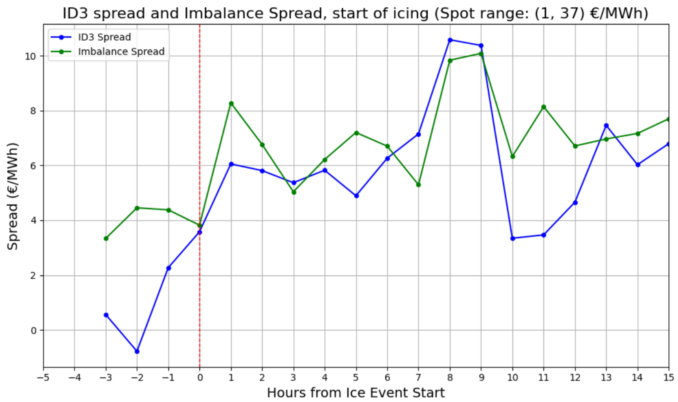


Figure 13: ID3 spread and imbalance spread around the start of icing events in lower spot price interval in SE2

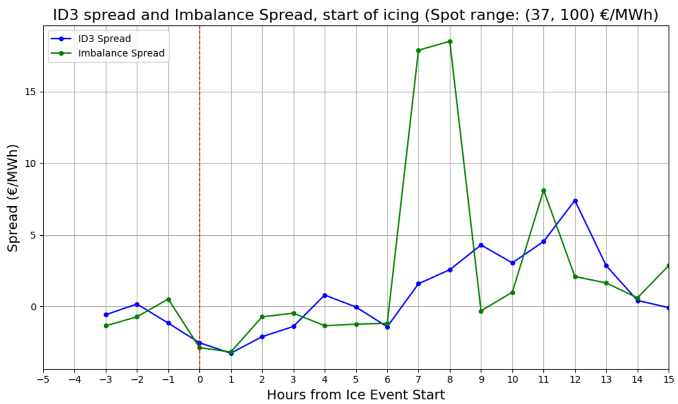


Figure 14: ID3 spread and imbalance spread around the start of icing events in medium spot price interval in SE2

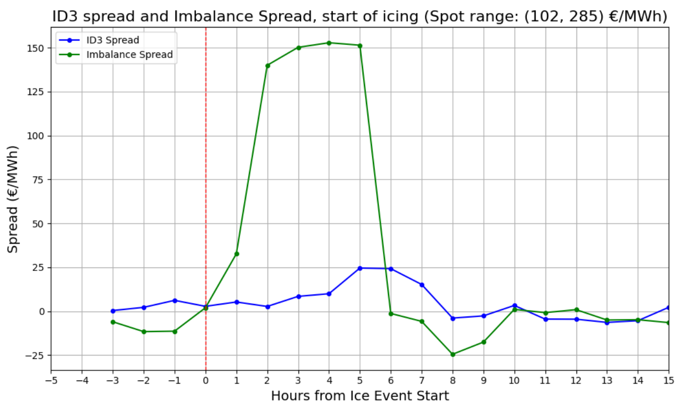


Figure 15: ID3 spread and imbalance spread around the start of icing events in higher spot price interval in SE2

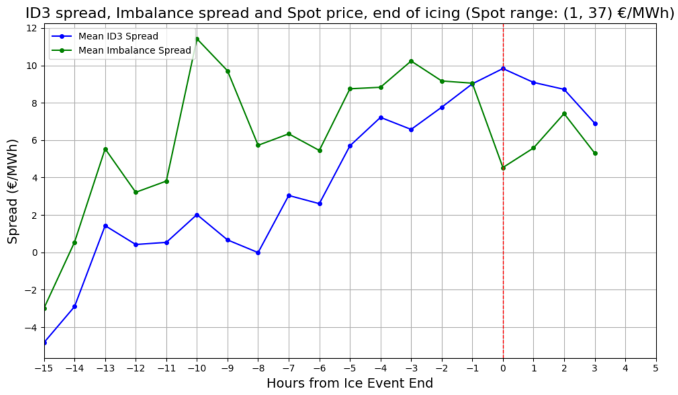


Figure 16: ID3 spread and imbalance spread around the end of icing events in lower spot price interval in SE2

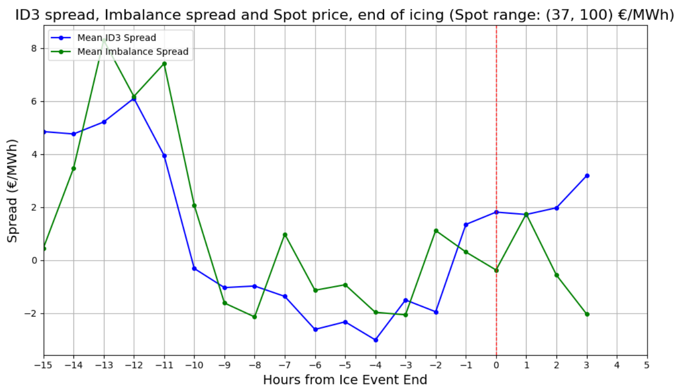


Figure 17: ID3 spread and imbalance spread around the end of icing events in medium spot price interval in SE2

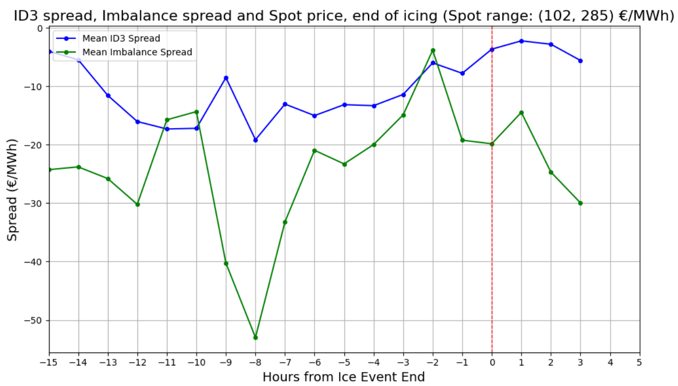


Figure 18: ID3 spread and imbalance spread around the end of icing events in high spot price interval in SE2

Start and end of icing events for different wind intervals

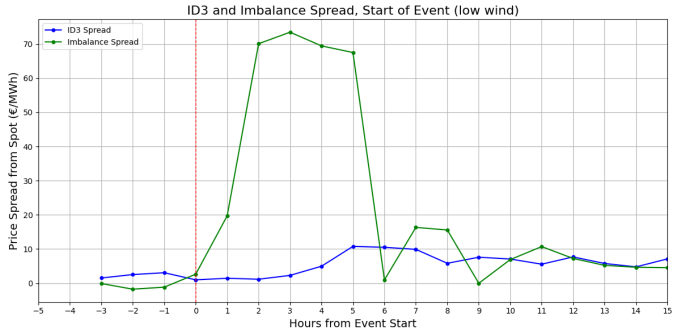


Figure 19: ID3 spread and imbalance spread around the start of icing events in lower wind speed interval ($< 7m/s$) in SE2

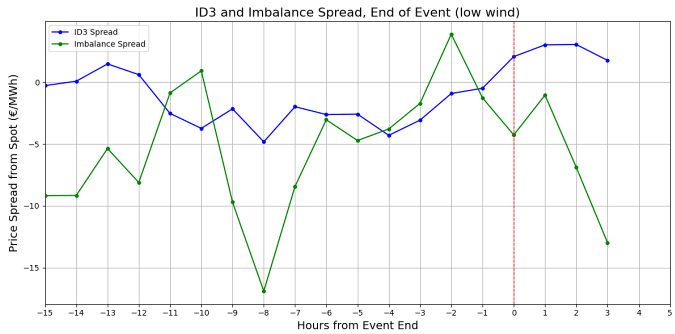


Figure 20: ID3 spread and imbalance spread around the end of icing events in lower wind speed interval ($< 7m/s$) in SE2

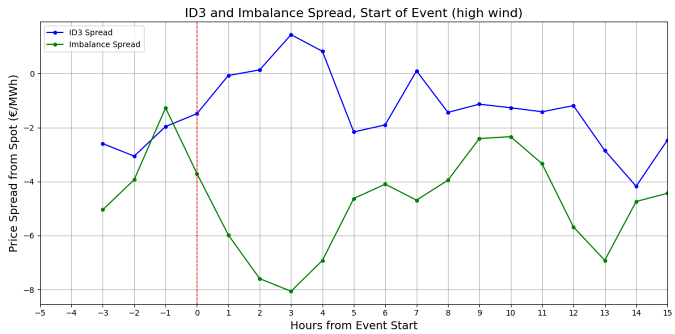


Figure 21: ID3 spread and imbalance spread around the start of icing events in higher wind speed interval ($> 7m/s$) in SE2

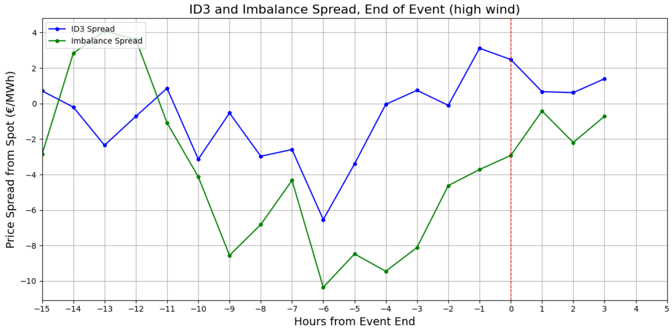


Figure 22: ID3 spread and imbalance spread around the end of icing events in higher wind speed interval (> $7m/s$)in SE2

B Additional results in FI

Distribution of imbalance spreads and ID3 spreads

Figure 23 shows the distribution of imbalance spreads and ID3 spreads relative to the spot price for all hours during icing events. Imbalance spreads equal to zero are excluded, as their high frequency would otherwise dominate the graph and hinder interpretation.

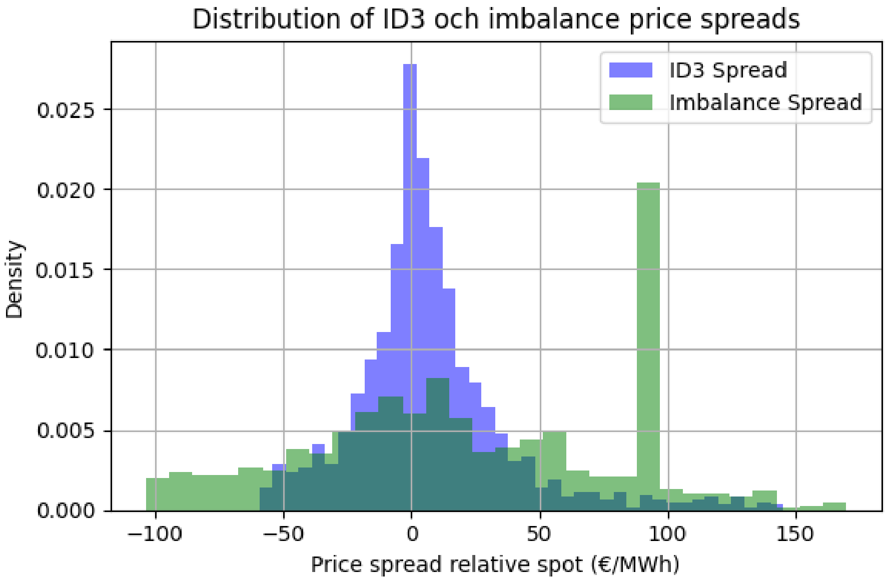


Figure 23: Distribution of ID3 spread and imbalance spread from spot price in SE2 during the icing events

Price spreads during start and end of icing events for different spot intervals

The following figures illustrate the same ID3 spread and imbalance spread over time as shown in the results section, however, these are divided into different spot price intervals and wind speed intervals.

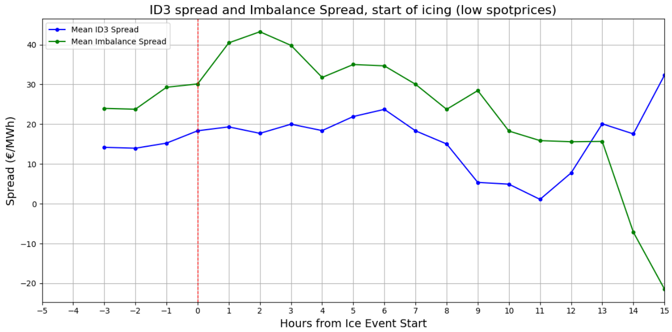


Figure 24: ID3 spread and imbalance spread around the start of icing events in lower spot price interval in FI

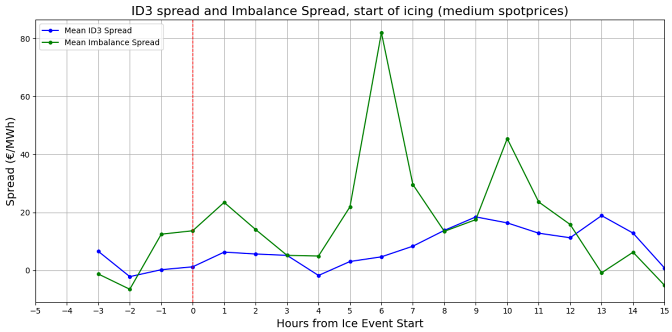


Figure 25: ID3 spread and imbalance spread around the start of icing events in medium spot price interval in FI

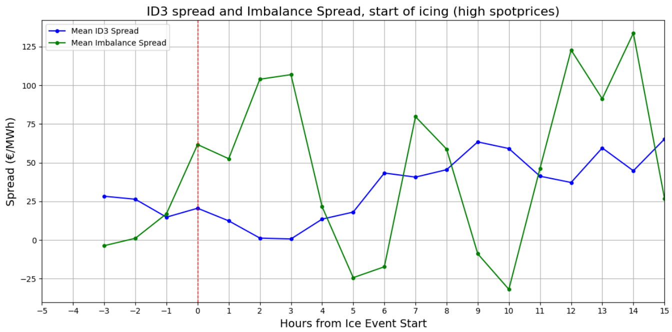


Figure 26: ID3 spread and imbalance spread around the start of icing events in higher spot price interval in FI

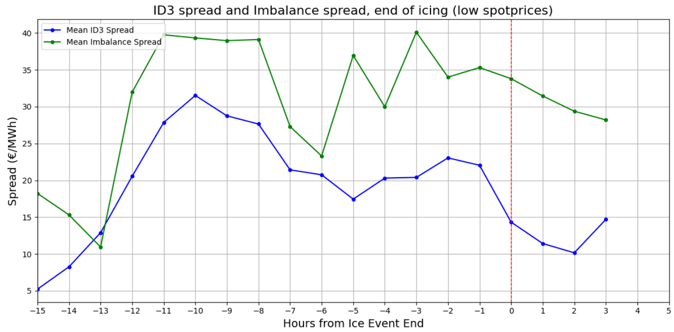


Figure 27: ID3 spread and imbalance spread around the end of icing events in lower spot price interval in FI

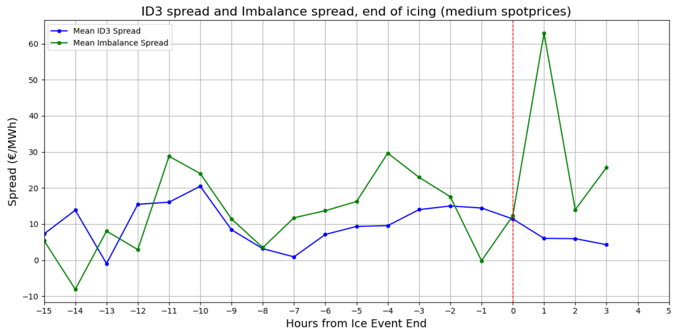


Figure 28: ID3 spread and imbalance spread around the end of icing events in medium spot price interval in FI

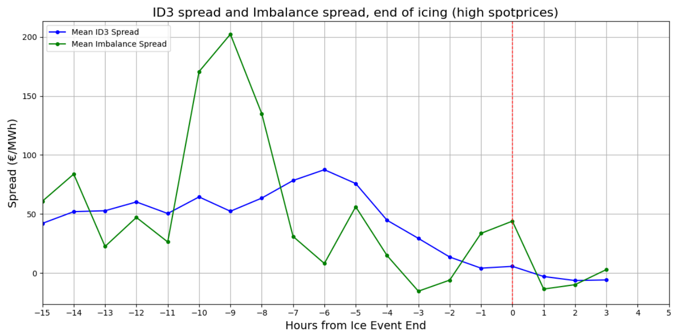


Figure 29: ID3 spread and imbalance spread around the end of icing events in high spot price interval in FI

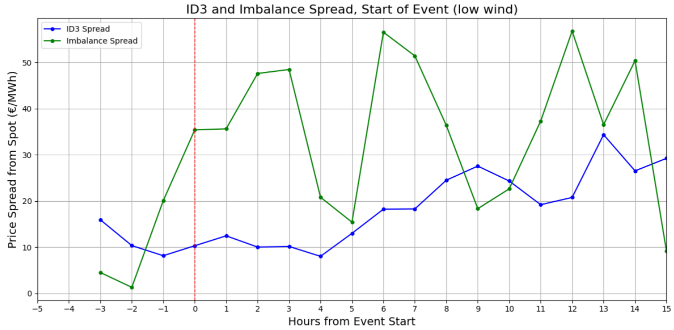


Figure 30: ID3 spread and imbalance spread around the start of icing events in higher wind speed interval ($< 7m/s$) in FI

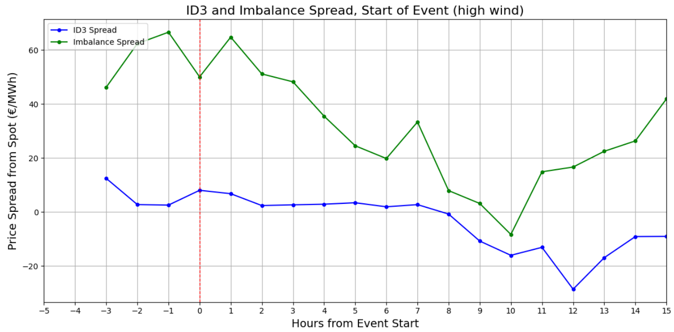


Figure 31: ID3 spread and imbalance spread around the start of icing events in higher wind speed interval ($> 7m/s$) in FI

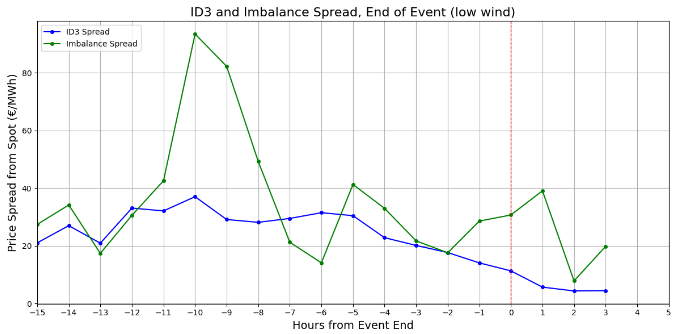


Figure 32: ID3 spread and imbalance spread around the end of icing events in lower wind speed interval ($< 7m/s$)in FI

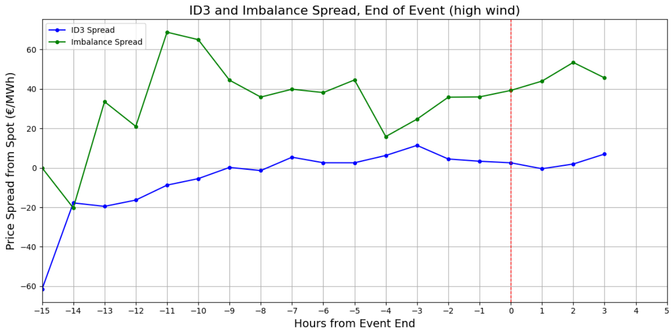


Figure 33: ID3 spread and imbalance spread around the end of icing events in higher wind speed interval (> $7m/s$) in FI