Master’s Programme in Advanced Energy Solutions

The effects of wind power forecast errors in intraday electricity markets in Finland

Comparison of day-ahead markets and forecast errors with intraday markets

---

Mikko Jantunen

Master’s Thesis
2023

Aalto-yliopisto
Aalto-universitetet
Aalto University

Author Mikko Jantunen

Title of thesis Effects of wind power forecast errors in intraday electricity markets

Programme Advanced Energy Solutions

Major Sustainable Energy Systems and Markets

Thesis supervisor Assistant Prof. Mahdi Pourakbari Kasmaei

Thesis advisor Jukka-Pekka Häkli, M.Econ.

Collaborative partner UPM Energy

Date 14.03.2023 **Number of pages** 58 + 7 **Language** English

Abstract

In this thesis, the effects of wind power forecast errors were studied within intraday markets between 2019 and 2022 H1. The study is done in the Finnish price zone and only Finnish wind power production is considered. The difference between day-ahead and hour-ahead wind power forecast is compared with day-ahead electricity price and volume weighted intraday electricity price three hours before delivery. This result was compared with the same forecast error and the price difference of day-ahead electricity price and imbalance settlement price. Also, the costs of intraday balancing of wind power are calculated and compared to potential imbalance settlement costs in a rudimentary manner. Furthermore, the volume drivers for the intraday market are analyzed.

The study shows that wind power does affect intraday pricing and volumes. Compared to imbalance pricing, the intraday market has been successful means of balancing in normal scenarios. In shock scenarios, the intraday markets are not that effective market as it lacks depth and consumer-side market players. Average intraday prices are cheaper than imbalance prices when it comes to balancing wind power forecast errors. Consumption errors affect the intraday market volumes more than wind power forecast errors.

Keywords Intraday, wind power, forecast, imbalance

Aalto-yliopisto
Aalto-universitetet
Aalto University

Tekijä	Mikko Jantunen
Työn nimi	Päivää edeltävän tuulivoimaennusteen virheen vaikutukset päivän sisäisessä sähkökaupankäynnissä
Koulutusohjelma	Advanced Energy Solutions
Pääaine	Sustainable Energy Systems and Markets
Vastuuopettaja/valvoja	Assistant Prof. Mahdi Pourakbari Kasmei
Työn ohjaaja	Jukka-Pekka Häkli, KTM
Yhteistyötaho	UPM Energy
Päivämäärä 14.03.2023 **Sivumäärä** 58 + 7	**Kieli** Englanti

Tiivistelmä

Tässä diplomityössä tutkitaan tuulivoiman ennustevirheitä intraday kaupankäynnin kannalta ajanjaksolta 2019 – 2022 H1. Tutkimus on tehty vain Suomen hinta-alueelta ja vain Suomen tuulivoimatuotanto on otettu huomioon. Päivää- ja tuntia edeltävää tuulivoimaennustetta verrataan Spot hintaan, sekä kolmea tuntia ennen toimitusta käytyyn intraday hintaan. Tätä tulosta verrataan samaan tuulivoiman ennustevirheeseen ja Spot hinnan sekä tasesähkön hinnan eroon. Lisäksi tuulivoiman intraday-tasapainottamisen kustannuksia lasketaan ja verrataan täysin tasevirheellä laskutettuun taseeseen. Myös intradayn volyymiajureita tarkastellaan.

Tämä tutkimus näyttää, että tuulivoima vaikuttaa intraday kaupankäynnin hintoihin sekä volyymeihin. Verrattuna tasepoikkeaman hintaan, intraday on verrattain tehokas tasapainottamisen keino normaaleissa tilanteissa. Suuremmissa ennustevirhetilanteissa intraday ei ole riittävä keino tasapainottaa ennustevirheitä, sillä intradaysta puuttuu markkinoiden syvyyttä ja kuluttajapuolen markkinatoimijoita. Keskimääräisillä intraday hinnoilla tuulivoiman ennustevirheiden tasapainottaminen on halvempaa intradayssa kuin sen maksaminen tasevirheenä. Kulutuksen ennustevirheet ovat suurempi volyymiajuri intraday kaupankäynnissä kuin tuulivoiman ennustevirheet.

Avainsanat intraday, tuulivoima, ennuste, tasesähkö

Contents

Preface

This is the part I use to thank everyone along my studies. All university actives from the Guild of Civil Engineers and Aalto University Student Union made this journey enjoyable. All events we have organized and attended have really been unique and a blast. This really can’t be experienced anywhere else. Thank you to ITMK’19, JTMK’20, JTMK’21, TJ’21, T150 VujuTMK and AaltoDJ.

Thank you UPM Energy for an interesting and topical topic for the thesis. Current world events have made this subject ever more interesting as markets are more volatile than ever. Thank you also to my thesis advisor JP, supervisor Mahdi and colleague Saila for being helpful when I needed a vision for what to write.

UPM Energy is the second largest electricity producer in Finland. It generates low-emission electricity in its own and co-owned power plants. In addition, UPM Energy's operations include physical electricity and financial portfolio management as well as services to industrial electricity consumers and producers.

Espoo, 14.3.2023

Mikko Jantunen

Abbreviations

BRP	Balance responsible party
DA	Day-ahead
ID	Intraday
LCOE	Levelized cost of electricity
mFRR	Manual frequency restoring reserve
OPX	Other power exchanges
SDAC	Single day-ahead coupling
SIDC	Single intraday coupling
TSO	Transmission system operator
VALCOE	Value added levelized cost of electricity
VWAP	Volume weighted average price

1 Introduction

The amount of intermittent and forecast-based renewable electricity is increasing in the Finnish electricity system. The amount of new wind power in 2022 is planned to increase by 56 % of the total amount of wind power capacity at the end of 2021 (Tuulivoimayhdistys, 2022a). As electricity cannot be yet stored efficiently on a large scale, the same amount of electricity must be produced at the same time as it is consumed. Production of renewable energy sources cannot necessarily be forecasted accurately enough for day-ahead (DA) actions. The forecast error is dealt with in intraday (ID) balancing markets, or it is either billed or compensated as an imbalance depending if the error was surplus or deficit. It is stated in the contract between the Finnish transmission system operator (TSO), Fingrid, and the balance responsible, that the changes in production or consumption must be balanced with reasonable means. (Fingrid, 2022a) Balance responsible is, for example, a big electricity production company which operates one or multiple power plants.

In similar works, research on the connection between ID prices and renewable forecast errors has been done for Nordic countries (Karanfil, 2017) and Denmark (Spodniak, 2020), but not specifically about Finland nor in recent years, while the share of wind power has grown significantly.

The focus of this thesis is to investigate if there is a strong correlation between the DA price and the ID price of electricity when there is a change in the DA and ID wind power forecast. This correlation is then compared with other electricity prices, for example, the imbalance cost of electricity.

Therefore, the primary research questions for this thesis are:

(1) Is the forecast error of wind power efficiently traded in ID markets, or are there other markets in which the balance error is dealt with?

(2) If the ID market is not the primary marketplace for forecast errors, then why is it so, and should it become more widely used?

(3) What other connections are there between electricity markets and wind power?

The short-term energy markets are an important research topic as the share of intermittent renewable production is rising rapidly, and balancing mechanisms will be under stress in the future, if not already. Comparing the previous research to new results can hint at the direction of how each marketplace is and will be utilized as a balancing source. Moreover, the research on the overall system cost of the energy transition is also important from an economic point of view. Efficient ID markets benefit both producers and consumers as this enables more efficient balancing for forecast errors. Efficient ID markets could mitigate the system integration cost of renewables as balancing risks for intermittent renewable production could be managed better. Identifying ID market fundamentals and price drivers will help price discovery.

This thesis compares Finnish Spot and ID market behavior to wind power forecast errors. Cross-border flows are not taken into account, nor other individual production or consumption error sources are in focus, but total consumption errors are considered. The time scope of this study is 1.1.2019 – 30.6.2022 (2022 H1).

2 Literature review

There is some research about renewable production forecasts and DA-ID and regulating electricity price differences. Most of the research focuses on European markets, more specifically, Scandinavian Nordics and Germany. Even though Finland is included in one of the studies, the study was done five years ago when there were under half of the wind power capacity constructed. Regardless, earlier studies provide a good foundation for this study as they can be used to support the findings in this research.

Rintamäki et al. (2020) studied the DA and ID markets and how a producer, which is flexible, can operate in a high-volume ID environment. They found that there are fewer market participants in ID markets than in DA markets, as there are bigger barriers to operating in the ID market. These barriers enable the few market participants to exploit market power. They also provided a theory that as intermittent renewable energy gets more common and drives DA prices, the ID markets become a marketplace for parties who pursue higher profits.

Amelin (2015) evaluated the Nordic ID trading scheme in a hydro-wind dominant electricity system. The study concluded that the Nordic electricity system is highly reliant on flexible hydropower, which can be used as frequency control and balancing power. Another discovery was that generating units' start-up time is a limiting factor in the efficiency of ID markets. An interesting finding was that, based on the case studies, increasing the share of wind power increased the impact of both ID trading and demand response in balancing power prices.

Söder et al. (2020) studied European electricity generation capacity and wind power. Finland was also a subject among these countries. They found that Finland is reliant on imported electricity. Furthermore, the use of wind power as a strategic reserve does not fulfill the requirements for that reserve, nor would it be financially profitable to limit the use of wind power to that reserve in Finland. Their conclusion about Finland is that wind power can decrease the need for strategic reserves.

Spodniak et al. (2020) studied the impact of wind power and its effects, among other variables, in short-term markets during 2015 – 2017 in Finland, Denmark and Sweden. They found that there is a certain threshold of wind power penetration, after which forecast errors affect the ID markets. They also found out that at the start of their research period, in 2015, Finland's wind power capacity was not over that threshold, but in 2017 there was an impact. Moreover, they found that demand was the main driver of the DA-ID market spread in Finland. They also expect that ID and regulating power markets are becoming more relevant in the future with more trading volume and price discovery.

Garnier and Madlener (2015) studied how to balance forecast errors in ID markets. They created a model which would execute trades in the market as efficiently as possible and thus noted the variables, which affect the ID market's price signals. They focused on both wind power and photovoltaics in situations when the producer does not have the capacity to balance the forecast errors in their own portfolio. They study German electricity markets and create a model, which trades in that price zone. They define market liquidity as the primary driver of ID trade costs. The second driver is the bidding strategy of the market operator.

Hu et al. (2021) analyzed Swedish intraday markets, comparing the wind power forecast errors with the price premium of ID markets during 2015 – 2018. They found that even though Swedish ID markets have a small trading volume, the market is functional and is based on fundamentals such as production and consumption forecast imbalances in all Swedish price areas. Wind power forecast errors did not affect SE1 in northern Sweden, as wind power penetration in that price area is low. They noted in their research that balancing energy prices might decrease in the price area when there is a positive error in wind power production forecasts. However, they could not estimate the impact which ID markets have in balancing prices.

Karanfil and Li (2017) examined the correlation between the changes in wind power forecast errors and differences between ID and DA market prices in Denmark. They also studied other variables, such as the amount of total power generation and total power consumption forecast errors. One other finding from their study was that the overall ID premium was non-existent in the subject price areas. As an explanation for this, they presented that the Nordics have lots of hydropower, which is rather cheap and quick to dispatch. This hydro is used as balancing power, and thus, according to Karanfil and Li, the interest to trade close to real-time is decreased. Using similar techniques to analyze price zone in Finland and compare it to imbalance pricing would provide important knowledge about the microstructure of Finnish electricity markets and tell if there would be need to develop the balancing or imbalance market scheme.

3 Electricity markets in the Nordics

Electricity markets in the Nordics are operated by Nord Pool. Nord Pool also operates in the Baltics, Central and West Europe, and the UK. Nord Pool operates in physical electricity markets, day-ahead and intra-day (Nord Pool, 2022a). Most of the electricity is traded in the SPOT market. In 2021, a total of 938 TWh of electricity was traded in Nord Pool DA markets. The total amount of ID trading in the same year was 25,18 TWh. (Nord Pool, 2021) Based on this data, 2,6 % of the total electricity is traded through ID markets. Other markets include future markets, which are traded in Nasdaq Commodities. The time horizon for future contracts is from weeks forward to years forward. Futures are often used to mitigate risks of volatile electricity prices. (Nasaq, 2022) Imbalances from production and consumption are handled and invoiced by eSett (eSett, 2022a). The timeline of different markets is presented in Figure 1.

From 22.5.2023 onwards, the 15-minute imbalance settlement period is about to go live. It will also mean that intraday product and imbalance settlement will also be available in 15-minute intervals within Nordic price zones. However, the imbalance market price will be determined hourly until Q2 2024, while the imbalance price and cross-border intraday trade will switch to 15-minute periods. (Nordic Balancing Model, 2022)

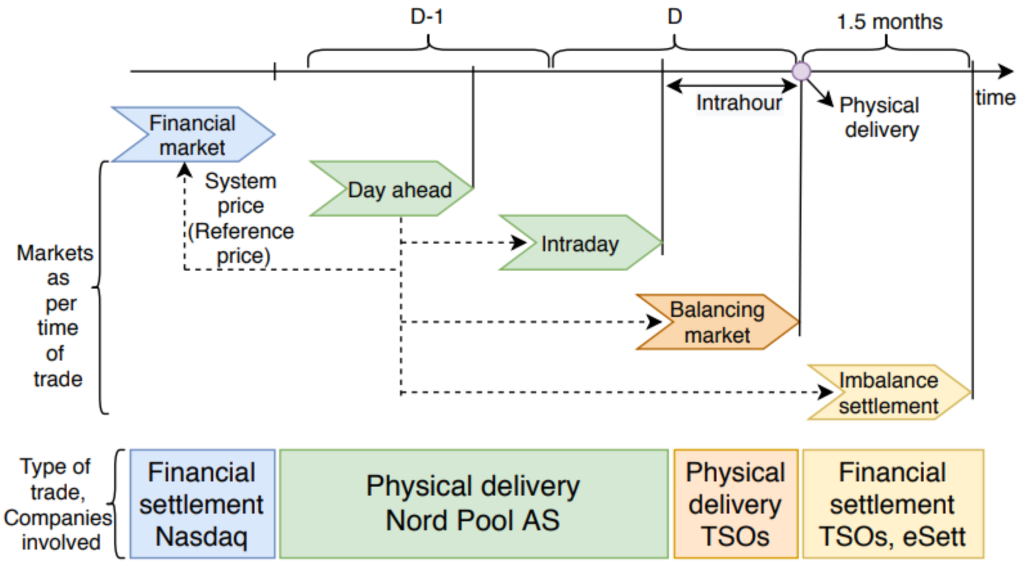


Figure 1. Timeline of different electricity markets. (A. Khodadadi, 2020)

3.1 Nord Pool day-ahead Spot market

Day-ahead markets of Nord Pool, or Spot market, focus on creating an equilibrium between supply and demand. The cost of electricity is based on market participants', both producers' and consumers', volume bids and offers for specific prices for certain hours. The products range from 60-minute delivery to 30-minute and 15-minute depending on the area. With this information, the price of the electricity can be calculated for each hour. The price for a certain hour is the market-clearing price where the consumption bids and production offer match and thus is the most expensive accepted offer in the markets (Nord Pool, 2022b). An example of this price matching is presented in Figure 2. The bids and offers are then also matched with other orders in Europe. This price zone coupling is called Single Day-Ahead Coupling (SDAC). The SDAC also takes the cross-border electricity flow constraints into account (ENTSO-E, 2022a). Offers for Nord Pool Spot must be submitted by 12.00 CET, and DA prices are published at 12.45 CET or later (Nord Pool, 2022c).

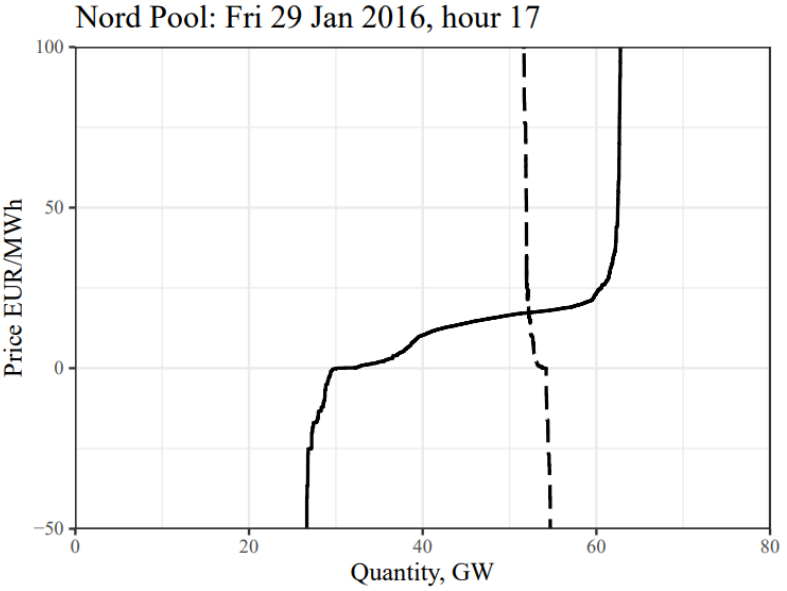


Figure 2. Demand and supply curve example. (Vehviläinen, 2020)

3.2 Nord Pool intraday market

Nord Pool intraday, or balancing market, is a market where hourly, 30-minute or 15-minute electricity products are bought and sold every day of the year. The length of the electricity product depends on the region, but at the moment in Finland, only 60-minute products are in use. Intraday markets function as limit order book double action markets (Nord Pool, 2022d). In Finland, the ID market for the following day opens at 14 local time and is open down to 0 minutes before delivery (Nord Pool, 2022e), but in practice, there is not much trading activity when there is under 60 minutes before delivery as most connections between price zones close 60 minutes before delivery. Intraday markets can be used to balance forecast errors for renewable energy production. As observed, usually, the most active period of trade in ID markets is 1 – 3 hours before delivery. This is backed by (Amelin R. S., 2016), who found that 50 % of European ID trades were done at a maximum of 3 h 15 min, and 25 % of the trades were done at a maximum of 1 h 42 min before delivery. Although this information is rather old, from 2015, and penetration of intermittent renewables was not that substantial at the time.

Soysal et al. (2017) studied intraday markets in Nordic and Baltic countries and the ID price asymmetries. They found that ID prices were almost always higher than DA prices. This, according to the paper, would incentivize intermittent renewable generators to sell less of their production in DA markets and more in ID markets in order to maximize profits.

Much like SDAC, ID trading has Single Intraday Coupling (SIDC), which enables trading across Europe. This increases liquidity and competition of ID markets and thus makes it easier to balance the forecast errors of renewable intermittent energy sources, such as wind power. (ENTSO-E, 2022b)

3.3 Day-ahead and intraday volumes

Volume of a marketplace is essential for its feasibility, especially in ID markets. Higher volumes are often an indicator of liquidity. High liquidity means that items are traded often and more efficiently within a marketplace. With liquid ID markets, forecast errors would be cheap and efficient to balance.

In this subsection, then volumes of DA and ID markets are examined. The liquidity of DA markets cannot be measured, but its volume can be compared with ID market volume to see if the share of ID trades has changed during the time scope. The data for ID volumes are fetched from a service to which UPM Energy has access to. The DA volumes are from Nord Pool’s Market Data website (Nord Pool, 2022h). Both bought and sold volumes are calculated as total in the ID and DA volumes. The data is from 2020 onwards, as the DA volume data for 2019 was not found on Nord Pool’s website.

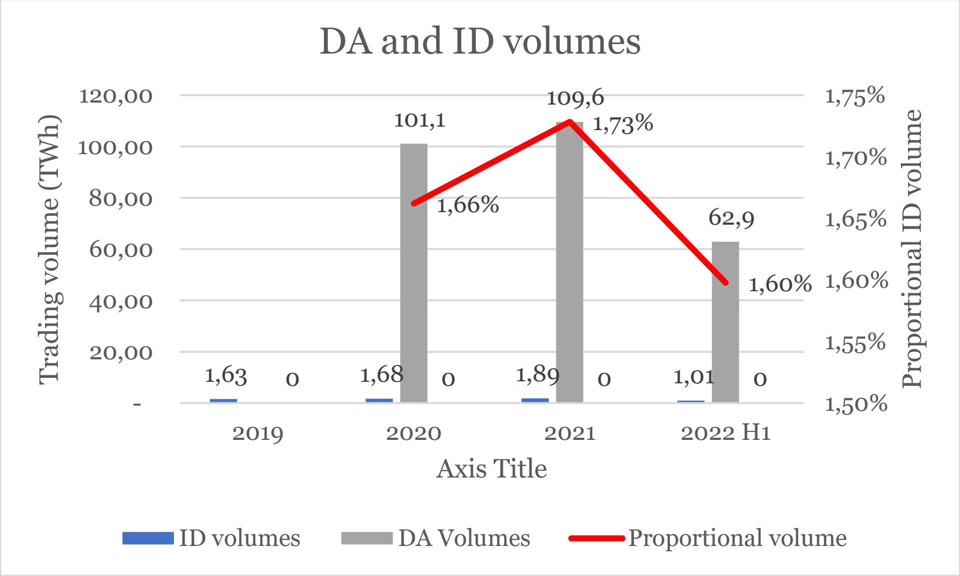


Figure 3. Volumes of DA and ID markets and percentage of ID volume compared to DA volume.

As can be seen from Figure 3, the proportional ID volume has been rather stable within 1,6 – 1,73 % during 2019 – 2021 H1. However, this is rather a small timeframe to see the long-term trend changes. The ID trade volume in 2019 was 1,63 TWh, which is close to the volumes in 2020 – 2021 H1. According to Nord Pool annual report 2021, the volumes in Nordic/Baltic area have been stable through 2019 – 2021, so it can be assumed that in FI market zone, the volume has not changed dramatically either (Nord Pool, 2022i).

3.4 Balancing markets and imbalance settlement

Balancing markets are used in moments when the supply and demand do not meet in the grid. These instances happen in abnormal or faulty situations but also within normal operations. The TSO is responsible for grid balancing action. Balancing in Nordics is held by auction. Reserve providers offer balancing energy capacity to TSO, which then accepts a suitable amount of balancing energy. Day-ahead and intraday production and consumption are submitted to the TSO at the latest at 45min before delivery. mFRR reserve is mainly used as balancing energy. If producer's balancing energy offer is accepted, the producer is obliged to dispatch up to the amount of accepted capacity. Balancing can also be done between price zones within certain limitations. The price of balancing power is published 1 hour after dispatch during normal grid operation. (ENTSO-E, 2021)

Balance responsible parties (BRP) often have some imbalance in their production or consumption, even in normal operation and with robust balancing effort. This is then compensated with the balancing electricity mentioned earlier. eSett is the provider of imbalance settlement services in Nordics. Imbalance settlement is invoiced weekly and consists of hourly imbalance volumes multiplied by hourly balancing costs and volume price. (eSett, 2022b)

3.5 Wind power's position in markets

The nature of wind power is intermittent and forecast-based. In addition to that, its marginal cost is virtually zero as its fuel, i.e., wind, is cost-free. Thus, wind power's role in electricity markets is to function as a price-setting source as wind power is produced at any positive market price and shifts the supply curve towards cheaper production. Sometimes wind power is produced even at negative prices as wind power is still subsidized in Finland, which is explained more in Section 4.1. This intermittency and low costs bring volatility to the system balance and system price.

There are multiple ways TSOs operate markets when it comes to wind power integration. Different systems are used in Danish, German and Iberian power markets. Denmark is using the same system as Finland when it comes to DA and ID markets. This system is researched in this thesis.

Germany's ID markets and balancing energy have been functioning in a 15-minute resolution since 2014. This has created a phenomenon called "German paradox". It is called "paradox" because opposed to the common way of thinking that the increase of wind and solar power would require the increase of balancing energy sources, but in Germany, the increase for balancing power has not risen. When implementing 15-minute markets and balance, production and consumption can be fitted better into the overall system. This better fit is presented in Figure 4. (Ehrhart, 2017). The amount of absolute error in supply in 15-minute system is much smaller than in 60-minute system. I reckon that when Finland's balance and ID markets turn into a 15-minute system, the need for balancing power decreases, and so does the balancing price. The bigger resolution of balancing means that balancing resources are better optimized and not as much balancing power production is needed.

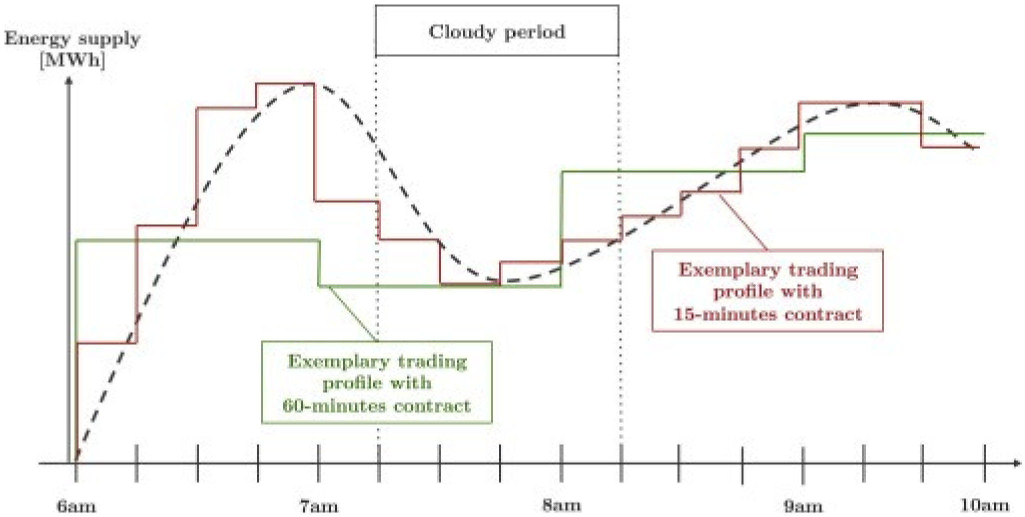


Figure 4. 15-minute balancing settlement period compared to 60-minute balancing settlement (Ehrhart, 2017). The dashed curve represents the actual energy supply and blue and red depict the fit of different contract periods to the actual supply.

In Spain, the ID markets are organized as multiple auctions with six gate closure times. The length of each ID auction period is varying and there are multiple gate-closing times for ID offers. This market creates a bigger trading volume in the ID market in comparison to other European ID markets. Furthermore, this market design favors the balancing needs which renewable energy sources create (Fernandes, 2015). So to speak, the Iberian ID market is functioning as multiple Nordic DA markets within one day. The multiple gates for ID offers allow the offers to cumulate before gate closure and thus create a more stable ID price.

For 100 % renewable power system, the times between market gate closing and actual delivery should be shorter in order to increase the accuary of intermittent renewable generation forecasts and the length of traded product should be shorter. (TradeRES, 2020) For example 1 – 4 hours before delivery could be suitable gate closure for more accurate wind power production. In countries with high wind power penetration the balancing cost of wind power is on average higher compared to countries with less wind power production. (The European Wind Energy Association, 2015) The earlier market gate closure pushes unavoidable forecast errors for wind power producers and causes balancing and imbalance costs.

4 Wind power position in Finland

Finland had 3257 MW of installed wind power capacity at the end of 2021. This amount is rising rapidly as 784 MW of new capacity was constructed in the first half of 2022, with 1044 MW more planned for the second half. For the year 2023, 1492 MW more capacity has been planned. This would roughly double the amount of constructed wind power in Finland in just two years. In Figure 5, the production and capacity are presented. The year 2022 is split into the first half (presented as 2022 H1), from which production data can be extracted, and to 2022 total (presented as 2022).

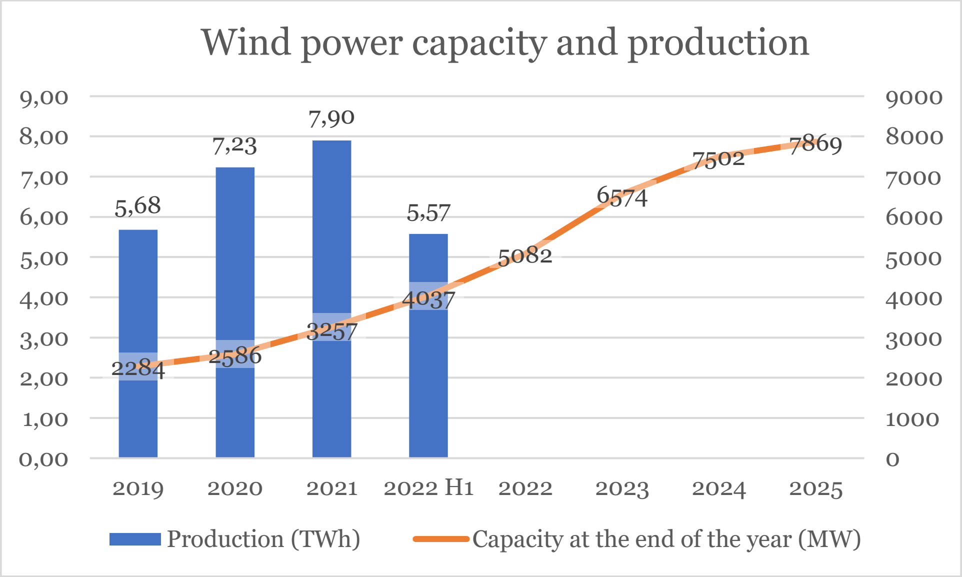


Figure 5. Amount of wind power produced yearly and end-of-year capacity. Future years are based on permitted wind power plants. Yearly production source (Fingrid, 2022b). Capacity source (Tuulivoimayhdistys, 2022a).

4.1 Subsidies

The wind power feed-in tariffs were introduced in Finland in spring 2011 with The Act on Production Subsidies for Electricity Produced from Renewable Energy Sources (Finlex, 2010). This act was introduced to increase the development of wind power by making it more profitable. Another reason was that the act would make Finland more energy self-sufficient and diversify production. The tariff would be paid for 12 years (National Audit Office of Finland, 2017). The reference price for wind power is 83,5 €/MWh. The feed-in tariff is the reference price unless the average electricity price of the quarter is 30 €/MWh or lower, which leads to the tariff being 53,5 €/MWh. (Finlex, 2010). The feed-in-tariff scheme for new wind power closed on 1.11.2017 (Nord Pool, 2022a).

In 2018, the Finnish Energy Authority arranged a bidding competition for all renewable energy sources. The goal of the bidding competition was to compete which parties could produce renewable electricity with the smallest subsidized premium. The amount of electricity production allocated to this competition was 1,4 TWh in a year. The premium will be paid for 12 years for the accepted projects and the new product must be up and running within 3 years of the acceptance. The average price premium for the accepted offers was 2,5 €/MWh, with the reference price being 30 €/MWh. Also, every application was a wind power project, and their yearly production is 1,36 TWh. (Finnish energy authroity, 2022b)

The total amount of wind power plants still within the feed-in tariff created in 2011 has a capacity of 2310 MW (Finnish Energy Authority, 2022c). This is roughly 57 % of the total capacity of Finland at the end of 2022 H1. According to Husu and Salo (2022), the feed-in tariff benefitted the wind power industry as they were able to enter a rather change-resistant field, which is mainly controlled by a few big corporations. They also state that wind power is already profitable and feed-in tariffs are not needed anymore in the future.

4.2 Wind power locations

The vast majority of wind power plants and parks in Finland are constructed on the west coast. The wind power projects are depicted in Figure 6. The uniform location for wind power plants may bring problems as the cannibalization effect, in which new wind power capacity decreases the profitability of wind power. This happens because there are more wind turbines producing electricity and thus the electricity prices may plummet when wind speeds are high. Having the wind turbines in the same general location means that the weather conditions for the big part of wind power are the same, and thus potential for cannibalization is high.

4.3 Slow development of Finnish wind power

Despite the wind power feed-in tariff, the Finnish wind power projects got some setbacks. The problems were within permits and issues regarding the environment and radar interference of the Finnish Defence Forces. (National Audit Office of Finland, 2017) Permitting is held as the biggest challenge of the European wind phase in. Rules for permits are too complex, too many administrators make the procedures for new permits too slow, and authorities do not have enough staff to process new permits. (European Wind Energy Association, 2020) Furthermore, according to Finnish Wind Power Association the guidelines for wind power noise pollution are stricter than in other societal functions, for example heat power plants or highways. This too limits the availability of area for wind power and makes the permitting process slower. Although it should be taken into consideration that European Wind Energy Association and Finnish Wind Power Association are both for new wind power and have biased opinions. (Finnish Wind Power Association, 2022) Though, an attorney team Bergmann shares this view that permitting has been problematic in Finnish wind power development. One of the biggest problems has been the fact that there has not been, and is not, a centralized way to apply for permits, but developers will apply for multiple separate permits, which have multiple different variables, which may slow the permitting process. (Bergmann, 2018) The average time in which an average-size wind power project is completed from start to finish is 4-6 years (Bergmann, 2022). Finnish Defence Forces has, for example, in 2022 rejected more wind power projects than they had accepted. Any project over the height of 50 meters has to be approved by Defence Forces. According to Jussi Karhila from Finnish Defence Forces, “We’re running out of good wind power plant locations.” (YLE, 2022)

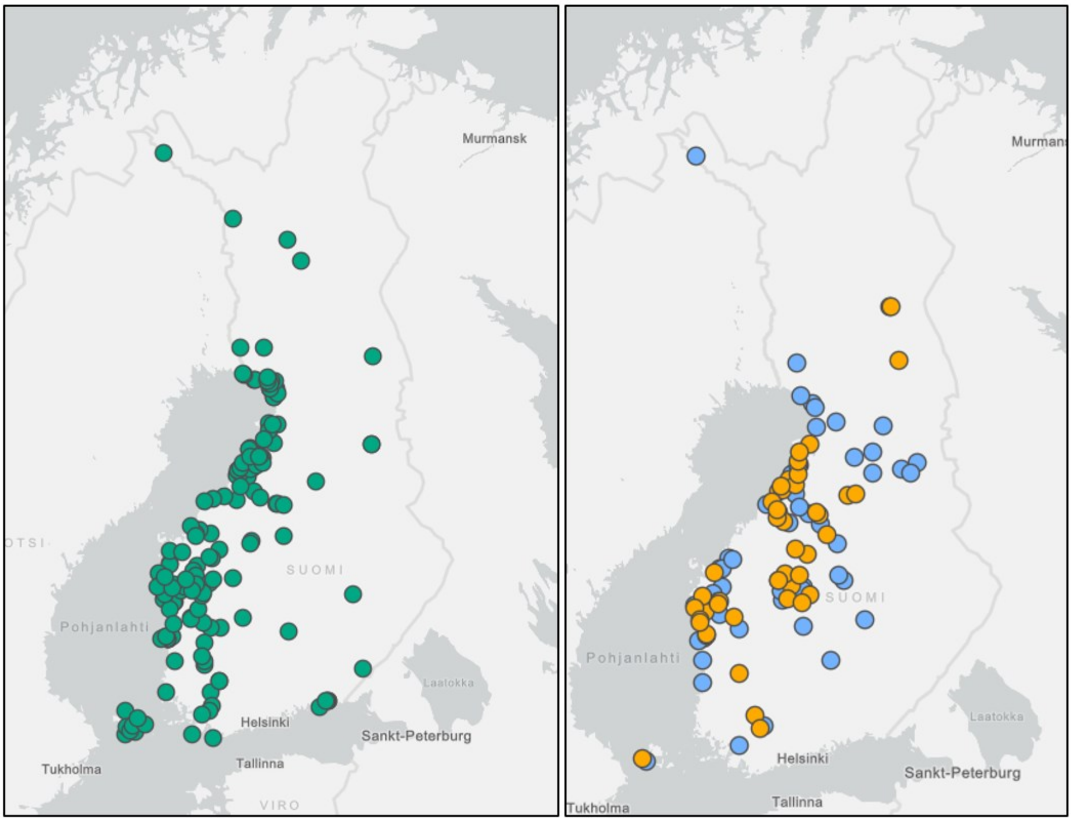


Figure 6. On the left are wind power projects, which are in production. On the right, the yellow bubbles depict wind power projects, which are under construction and the blue bubbles mean projects, which are fully permitted. (Tuulivoimayhdistys, 2022b)

4.4 The cost of wind power

Wind power, as all other means of electricity production, has a cost, which must cover the investment and running costs of the generation. Wind power is capital intensive generation method as its marginal costs are negligible as it does not need any consumable fuel and its main resource, wind, is renewable. Thus, the main cost of wind power is the investment cost, which is either defined as the interest rate of loan, potential profit from other investments or a combination of these two. International Renewable Energy Agency has released a report which presents the costs of renewable power generation in 2021 (IRENA, 2022). The average levelized cost of electricity (LCOE) of wind power in Europe was 0,042 USD/kWh, which in 2021 average EUR/USD exchange rate (EUR = 1,183 USD) is roughly 36 €/MWh. Furthermore, Finland and Sweden had one of the most competitive LCOE in Europe, but the exact cost was not specified.

With increasing the amount of wind power in the grid, LCOE could become an irrelevant meter for the cost of wind power. Instead, value-added LCOE (VALCOE), takes the cannibalization effect of wind power into account. Cannibalization, by definition, means that production of a new product, electricity in this case, removes the value of earlier production and displaces older product. This can be seen as a price drop in electricity prices when the wind power production forecast is high. The gained value of wind power is getting ever so lower as new production is dispatched. This is the case either because wind as a weather event is not regional, but more global or because wind power production is often concentrated in one area. In Finland’s case, the concentration is on the west coast. The capture rate of wind power is calculated in the next Subsection 4.5.

4.5 Capture rate of wind power

Calculating the capture rate of wind power is crucial for new wind power investments as it determines the future value of the wind power project. The capture rate defines the captured value of the production asset. For example, a wind power plant with a capture rate of 0,95 the asset generates 95 % of the average electricity price.

The capture rate is calculated with daily values. The average daily price and daily average wind power production are compared with actual hourly Spot prices and day-ahead forecasts. DA forecasts are used because the Spot price is determined with day-ahead forecasts. Then, the wind power production weighted profits are divided by the daily profits of a flat production rate and the result is the capture rate. The inspection period of the capture rate is from the start of 2021 to the end of 2022 H1.

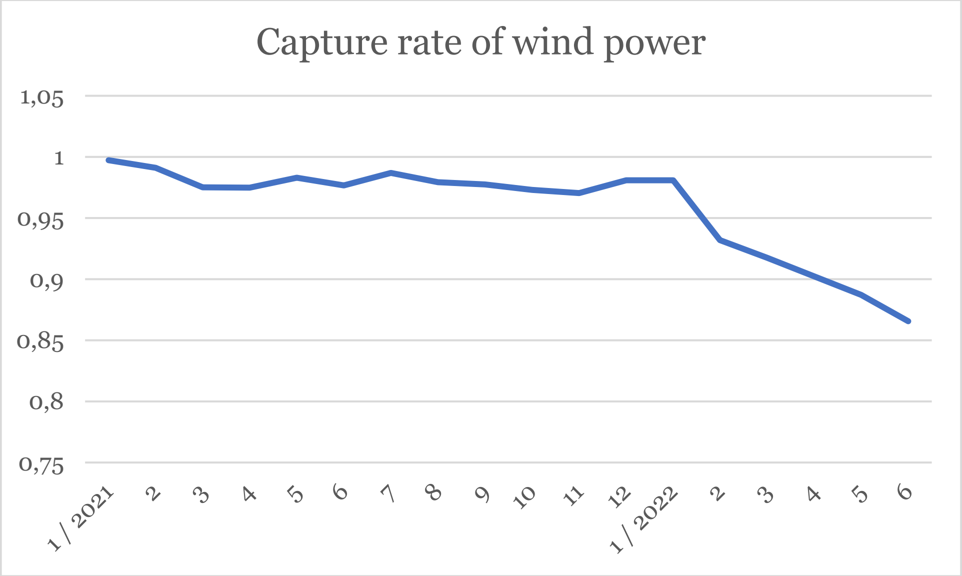


Figure 7. Capture rate of wind power from 1/2021 to 6/2022 in Finnish price zone.

The capture rate of wind power is decreasing, and it can be seen in Figure 7. This is due to the increasing amount of wind power. All of the year 2021 the capture rate is well over 0,95, but during 2022 it decreases dramatically. One explanation for this could be the high electricity prices of H1 2022, which can be seen in Table 1. If wind power has the potential to cut off expensive fossil-sourced electricity completely, then the overall cannibalization is greater and thus capture rate lower than during lower average prices.

5 Research methods and data

5.1 Research methods

The primary research method was done by comparing the difference in DA price with the volume-weighted average price of the last two trade hours, T-2 / T-0, in the ID market with the difference of wind forecast day-ahead and hour-ahead of delivery. I chose to examine the last two hours of the ID market, as it depicts best the latest information the market has at that moment. Volume-based average depicts the market valuation of electricity better than the average price of the trades, as potentially smaller panic-purchases or sells do not get that big of an impact. The hypothesis is that most, or sufficiently, of the ID trading is done during those hours. The reason why only the last trading hour is not observed is that in Finnish ID markets, the trade volume decreases significantly during the last hour, as trading with other price areas is open until delivery hour T-1. These market timestamps are comparable with wind forecast timestamps as wind power DA offers are made with the DA wind forecast information and if BRP operates in ID markets, the latest trades are made with the hour before forecast. It is assumed that the wind power forecast from Fingrid is similar to the forecasts the trading parties use.

The ID trades within and between OPX and FI are examined in this research. OPX means other power exchanges and was chosen to be within the study as a significant portion of ID trades have OPX as the other trading party with the Finnish ID trades. Trades between other price zones are neglected. This was chosen as price drivers in neighboring price zones are affected by different variables compared to Finnish price zones. Even though there are similarities, such as if there is a windy day in Finland, it is probably windy in Sweden, these were chosen to exclude due to pinpoint the research on Finnish prices. The true location of OPX operators cannot be confirmed, but as OPX trades had such a significant portion of all trades, so it is included.

There are also filters in the analyzing code, which can filter either the hours with at least a certain amount of wind power percentage in the system or the hours when another consumption error is under a certain threshold. These filters were chosen because, with those, other variables in the research method can be neglected. The hypothesis is that if there is only a miniscule amount of wind power in the grid, even bigger relative wind power forecast errors will not change the price, as the absolute forecast error is small. Moreover, other DA-ID consumption forecast errors can also affect the market price, if the parties responsible for the error function actively within ID markets or do not have other means of production or consumption to balance the error themselves. Spodniak et al. (2020) found out that in Finland, the spread between the DA and ID prices was mostly demand-driven, and thus consumption forecast errors must be considered when handling the data.

5.2 Data and sources

The Spot data were acquired from different sources to which UPM Energy has access. The intraday data was downloaded from Nord Pool's SFTP server to which UPM Energy has access as well (Nord Pool, 2022g).

Wind power production and total consumption forecast data was downloaded from Fingrid Open Data which is free to use (Fingrid). It is possible, especially in wind power forecasts, that commercial forecast services are more accurate than Fingrid's forecast. Fingrid Open Data is used due to the availability and ease of access.

5.3 Price anomalies in Europe in recent years

The price of electricity has had huge volatility from 2020 to 2022. Table 1 presents the yearly average Finnish Spot price of electricity from 2018 to the first half of 2022. This price volatility and anomalies can have an effect on the results of the analysis and must be taken into consideration. If the price of electricity changes dramatically during or between the examination periods, the results may be unreliable, or the results cannot be compared with each other. The events in this subsection consider the whole of Europe, but their effects can be seen in Finnish electricity markets.

Covid-19 pandemic from 2020 onwards had an effect on the price of electricity, especially during 2020 when it was substantially less than in other years. The low demand decreased the market price, and at times, it could be supplied only with renewable energy. Renewables have more often lower marginal costs than fossil sources. Furthermore, during this year the price of energy commodities, such as oil and gas dropped (European Central Bank, 2022). These commodity price drops probably contributed further to the low electricity prices.

Table 1. Average electricity Spot prices in Finland (Nord Pool, 2022f)

Year	Spot price average (€/MWh)
2022 H1	104,72
2021	72,34
2020	28,08
2019	44,04
2018	46,80

In 2021 the demand for electricity rebounded back and thus the gas consumption for peak electricity loads rose as well. The rising costs of emissions in the EU Emission Trading Scheme had also, even though a smaller, effect. (European Central Bank, 2022)

During 2022, according to European Central Bank (2022), the Russian invasion of Ukraine raised gas prices. This was due to the decreasing amount of Russian gas availability in Europe which drove the global gas price up and the electricity thus price followed. The initial price volatility was due to already low storage levels. Also, the import of electricity has been cut off with Russia. Furthermore, according to International Energy Agency (IEA, 2022) the rising coal and carbon emission prices contributed further to the price of electricity. France's nuclear power plants have also been in low availability, and this has also contributed to electricity scarcity in Europe. Moreover, the drought in Europe during summer 2022 has impacted the availability of hydro power and left hydro reservoirs rather low, which in turn affected and will affect the electricity prices. (Baltic Sea System Development Steering Committee, 2022)

6 Wind power error results

This section presents the results and correlation between the data and discusses the possible deviations between them. The data is compared year to year and filters are used to examine and pinpoint data. The results are depicted as scatter diagrams. Each point in the scatter depicts one hour. The price spread of the compared markets is on the y-axis. The price spread is calculated as the difference between the ID price or the imbalance price compared with the DA price. The wind power forecast error is on the x-axis. Positive values in the x-axis means that the ID wind power forecast is higher than the DA forecast and vice versa. The correlation coefficient is the slope of the trendline of the scatter plot and depicts the difference of price as wind power amount increases compared to the DA forecast. Trendline is the red dashed line and the x- and y-axis are highlighted with bold lines. It is expected that the correlation coefficient is negative, as it would present that as the wind power forecast, and thus the supply, increased close to the delivery hour, the price in ID markets would decrease compared to the DA price. For example, a correlation coefficient of -0,1 would mean that when the hour before the delivery forecast is 100 MWh more than the DA forecast, the price in ID markets would be 10 €/MWh less. The axis has different zoom levels depending on the biggest values in each data. For example in Figure 8 the y-axis goes above 1500 whereas Figure 9 has the maximum y-value of around 600. The filtered figures have fewer datapoints than unfiltered datapoints as the filters remove datapoints outside the filter.

The graphs presented in this section are two interesting or differing graphs out of the same filtering. The rest of the graphs are presented in Appendix A.

6.1 ID – DA correlation

Comparing the ID and DA market prices explains if the ID markets are efficiently used as the balancing market for wind power forecast errors. Comparing different years with each other helps to explain what amount of wind power capacity can create a significant amount of price correlation.

6.1.1 No filter

Without any filters, the data includes variables from consumption errors, which affect the results of the dataset. It can be said from the non-filtered data that there is little correlation between wind power in total ID markets when excluding the year 2019. It can also be said that overall ID markets has a positive price premium as the trendline crosses the y-axis above the x-axis except for 2019.

In this subsection, 2022 H1 and 2019 graphs are presented. The other graphs can be seen in Appendix A 1.

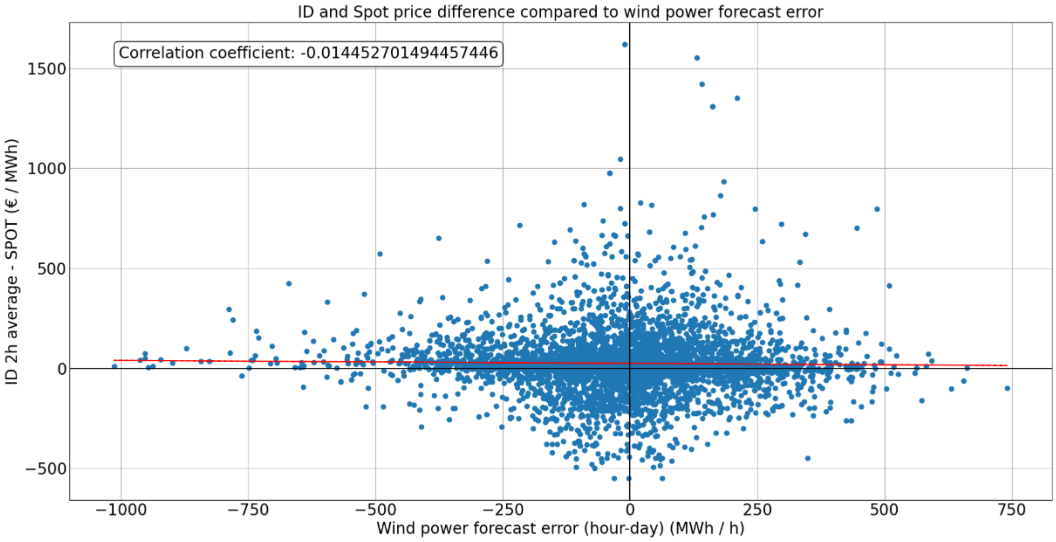


Figure 8. ID - Spot difference, 2022 H1, no filter

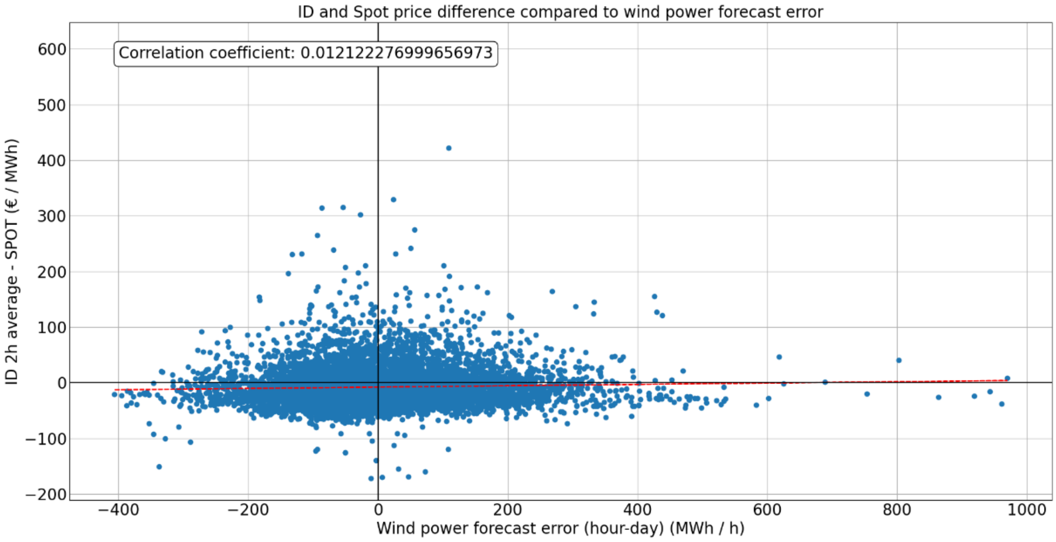


Figure 9. ID - Spot difference, 2019, no filter

Table 2. ID correlation coefficients from no filter graphs

Year	Correlation coefficient
2022 H1	- 0,01445
2021	- 0,02102
2020	- 0,02081
2019	0,01212

As can be seen from Table 2, the year 2019 seems to be an outlier when it comes to the correlation coefficient of ID – DA prices and wind power forecast errors. From Figure 5 can be seen that the wind power capacity and production were 2284 MW and 5,68 TWh, respectively, whereas, in 2020, the same figures were 2586 MW and 7,23 TWh, respectively, which can be seen in Figure 5. The overall wind power capacity did not change that significantly, but the production amount did. One explanation for this could be that the year 2019 was not that windy overall. Furthermore, the new wind turbines installed in 2020 could have higher capacity factor, so the impact of wind power in ID markets in 2020 was much bigger.

Comparing Figure 8 and Figure 9 it can be seen that in 2022 H1 the price spreads overall were much bigger than in 2019. Also, the wind power forecast errors are bigger in 2022 H1 as expected as the overall wind power capacity has increased. The price premium in 2019 seems to be negative because the trendline cuts the y-axis with a x-value of under zero. In 2022 H1 the price premium is positive.

A possible explanation for this rather rapid change could be due to the first wave of Covid. The overall demand for electricity decreased and wind power had proportionally larger share of electricity production and thus had larger impact in ID markets. Furthermore, participation in ID markets could have increased during 2020 as lower DA prices may drive market participants into ID markets (Rintamäki et al., 2020). On the other hand, the year 2019 could be an outlier from earlier data too. To contradict with Rintamäki from Figure 3 can be seen that proportionally the volumes in ID trading have not increased between 2019 – 2022 H1. The markets could have shifted towards wind power fundamentals without any increased ID volume.

The values for 2020 and 2021 are rather similar and 2022 H1 seems to have a slight decrease in correlation. The reason for 2022 H1 decrease could be the surprising events in Europe and energy prices have seen dramatic volatility and thus the overall impact of wind power forecast errors had a decreased impact.

6.1.2 Consumption forecast error filter

The filter used in consumption errors removes the days in which other electricity consumption errors are more than 300 MWh / h. This way, the analysis can be pinpointed to those hours when wind power could be the biggest factor for ID – DA price deviations, as Karanfil and Li (2017) suggested that consumption forecast errors were a bigger driver in ID prices than wind power forecast errors. This filter shall be called as ConEr filter.

Graphs presented in this subsection are from the years 2021 and 2020. The rest of the graphs can be seen in Appendix A2.

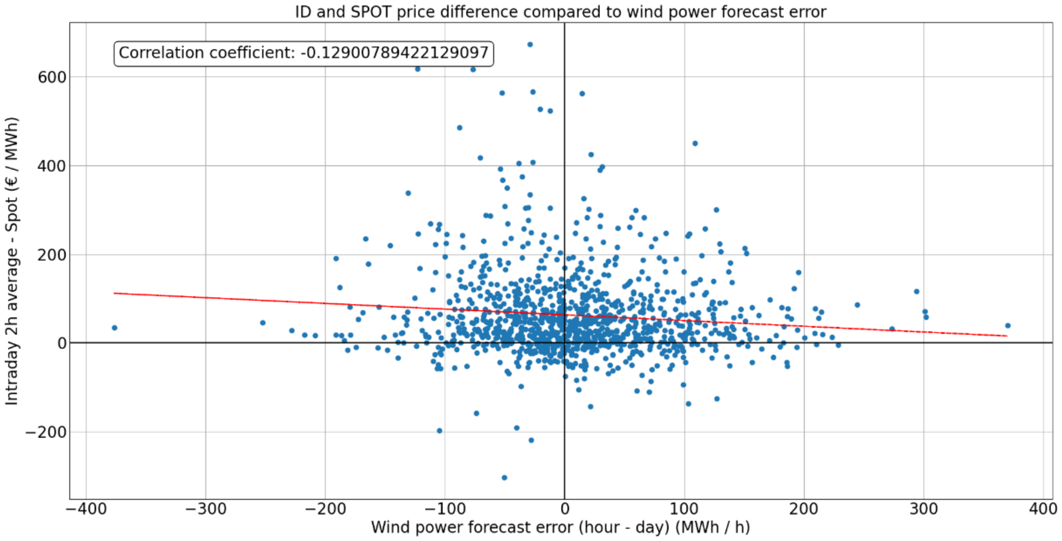


Figure 10. ID - Spot difference, 2021, consumption error filter

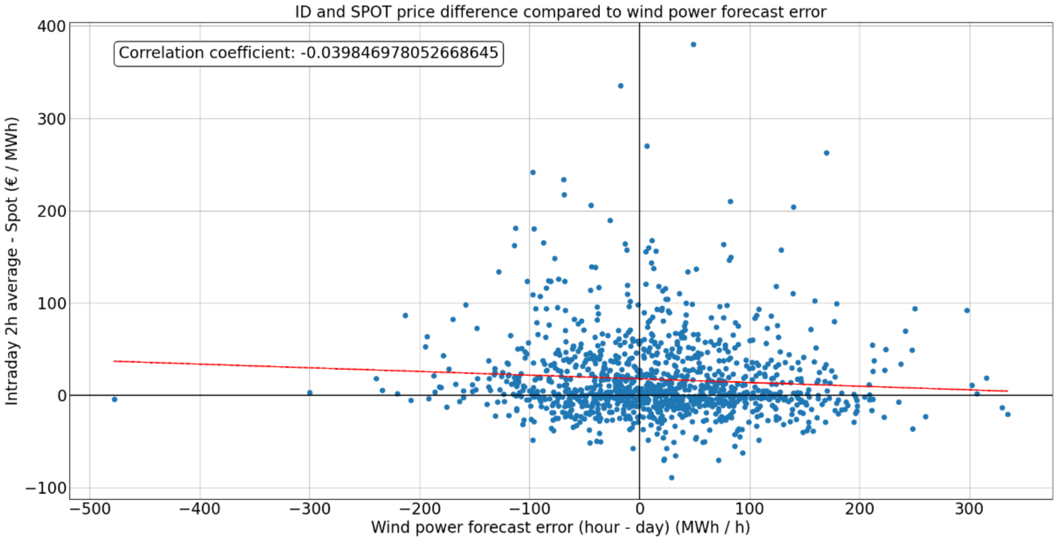


Figure 11. ID - Spot difference, 2020, consumption error filter

Table 3. ID correlation coefficients from ConEr filter graphs

Year	Correlation coefficient
2022 H1	- 0,15415
2021	- 0,12901
2020	- 0,03985
2019	- 0,01945

From Table 3 can be seen that correlation of wind power increased drastically between the year 2020 and 2021 when consumption errors were filtered out of the data. Even though the actual production of wind increased only moderately between 2020 and 2021, the capacity built was significant, which can be seen in Figure 5. Perhaps the year 2021 was not that windy, but there could have been periods of high error count, which in turn increased the overall correlation. From Figure 10 and Figure 11 it can be observed that the error values go higher in absolute value in 2021, which supports the theory mentioned. Furthermore, in 2021 the price premium is significantly higher with ConEr filter than in 2020

The impact of wind power forecast errors in ID prices can be seen with ConEr filter. When comparing the results between no filter, the ConEr filtered results show a clear negative correlation coefficient. This is expected as the more wind power is in the system, the less the price will be. Also, perhaps the biggest variable, consumption errors, are minimized with this filter enhancing the results. Moreover, the year 2019 has a small negative correlation with the ConEr filter, which it did not have when no filter was in use. For the years 2020 and 2021, one other explanation for this dramatic correlation difference could be the overall price increase, which can be seen in Table 1. Higher prices make the absolute value of correlation coefficient larger because the values the y-axis gets are also higher.

6.1.3 Total wind power production threshold filter

When creating a threshold filter, it must be studied what threshold is viable for research. In this filter, the amount of wind power proportional to total production is studied. Different thresholds were studied with 2022 model to determine the most suitable threshold. The tried options were 10 %, 20 % and 30 % and their results were –0,03365, -0,03686 and -0,00531, respectively. The chosen wind power threshold was 20 % as it gave the most correlation with wind power forecast errors in 2022 H1. The 10 % and 30 % wind threshold graphs can be seen in Appendix A3.

In this subsection graphs from the year 2021 and 2020 are presented. Other graphs can be seen in Appendix A4.

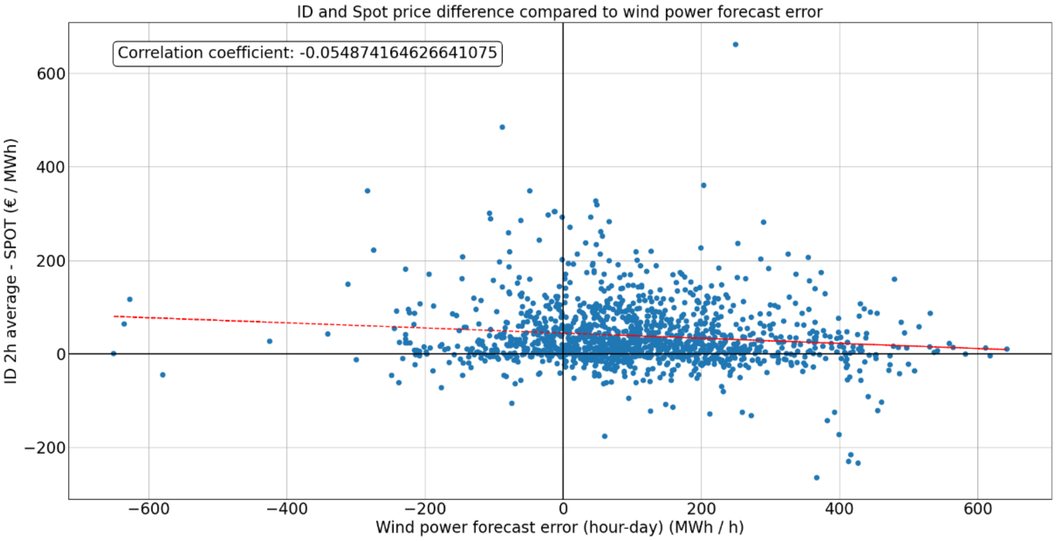


Figure 12. ID – Spot difference, 2021, threshold filter

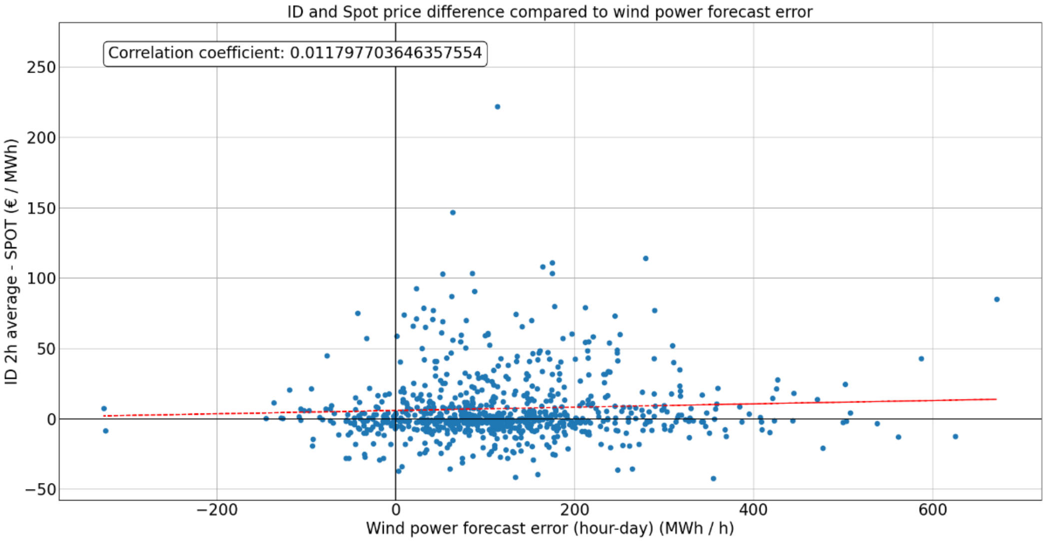


Figure 13. ID – Spot difference, 2020, threshold filter

Table 4. ID correlation coefficients from threshold filter graphs

Year	Correlation coefficient
2022 H1	- 0,03686
2021	- 0,05487
2020	0,01180
2019	- 0,02415

According to the results, the threshold filter is not an efficient filter to pinpoint the wind power forecast differences in ID markets, which can be seen from Table 4. In fact, the correlation coefficient is positive in 2020. From Figure 12 and Figure 13 it can be seen that the scatter is widely spread. The threshold filter does not give as significant correlation coefficients compared to ConEr filter. From the dispersed scatter can be derived that price differences occur, when there is a lot of wind power in the grid. Another note is that all figures with threshold filters have a price premium.

6.2 Imbalance – Spot correlation

Comparing ID prices to imbalance prices can give a sign as to how much wind power is traded in ID markets and, or, how inefficient it is to predict wind power production even one hour ahead of delivery as unpredicted wind power production will be settled in the imbalance settlement.

6.2.1 No filter

With no filters, the overall system imbalance price can be examined. 2022 H1 and 2019 are shown in Figure 14 and Figure 15, respectively. Other figures can be found in Appendix A5. Figure 14 apparently has some high balancing price spread compared to Spot price. This data point can be located from Fingrid Open Data, imbalance prices for 2022 H1. The imbalance price in 4.2.2022 at 07 – 08 was 3500 €/MWh and this explains the zoom level of the figure as the graph includes all the data points. The wind power forecast error between day-ahead, from Fingrid Open Data respectively, for that particular hour was 341 MWh/h lower than hour-ahead forecast.

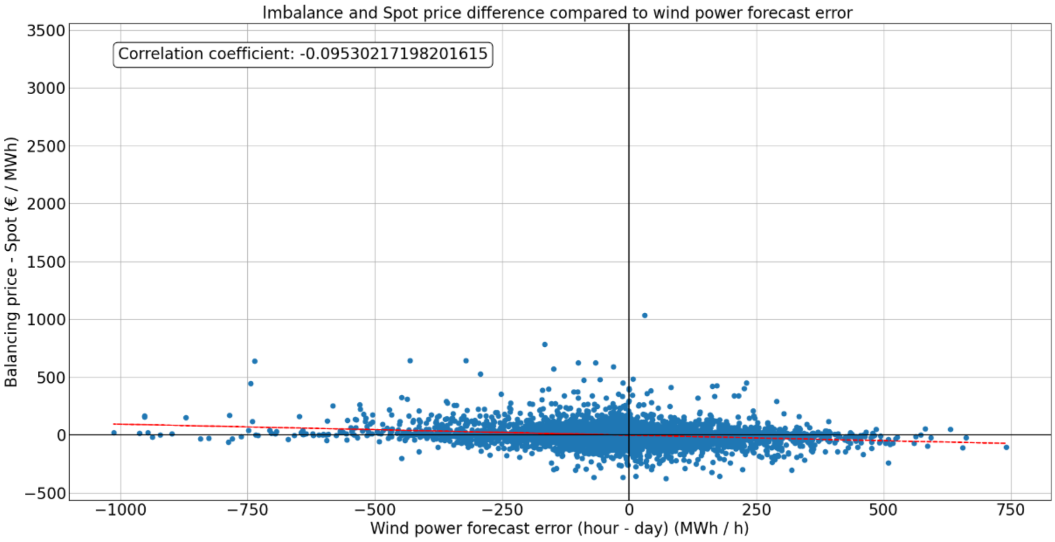


Figure 14. DA – imbalance price difference, 2022 H1, no filter

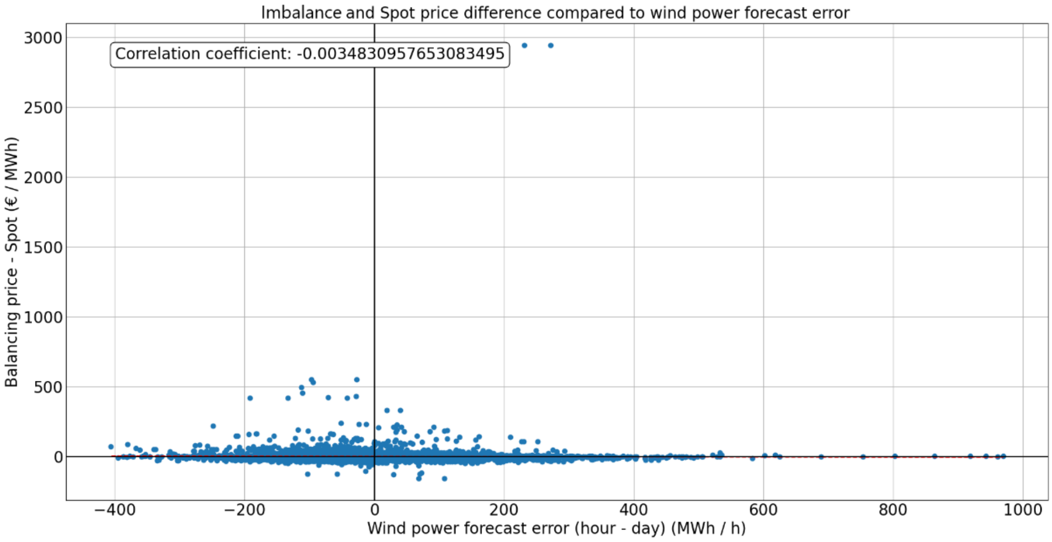


Figure 15. DA – imbalance price difference, 2019, no filter

Table 5. Imbalance price correlation coefficients from no filter graphs

Year	Correlation coefficient
2022 H1	- 0,09530
2021	- 0,05543
2020	0,00100
2019	- 0,00348

It can be seen from Table 5, that correlation between imbalance price and wind forecast error has been increasing during the examination period. Figure 14 and Figure 15 show that the price premium of imbalance is close to zero as the trendline crosses y-axis roughly at zero. The correlation coefficient of 2019 is so small that it could be said that the wind power forecast errors were not a factor when it comes to the imbalance prices.

The graph of 2020, and its result, seems to be an outlier, which does not fit the rest of the data as the graph shows that there would not be any imbalance prices, which would be higher than the Spot price. The graph can be found in Appendix A5. This data is disregarded.

The correlation coefficient grows to 2022 H1 to be significant. This could be the result of ever-increasing shares of wind power in the Finnish electricity system. It could be a possibility that wind power producers have too much forecast error in their balance, and the ID markets cannot efficiently balance this forecast error, and other means of balancing production in their portfolio cannot match the forecast error either.

6.2.2 Consumption forecast error filter

As ConEr filter proved to be an efficient way to isolate the wind power's effect in ID-Spot difference, it could produce relevant information for the imbalance data as well.

Figure 16 and Figure 17 represent the data from 2022 H1 and 2021 respectively. Data from the years 2020 and 2019 can be found in Appendix A6.

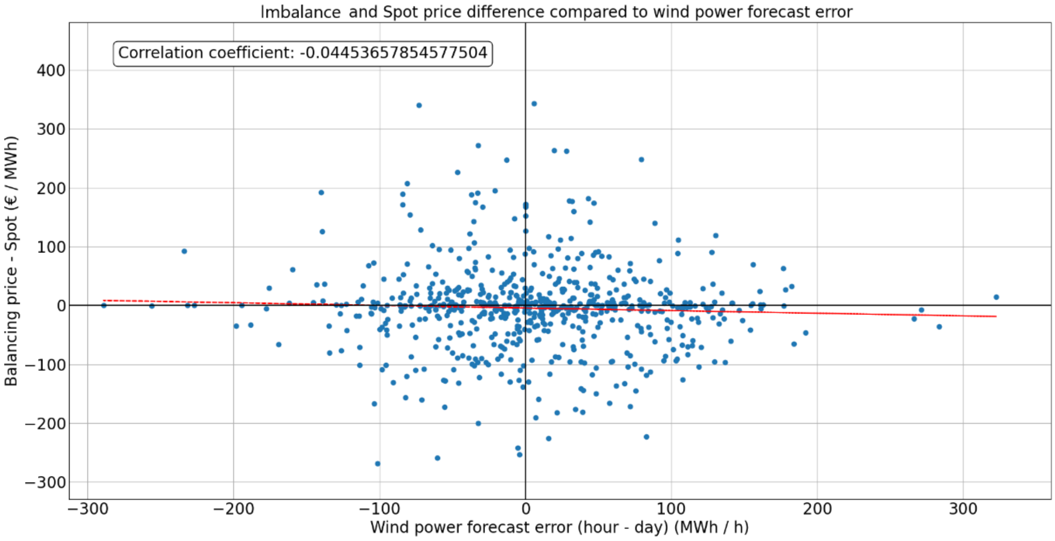


Figure 16. DA – imbalance price difference, 2022 H1, ConEr filter

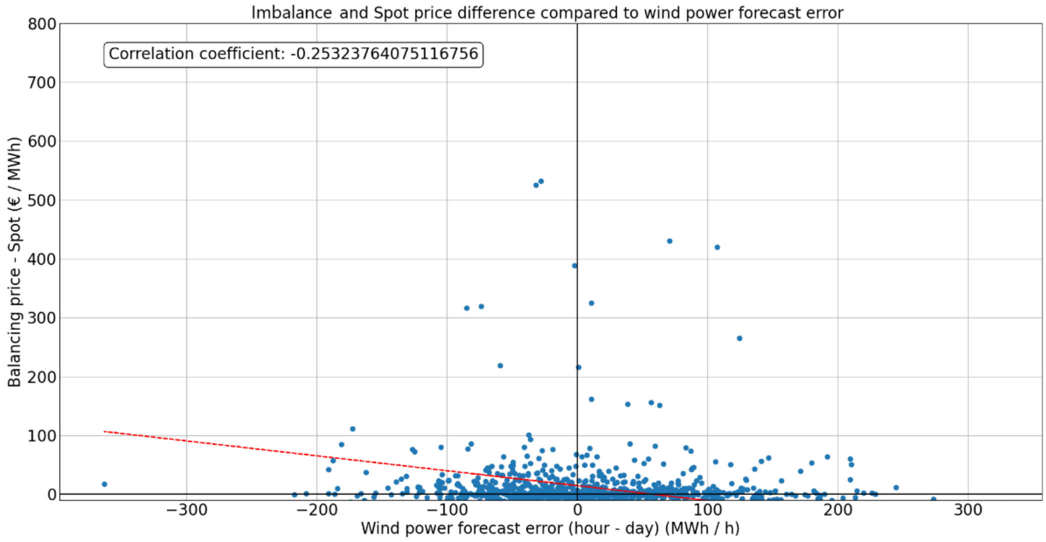


Figure 17. DA – imbalance price difference, 2021, ConEr filter

Table 6. Imbalance price correlation coefficients from ConEr graphs

Year	Correlation coefficient
2022 H1	- 0,04453
2021	- 0,25324
2020	0,00255
2019	0,01641

The first thing which can be noticed from Table 6 is the correlation coefficient in the year 2021, which is – 0,25324. This is the biggest correlation coefficient so far from the data. There might be multiple reasons for this, which are discussed and compared with ID markets later in the thesis.

The overall spread of datapoints in Figure 16 is much wider than in Figure 17 as in 2021 data, the common spread seems to end in y-axis at 100 €/MWh whereas in 2022 H1 there are multiple datapoints at 200 €/MWh. Though the wind forecast error amounts seem to be close to each other.

Again, the graph from the year 2020 seems to have no positive values in the y-axis. The graph can be seen in Appendix A6. I will disregard its data.

6.2.3 Total wind power production threshold filter

In this subsection, the same filter 20 % threshold filter is used as in subsection 6.1.3. Figure 18 and Figure 19 represent the data from 2022 H1 and 2021 respectively. Data from the years 2020 and 2019 can be found in Appendix A6.

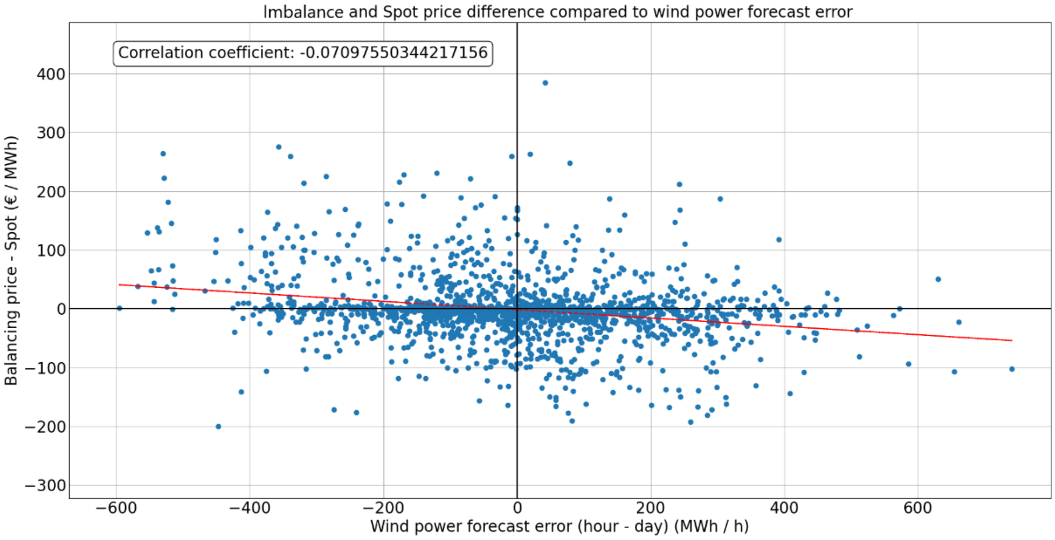


Figure 18. DA – imbalance price difference, 2022 H1, threshold filter

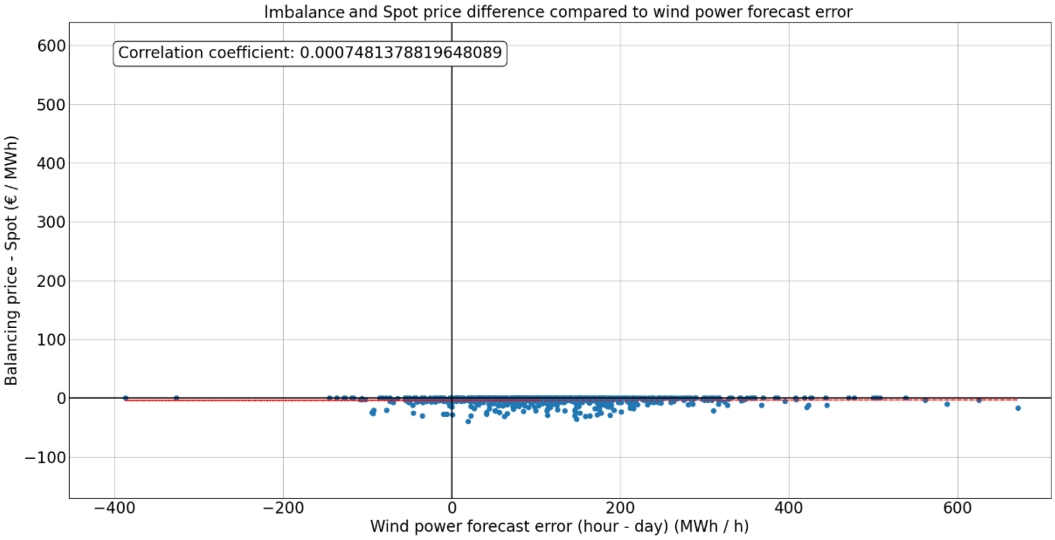


Figure 19. DA – imbalance price difference, 2020, threshold filter

Table 7. Imbalance price correlation coefficients from threshold filter graphs

Year	Correlation coefficient
2022 H1	- 0,07098
2021	- 0,02784
2020	0,00075
2019	- 0,0096

Compared to previous results, this filter still gives no positive values to 2020 graph, so it cannot be analyzed either, as other 2020 imbalance prices. The graph of 2020 imbalance difference can be seen in Figure 19.

As can be seen in Figure 18 and the figures in Appendix A7, there is no price premium in any of the graphs when applying the threshold filter. It can be visually observed from Figure 19 that the data points are biased to the right signaling that there were significantly more hours in 2020 when closer to the delivery hour, and the forecast was higher than expected in the day ahead forecast when threshold filter is applied.

Table 7 presents the correlation coefficients of threshold filtered graphs. Year 2019 seems to have no significant correlation, but the amount of scatter points is miniscule signaling that wind power was not a significant portion of the total electricity mix. Disregarding the data anomaly of year 2020, the correlation has increased from 2019 to 2022 H1.

6.3 Total volume weighted average ID price

To study how much the total ID volume follows the price signals compared to the last 2 hours, a similar kind of analysis is made, but with the total volume weighted average prices (VWAP). With this analysis, it can be seen if majority of the ID markets are done 2 hours before delivery or earlier. Correlation coefficients similar to the results of Subsection 6.1 would signal that most of the ID trading is done during late hours. Significantly smaller correlation coefficients would tell that the ID trading is spread out from earlier to later hours and forecasts and price signals for the delivery hour are not that clear.

The periods analyzed were 2021 and 2022 H1 and only the ID–DA spread was compared by the function of wind power forecast error. In upper-left corner of the figure is the function of the trendline. The first variable term tells the correlation coefficient of the trendline, and the latter constant term tells the price premium.

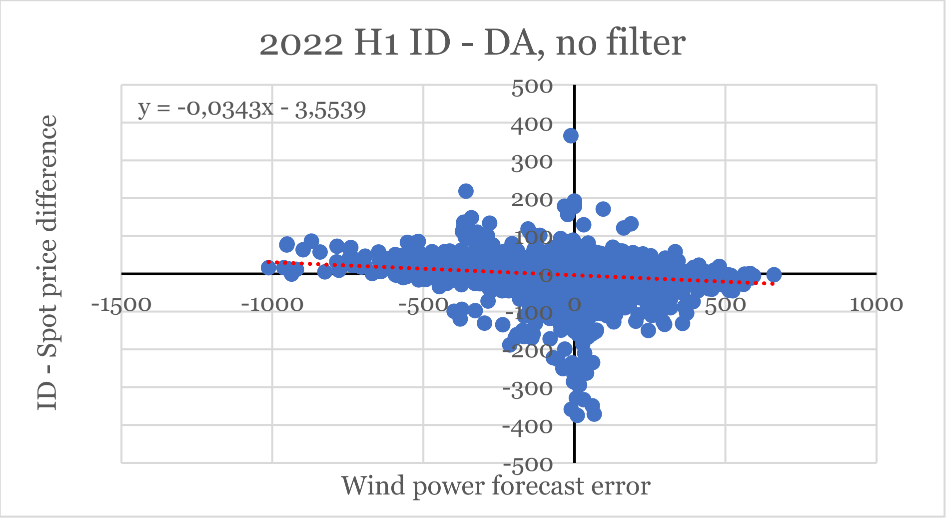


Figure 20. 2022 H1 total average ID – DA price difference, no filter

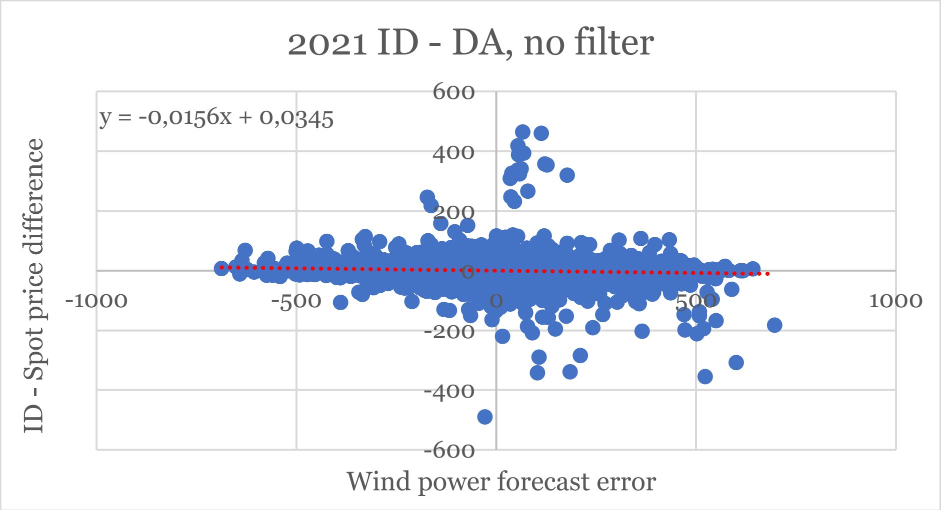


Figure 21. 2021 total average ID – DA price difference, no filter

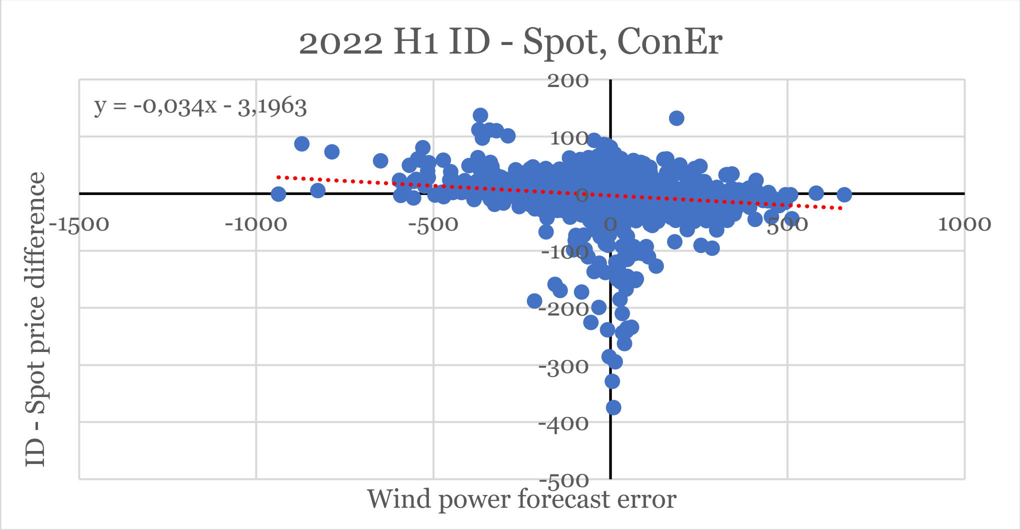


Figure 22. 2022 H1 total average ID – DA price difference, ConEr filter

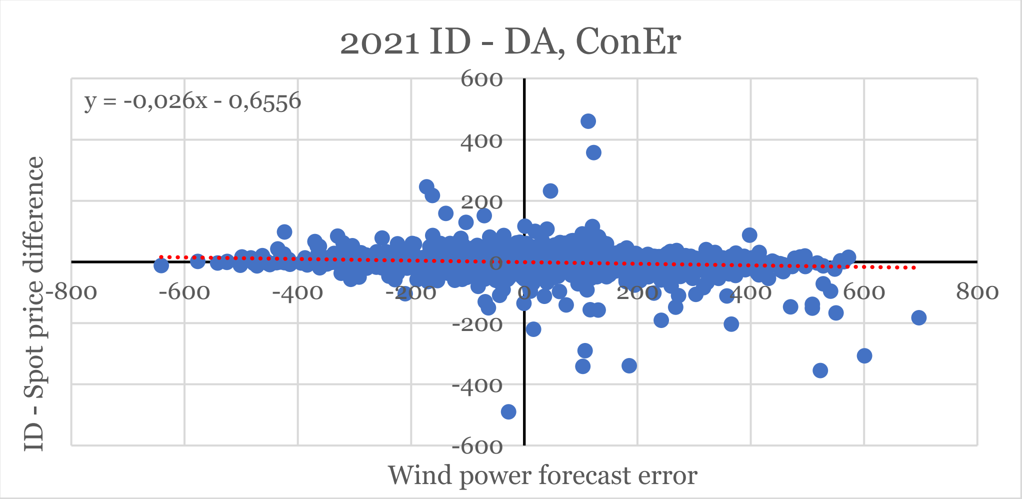


Figure 23. 2021 total average ID – DA price difference, ConEr filter

As can be seen from Figure 20 - Figure 23 there is more correlation in the 2022 H1 than in the year 2021. This tells that the ID markets overall have become more dependent on wind power as the share of wind power in the Finnish electricity system increases. In Table 8, the correlation coefficients of last 2 hours averages and total volume weighted averages can be seen. Comparison between total no filter and ConEr filtered graphs of total ID trades tells that in 2022 H1 there were no practical differences between filtered and non-filtered results. In 2021, the difference was significant as the correlation increased from – 0,0156 to – 0,026 with non-filtered and filtered data, respectively. However, the correlation coefficient was overall higher in filtered and unfiltered VWAP data.

Table 8. Comparison of last hours ID trades and total volume weighted average prices correlation coefficients.

	Last 2 ID hours	Total volume weighted average
2022 H1 no filter	- 0,01445	- 0,0343
2022 H1 ConEr filter	- 0,15414	- 0,034
2021 no filter	- 0,02102	- 0,0156
2021 ConEr filter	- 0,12900	- 0,026

This analysis suggests that overall electricity is traded quite a lot in the early hours. When compared to the results from Subsection 6.1, the correlation coefficients from total WVAP data are often smaller, especially when applying the ConEr filter. From Table 8 it can be seen that the correlation between wind power forecast errors and ID – Spot price spreads were mostly significantly higher within the last 2 hours compared to total ID trades. The only exception here is the 2022 H1 no filter, where the total volume weighted dataset correlates more than the last 2 hours. This seems quite counterintuitive as it could be thought that at the later stage of ID trading when the wind power error is better known, the correlations would be increased.

6.4 Analysis

As in 2021 and 2022 H1, the wind power capacity has been significantly bigger than in previous years, comparison of DA – ID and DA – imbalance price spread with ConEr filter is the best way to look their differences.

Table 9. Comparison of DA - ID and DA - imbalance correlation coefficients from 2019 to 2022 H1 ConEr filters and corresponding wind power capacity at the end of the year.

	DA – ID correlation coefficient	DA – imbalance correlation coefficient	End of period wind power capacity
2022 H1	- 0,15415	- 0,04453	4037
2021	- 0,12901	- 0,25324	3257
2020	- 0,03985	0,00255	2586
2019	- 0,01945	0,01641	2284

From Table 9, it can be seen that the correlation coefficient values in DA – ID column are much more uniform compared to DA – imbalance column. The DA–ID are also rising along with the new wind power capacity with some threshold capacity amount and slowing when a certain amount of wind power capacity has been reached. It seems to be like the minimum amount of wind power capacity to affect ID market prices could be somewhere around 2000 MW and the rise seems to get slower after 3500 – 4000 MW. There is a huge jump in the correlation between the years 2020 and 2021 when wind power capacity rises from 2586 MW to 3257 MW. It seems like somewhere between those capacities may be the area of the biggest change.

If we look at the ID market's pricing for wind power, it looks like the valuation for wind power in that market was around 0,15 €/MWh. For every megawatt increase in wind power forecasts, the ID price decreases 0,15 €. This is far less than the LCOE of wind power, which is roughly 38 €/MWh (IRENA, 2022). This tells more about the market valuation of wind power energy rather than the LCOE of wind power.

Another interesting finding about Table 9 is the year 2021, when wind power capacity grew almost by 700 MW in a year compared to the earlier year when new wind power capacity was built roughly 300 MW. This was a significant sudden increase in new wind power capacity, and it looks like the market players were not ready to balance this sudden new wind power as while the

DA – ID correlation grew significantly, the DA – imbalance correlation coefficient had even more dramatic change, nearly double of the ID correlation. This DA – imbalance correlation reduced the next year, but the DA – ID correlation grew even more. This seems like that the wind power market participants had been getting involved more into ID markets, which the increased correlation in ID markets shows, but maybe to better forecasts, as the sum of 2022 H1 correlation coefficients is nowhere near the sum of 2021 figures.

Karanfil and Li (2017) mentioned the availability of cheap hydropower to balance production in the Nordics errors lowers the imbalance pricing. It could have been that hydropower producers were not ready for the increased effects of increased wind power capacity and thus more errors and balancing needs. Along with other market participants, when they saw increased demand for balancing power in 2021, they could have increased their partition in balancing power markets in 2022. The DA – imbalance price spread could have thus decreased. The increase in balancing power need, according to market dynamics, also increases the potential profits and thus could have driven more capacity into the market decreasing the DA – imbalance spread from 2021 to 2022 H1 as a counter-reaction.

Also, as the consumption side operators play a rather big role in Finnish electricity markets, they could have also been more active in short-term balancing and have either entered ID markets as counterparty balance to wind power or in balancing markets utilizing demand response in 2022 H1. Though, these claims need further research from the consumption side.

As the biggest correlations could be seen when applying the consumption forecast error filter, it could be derived that consumption errors may cause a bigger impact in ID trading than wind power forecast errors. Imagine a case when there is lots of wind power in DA offers, for example, 2000 MWh. If we would lose 500 MWh of that due to forecast error, there would still be, in regular case, enough other production to cover that wind power deficit. If there would initially be a low wind situation and there would be a rather big consumption error, which would lead to a system power deficit, that could lead to the ramp-up of more expensive means of production. Or in an opposite error, the more expensive sources of electricity could be switched off decreasing the overall production costs. The effects of wind power forecast errors may have a different amount of price effect depending on the overall system state and means of production. If we look at Figure 2, there seem to be different levels on the DA supply curve. If the price balance is at the middle of the curve, at a rather flat price spot, a forecast error might not result in a large price difference. If, on the other hand, at the right side of the curve, in a situation when lots of expensive production is in use, the increase of wind power may have a great effect in the price as the more expensive means of electricity generation may be shut off and their DA position can be bought off with a lower price.

7 ID balancing cost and volume analysis

Examining the microstructure of ID markets helps to identify the market participants, structure and drivers of price or volume. As this thesis is focused on wind power, the balancing costs of wind power forecast errors are calculated for the whole Finnish grid.

The wind power and imbalance price data for this section is fetched from Fingrid Open Data (Fingrid). DA and ID prices from a source that the UPM Energy has access to. This section analyses the time period of 2021 – 2022 H1 as one dataset.

7.1 Balancing costs

In order to examine if trading wind power forecast errors even is efficient, I compare the costs of ID trading with total imbalance settlement. As the volumes in ID markets go to nearly zero during the last hour before delivery, in the ID trading scenario, I calculate the cost or profits in two segments. The ID position is traded from the DA forecast till one hour before delivery. The rest of the forecast is regarded as an imbalance. In the total imbalance scenario, I compare the DA forecast with the actual produced electricity as an imbalance. This scenario is depicted in Figure 24. The ID prices used in this scenario are the VWAP. The data used is from 2021 – 2022 H1 and it is analyzed as one dataset. The volume fees are included in the total costs. The imbalance volume fee is 1,5 €/MWh (eSett, 2022b). The ID volume fee is also taken into account, but its amount cannot be disclosed.

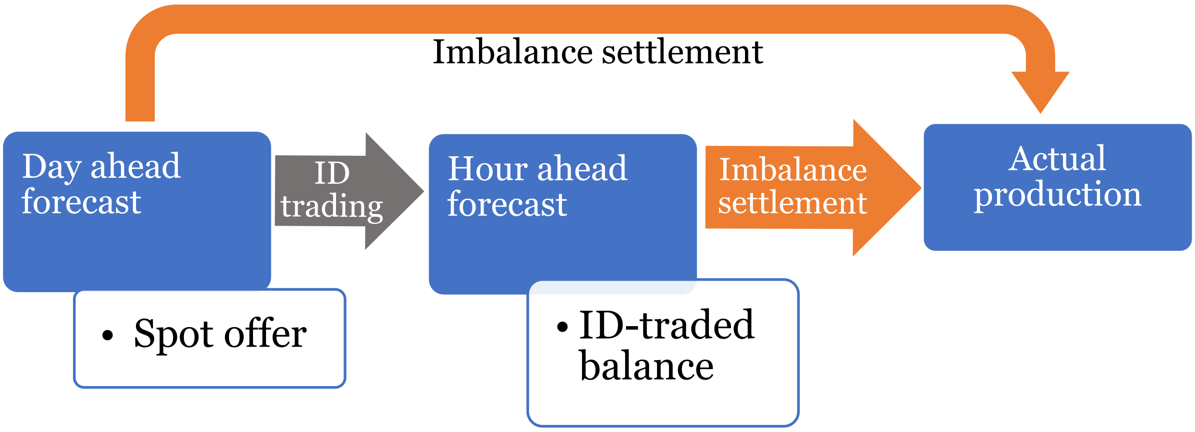


Figure 24. Representation of ID traded wind power position and total imbalance forecast error scenario.

7.1.1 Forecast errors

In order to compare the costs of total imbalance settlement and ID traded error with imbalance settlement, the absolute forecast errors of each time period must be defined. This will give an insight into the scale of forecast errors and the differences in accuracy between different forecast horizons.

Table 10. Actual wind power production with DA forecast error and hour ahead forecast error amount

	MWh
Actual production	13 468 297
DA forecast absolute error	2 425 307
Hour-ahead forecast absolute error	1 554 704

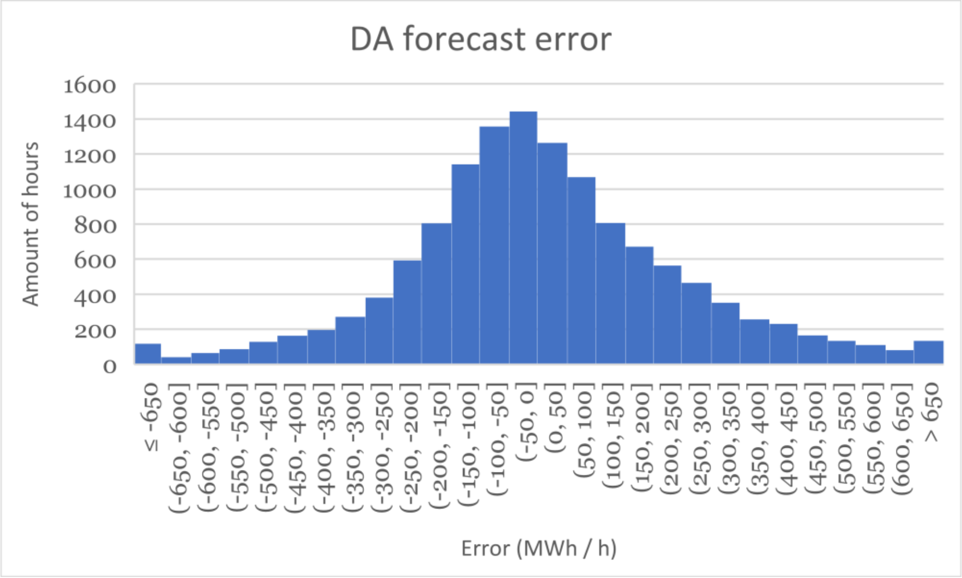


Figure 25. Day-ahead wind power production forecast error distribution. Absolute average error 18,0 %.

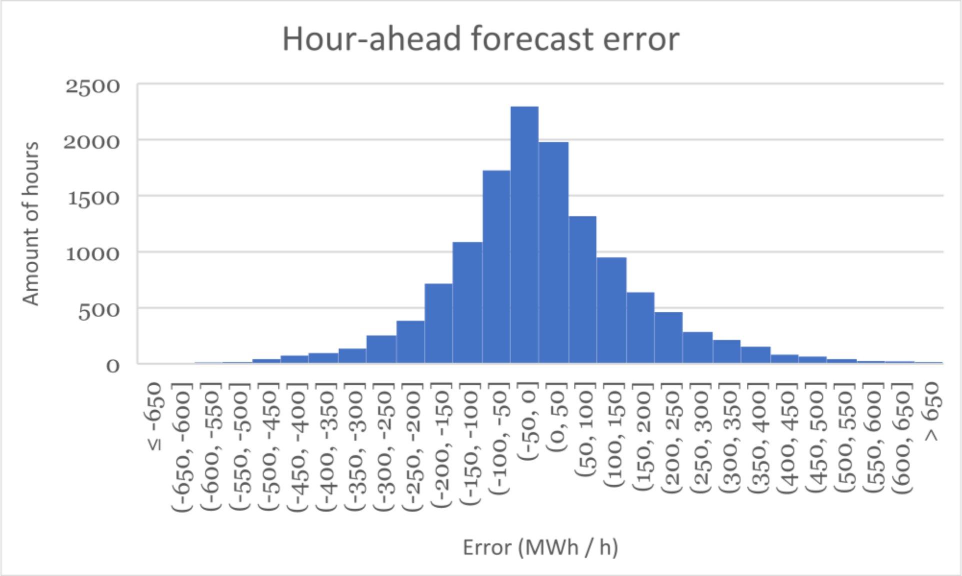


Figure 26. Hour-ahead wind power production forecast error distribution. Absolute average error 11,5 %.

The error distribution and can be seen in Figure 25 and Figure 26. The absolute average errors for DA and hour-ahead forecasts are 18,0 % and 11,5 % respectively and the amount can be seen in Table 10. . The forecast is more accurate the closer to delivery it is as expected. Still, 11,5 % is a rather big error in the hour-ahead forecast. The error distribution gets tighter when closer to the delivery time and the fat tails in DA forecast at over 650 MWh / h disappear completely in the hour-ahead forecast. The day-ahead forecast is leaning towards negative errors in smaller amounts of forecast errors as the peak of the histogram is more on the negative side but evens out at higher forecast errors. Hour-ahead errors are distributed overall more to the negative side.

7.1.2 Balancing cost calculation

To calculate the cost of balancing, first, the amount of balancing must be determined. The DA error can be easily downloaded from Fingrid Open Data (Fingrid), but the amount of balance to trade in ID markets must be calculated by subtracting the DA forecast from the hour-ahead forecast. This gives the volume of wind power, which can be known before delivery but is not perfectly accurate compared to actual production. The error between hour-ahead and actual production is calculated as an imbalance.

There are two different total costs calculated – DA imbalance cost and ID traded total cost. These are bolded and presented in Table 11. The ID traded total cost consists of the cost of the ID trading and the imbalance between the hour ahead forecast and actual production. This is calculated separately to deliver more clear results.

Table 11. Cost calculations for balancing wind power forecast errors.

	Absolute cost (€)	Cost per unit (€/MWh)
DA imbalance	**39 411 792**	**16,26**
ID balancing	- 5 072 321	- 3,01
Hour-ahead imbalance	31 788 958	20,45
ID traded total costs	**26 716 637**	**11,02**

As can be seen in Table 11, the total costs of ID traded forecast error are lower than the DA imbalance cost with 11,02 €/MWh and 16,26 €/MWh, respectively. The ID balancing part even turned out to be profitable. Though, this is calculated with VWAP and does not necessarily represent the real-world scenario. If 100 % of the known error would be dealt with within the ID market, the price would shift higher if DA forecasts are lower than hour-ahead forecasts and vice versa. This would probably make the ID trading less cost-effective. The potential price creeps during ID trade hours and the effect of timing the trades is not taken into account in this scenario.

7.2 ID volume drivers

Time to time, ID markets can be observed to be rather liquid with small price spreads. These often happen during days with high wind power volume. My hypothesis is that either the low prices or the high amount of intermittent renewable energy cause liquidity to rise. A higher amount of total wind power production may lead to higher absolute errors, which must be balanced. However, this is a hard subject to research as a high amount of wind power almost always results in lower prices of electricity.

In this subsection, data from 2021 and 2022 H1 are analyzed as one data set. Due to the purpose of this analysis, the history development is irrelevant, and the data is combined to provide a larger dataset. According to Garnier & Madlener (2015), one of the main drivers of ID liquidity is the amount of intermittent renewables, wind power in this case, in the system. They state that liquid markets are required so that the forecast errors of intermittent renewables can be balanced. The data is normalized with min-max normalization, where the smallest data point in each axis gets a score of 0 and the largest data point gets a score of 1. This allows the comparison of different variables.

In Figure 28, the ID volume is analyzed as a function of the Spot price. The data seems to be a cluster in the bottom left with few outliers. This creates the trendline to be a positive slope. The R-squared value of the Spot price – ID volume trendline is 0,0158.

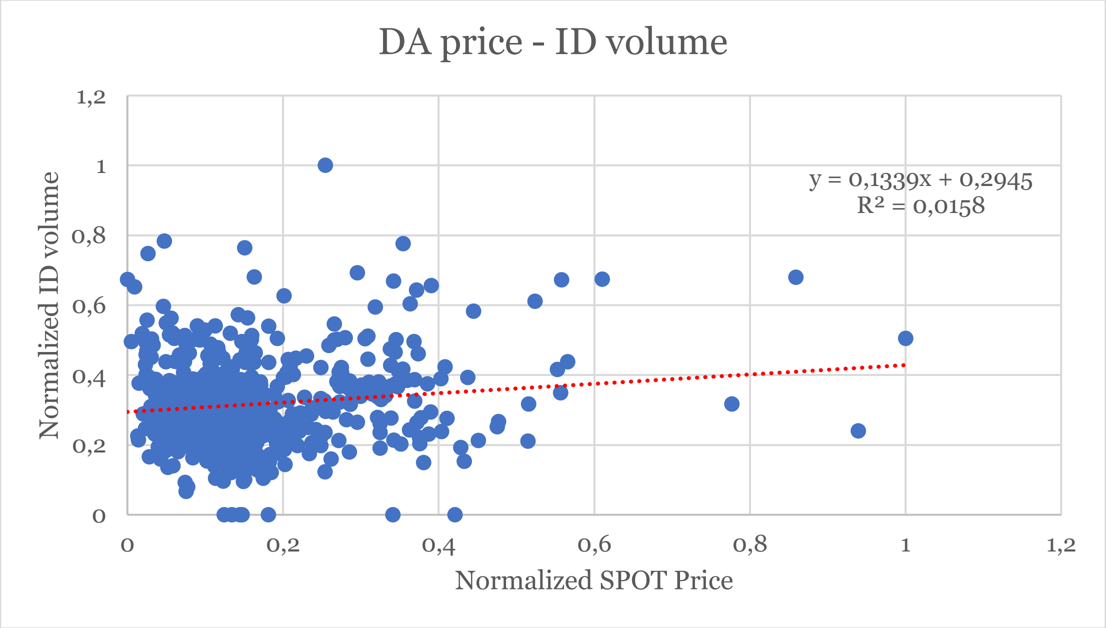


Figure 27. Normalized ID trade volume as a function of Spot price.

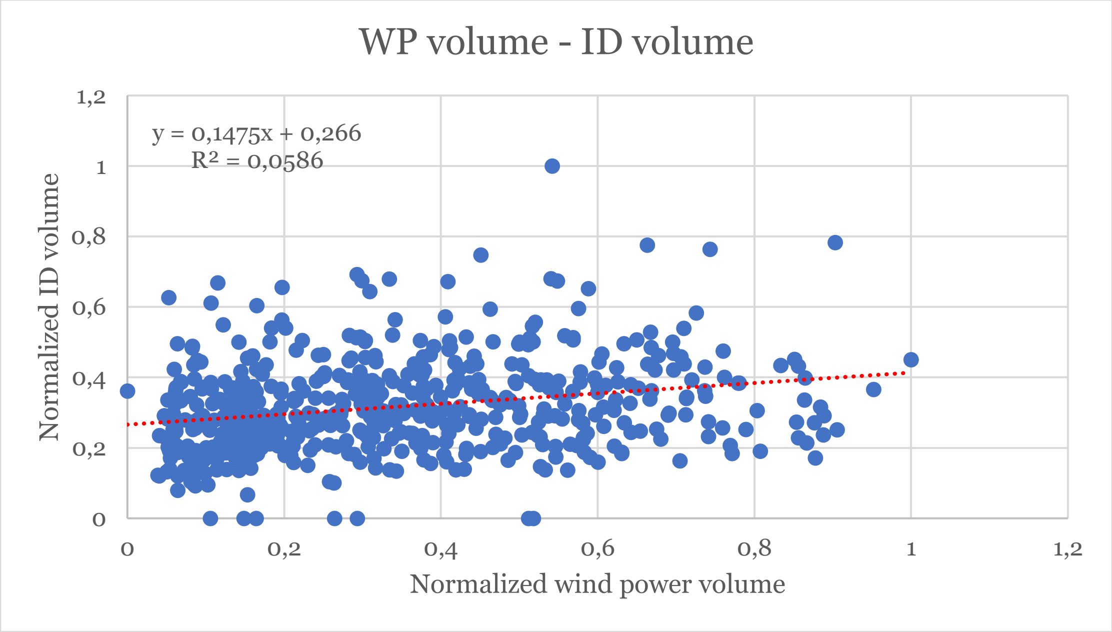


Figure 28. Normalized ID trade volume as a function of normalized wind power production volume.

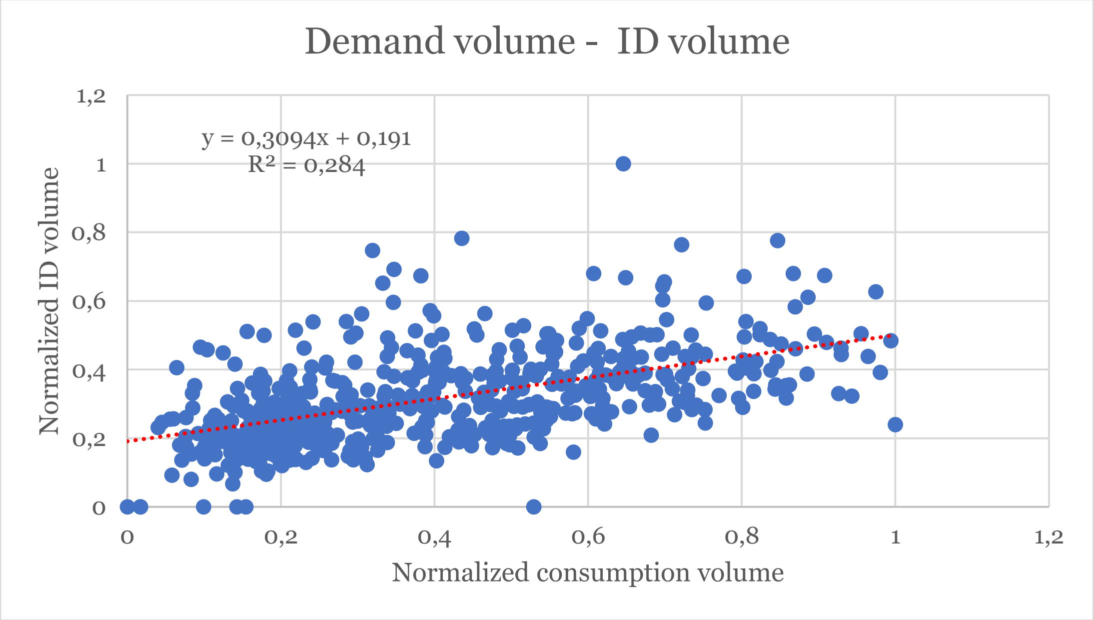


Figure 29. Normalized ID trade volume as a function of normalized power demand volume.

In Figure 28, ID volume is studied as a function of wind power volume. The scatter of this figure follows the trendline much more than in Figure 27. R-squared value of Figure 28 is 0,0586. Figure 28 has rather high ID volume data points with low wind power volume both decreasing the correlation co-efficient and R-squared.

As can be seen from Figure 28 and Figure 28, wind power volume is much clearer ID volume driver than Spot price. The R-squared value when studying the wind power volume is much higher, although overall rather low, than when Spot-price is studied. The correlation coefficients and standard terms of trendlines are rather similar, so they cannot be used to analyze the differences in correlation.

Another possibility as an ID volume driver could be a daily price spread. If trading parties have noticed and taken advantage of daily price spreads and utilize demand response, they can impact the ID market and take advantage of daily price differences. Shifting consumption into cheaper hours within their own restrictions allows consumers to benefit financially and have an opportunity to balance daily high price spreads, although this price balancing would happen only in ID markets.

Figure 29 depicts the correlation between consumption volume and ID trade volume. Compared to wind power production, this provides both a bigger correlation coefficient and R-squared. This means that the overall consumption volume in the Finnish electricity system affects the ID liquidity more than overall wind power production.

The liquidity in Finnish ID markets is mainly driven by consumption volume. Wind power production volume is also a driver but does not have as big of an impact. DA price does not seem to have a significant positive or negative impact on the ID volume, even though a higher amount of wind power volume usually results in a smaller DA price.

8 Results and discussion

As wind power capacity has increased, so has the negative correlation between wind power forecast errors and close to delivery ID prices. Comparing DA – ID correlation results with DA – imbalance correlation benchmarked the results and provided useful information about the behaviour and of wind power operators and how it has developed within the last years. In 2021 when there was a rapid new development of new wind power production, the correlation between wind power forecast errors and DA – imbalance price correlation was extraordinarily strong. In the same year, though, the DA – ID price spread correlation rose significantly too, but not as much as in DA – imbalance. In 2022 H1, the DA – ID price spread correlation increased further, but the DA – imbalance spread dropped low.

One reason for the sudden spike and drop of DA – imbalance correlation in 2021 and 2022 H1 could be that the wind power balancing operators have increasingly gotten involved in the ID markets. Imbalance costs have spiked higher in 2021 and 2022 H1 and thus the imbalance risk has followed. 4.2.2022 at delivery hour 06 – 07, the imbalance price suddenly spiked at 3500 €/MWh (Fingrid, 2023a). These kinds of cost risks could drive operators into ID markets, where the cost of balancing is known, and thus the risks are lower.

The data supports that, by trading in ID, the overall costs of imbalances can be lowered, but the data does not take the timing of the trades into account. As the forecast gets more accurate, the closer it is to delivery time, the prices would change when the wind power forecast changes and thus make the prices less advantageous to wind power balancing.

Low predictability of wind power between the day ahead and even the hour ahead does not help the penetration of ID trading in order to mitigate the imbalance of production. In this thesis, only the hour ahead forecast was used to analyze ID and imbalance markets because the whole ID balancing works based on forecasting, which is not always accurate.

An example day of the theory and results provided in this thesis is 12.12.2022. During that day, the DA – hour-ahead wind power forecast errors for the whole day had an average of 331 MWh/h, meaning that there was more wind power production than forecasted. DA forecast, compared to the actual production forecast, had an average error of 553 MWh/h and there were eight hours when the DA forecast had an error of 800 MWh/h. This created huge price spreads for the ID and imbalance prices compared to the DA price. The average DA price was 385,76 €/MWh, average hourly ID price was 288,70 €/MWh while the average of the last trades of each product was 244,25. The average imbalance price for this day was 141,17 €/MWh. So, in this case, even though some of the DA forecast errors were dealt with in ID markets, either the depth of the is not enough for these extreme situations and no more offers were in the limited order book, or the market operators do not utilize the ID markets as much as they should. Comparing the last trade with the average price values, the error is not significant suggesting that the forecast error may have been known rather early on before delivery. In this day, the potential for ID trading utilization with demand response would have been well profitable.

Wind power production volume seems to be still a secondary volume driver in the Finnish ID market. Consumption volume has a bigger impact on the ID market volumes. This thesis uses consumption errors (ConEr) as a filter to focus on the wind the effects of wind power forecast errors, but switching these variables around would be an interesting topic for future research: effects of consumption forecast errors in ID markets with wind power forecast error filter. With ever-increasing amount of wind power in the electricity system, wind power could become the biggest volume and price driver in Finnish markets.

This thesis was based on publicly available wind forecasts from Fingrid. If commercial forecasts are more accurate, the results presented here would be subject to change. Though, assuming that different parties in Finland use different wind power forecast provider, choosing one forecast would prove to be problematic.

9 Conclusions

Finnish ID market price follows the wind power forecast errors. When the hour-ahead forecast of wind power production is higher than the day-ahead forecast, the prices in ID markets tend to decrease and vice versa. This has come into effect in just recent years, particularly 2020 onwards. The effects of this are explained mostly by new wind power capacity, which has been built and thus the absolute values of forecast errors have increased.

Comparing DA - ID price spread to DA – hour-ahead wind power forecast errors with DA – imbalance price spread with the same forecast errors proved to be a good way to benchmark the utilization of ID markets as all imbalance, which is not dealt with in ID markets can be seen in imbalance price. Further filtering of the data pinpoints the desired value as other variables can be decreased. Using consumption error filtering, the effects of wind power can be seen more accurately.

Even though historically the ID volumes have not increased in relation to DA volumes, the liquidity of ID markets has increased when it comes to wind power balancing. With increasing the amount of wind power in the future, it could become the price and volume setter in the ID market.

Handling DA forecast error of wind power is cheaper in ID markets when using volume weighted average prices compared if the whole imbalance would be dealt with in imbalance settlement. Strategy and timing of the trades affect the cost of ID trading, but that topic is not addressed in this thesis.

References

A. Khodadadi, L. H. (2020). doi:10.1109/EEM49802.2020.9221992

Amelin, M. (2015). An Evaluation of Intraday Trading and Demand Response for a Predominantly Hydro-Wind System Under Nordic Market Rules. *IEEE Transactions on Power Systems, 30*(1).

Amelin, R. S. (2016). Trading behaviour on the continuous intraday market Elbas. *Energy Policy, 88*, 544 - 557. doi:10.1016/j.enpol.2015.10.045

Baltic Sea System Development Steering Committee. (2022). *Nordic and Baltic Sea*. Retrieved from https://www.fingrid.fi/globalassets/dokumentit/fi/tiedotteet/energiauutiset/nordic-and-baltic-sea-winter-power-balance-2022-2023-report.pdf

Bergmann. (2018). *Wind Energy Finland Opportunities 2018/19*. Retrieved 8 12, 2022, from https://www.bergmann.fi/pdf/wind_energy_finland_2018-19.pdf

Bergmann. (2022). *Wind Energy Finland Opportunities 2022/23*. Retrieved 12 9, 2022, from https://www.bergmann.fi/pdf/wind_energy_finland_2022-23.pdf

E. R. Soysal, O. J. (2017). Intraday market asymmetries — A Nordic example. *2017 14th International Conference on the European Energy Market*, 1 - 6. doi:10.1109/EEM.2017.7981920

Ehrhart, F. O.-M. (2017). The “German Paradox” in the balancing power markets. *Renewable and Sustainable Energy Reviews, 67*, 892 - 898. doi:https://doi.org/10.1016/j.rser.2016.09.040

Energiavirasto. (2022a). *Tuotantotuki*. Retrieved 10 10, 2022, from https://energiavirasto.fi/tuotantotuki

Energiavirasto. (2022b). *Preemiojärjestelmä*. Retrieved 10 10, 2022, from https://energiavirasto.fi/preemiojarjestelma

ENTSO-E. (2021). *Nordic Balancing Philosophy*. Retrieved from https://eepublicdownloads.azureedge.net/clean-documents/Publications/SOC/Nordic/2022/Nordic%20Balancing%20Philosophy%20updated%202021%20for%20publication.pdf

ENTSO-E. (2022a). *Single Day-ahead Coupling (SDAC)*. Retrieved 10 5, 2022, from https://www.entsoe.eu/network_codes/cacm/implementation/sdac/

ENTSO-E. (2022b). *Single Intraday Coupling (SIDC)*. Retrieved 12 7, 2022, from https://www.entsoe.eu/network_codes/cacm/implementation/sidc/

eSett. (2022a). *eSett in Brief*. Retrieved 9 29, 2022, from https://www.esett.com/about/esett-in-brief/

eSett. (2022b). *Nordic Imbalance Settlement Handbook*. Retrieved from https://www.esett.com/app/uploads/2022/10/NBS-Handbook-v4.1.pdf

European Central Bank. (2022). *Energy price developments in and out of the COVID-19 pandemic – from commodity prices to consumer prices*. Retrieved 10 24, 2022, from https://www.ecb.europa.eu/pub/economic-bulletin/articles/2022/html/ecb.ebart202204_01~7b32d31b29.en.html

European Wind Energy Association. (2020, October). *Permitting*. Retrieved 10 31, 2022, from https://windeurope.org/policy/topics/permitting/

Fernandes, J. C.-Á. (2015). The Spanish intraday market design: A successful solution to balance renewable generation? *Renewable Energy*, 422 - 432. doi:https://doi.org/10.1016/j.renene.2014.08.017.

Fingrid. (2022a, 9). *Tasevastuuta ja taseselvitystä koskeva asiakirja, Osa 1: Fingrid Oyj:n yleiset tasehallinnan ehdot (in Finnish)*. Retrieved from https://www.fingrid.fi/globalassets/dokumentit/fi/palvelut/tasesahkokauppa-ja-taseselvitys/liite-1-osa-1-fingrid-oyjn-yleiset-tasehallinnan-ehdot-.pdf

Fingrid. (2022b, 9). *Tuulivoiman tuotanto*. Retrieved 9 14, 2022, from https://www.fingrid.fi/sahkomarkkinainformaatio/tuulivoiman-tuotanto/

Fingrid. (2023a, 2 7). *Imbalance price from 1.11.2021*. Retrieved from https://www.fingrid.fi/en/electricity-market-information/imbalance/imbalance-price/

Fingrid. (n.d.). *Open Data*. Retrieved from https://data.fingrid.fi/en/

Finlex. (2010). *Act on the Production Subsidy for Electricity Produced from Renewable Energy Sources*. Retrieved from https://www.finlex.fi/fi/laki/alkup/2010/20101396

Finnish Energy Authority. (2022c). *Syöttötariffijärjestelmään hyväksyttyjen voimalaitoksien tietoja*. Retrieved 7 12, 2022, from SATU: http://tuotantotuki.emvi.fi/Installations

Finnish energy authroity. (2022b). *Preemiojärjestelmä*. Retrieved 10 10, 2022, from https://energiavirasto.fi/preemiojarjestelma

Finnish Wind Power Association. (2022). *Wind power has been set stricter sound guidelines than other societal functions*. Retrieved 12 8, 2022, from Wind power has been set stricter sound guidelines than other societal functions

Garnier, E. &. (2014). *Balancing Forecast Errors in Continuous-Trade Intraday Markets*. FCN Working Papers 2/2014, E.ON Energy Research Center, Future Energy Consumer Needs and Behavior (FCN). Retrieved from https://ideas.repec.org/p/ris/fcnwpa/2014_002.html

Garnier, E. &. (2015). Balancing forecast errors in continuous-trade intraday markets. *Energy Syst 6*, 361 - 388. doi:https://doi.org/10.1007/s12667-015-0143-y

Hanna-Mari Husu, M. S. (2022). The formation of feed-in tariffs and the emergence of wind power in Finnish routine corporatism: favoring the economics of large-scale energy production. *Environmental Politics, 31:3*, 478 - 497. doi:10.1080/09644016.2021.1926774

IEA. (2022). *Electricity Market Report - July 2022*. Retrieved from https://www.iea.org/reports/electricity-market-report-july-2022

IRENA. (2022, July). *Renewable Power Generation Costs in 2021*. Retrieved 31 10, 2022, from https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

Karanfil, F. a. (2017). The Role of Continuous Intraday Electricity Markets: The Integration of Large-Share Wind Power Generation in Denmark. *The Energy Journal, Vol. 38*, 107-130. Retrieved from https://doi.org/10.1016/j.apenergy.2020.116063

Lennart Söder, E. T.-M. (2020). Review of wind generation within adequacy calculations and capacity markets for different power systems. *Renewable and Sustainable Energy Reviews, 119*. doi:10.1016/j.rser.2019.109540

Mousavi, S. &. (2019). Strategic wind power investment in competetive electricity markets considering the possibility of participation in intraday market. *IET Journals Vol. 14*, 2676-2686. Retrieved November 29, 2019, from Aalto University brand library: https://www.aalto.fi/en/visual-library#/visual-elements/typography

Nasaq. (2022). *Nordic & European Power - manage power price risks efficiently*. Retrieved 9 29, 2022, from https://www.nasdaq.com/solutions/nordic-european-power

National Audit Office of Finland. (2017). Retrieved 6 10, 2022, from https://www.vtv.fi/app/uploads/2018/06/26142316/feed-in-tariff-as-an-instrument-for-subsidising-wind-power.pdf

Nord Pool. (2021). *Trading Figures*. Retrieved 30 9, 2022, from https://www.nordpoolgroup.com/en/message-center-container/newsroom/exchange-message-list/2022/q1/nord-pool-announces-2021-trading-figures/

Nord Pool. (2022a). *Trading*. Retrieved 9 22, 2022, from https://www.nordpoolgroup.com/en/trading/

Nord Pool. (2022b, August). *Day-ahead price formation*. Retrieved from Nord Pool website: https://www.nordpoolgroup.com/en/the-power-market/Day-ahead-market/Price-formation/

Nord Pool. (2022c). *Day-ahead market*. Retrieved 9 30, 2022, from https://www.nordpoolgroup.com/en/the-power-market/Day-ahead-market/

Nord Pool. (2022d). *Intraday trading*. Retrieved 10 19, 2022, from https://www.nordpoolgroup.com/en/trading/intraday-trading/order-types/

Nord Pool. (2022e). *Market opening times for contracts with delivery next day*. Retrieved 10 19, 2022, from https://www.nordpoolgroup.com/49c163/globalassets/download-center/xbid/nord-pool-sidc-gate-opening-times-gate-closing-times.pdf

Nord Pool. (2022f). *Day-ahead prices*. Retrieved 24 10, 2022, from https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Area-Prices/FI/Yearly/?view=table

Nord Pool. (2022g). *Other Products*. Retrieved 8 12, 2022, from https://www.nordpoolgroup.com/en/services/power-market-data-services/Product-details/

Nord Pool. (2022h, 12 10). *Day-ahead volumes*. Retrieved from https://www.nordpoolgroup.com/en/Market-data1/Dayahead/Volumes/FI/Hourly1/?view=table

Nord Pool. (2022i). *2021 Annual Review*. Retrieved from https://www.nordpoolgroup.com/4ac588/globalassets/download-center/annual-report/nord-pool-annual-review-2021.pdf

Nordic Balancing Model. (2022). *15 min Imbalance Settlement Period*. Retrieved 27 10, 2022, from https://nordicbalancingmodel.net/roadmap-and-projects/15-min-time-resolution/

Rintamäki, T., Afzal, S. S., & Salo, A. (2020). Strategic offering of a flexible producer in day-ahead and intraday power markets. *European Journal of Operational Research, 284*(12), 1136 - 1153. doi:https://doi.org/10.1016/j.ejor.2020.01.044.

Spodniak, P. O. (2020). The impact of wind power and electricity demand on the relevance of different short-term electricity markets: The Nordic case. *Applied Energy 283*. doi:10.1016/j.apenergy.2020.116063

Statistics Finland. (2021). *Energy prices rose in the first quarter*. Retrieved 10 24, 2021, from https://www.stat.fi/til/ehi/2021/01/ehi_2021_01_2021-06-10_tie_001_en.html

The European Wind Energy Association. (2015). *Balancing responsibility and costs of wind power plants*. Retrieved from https://www.ewea.org/fileadmin/files/library/publications/position-papers/EWEA-position-paper-balancing-responsibility-and-costs.pdf

TradeRES. (2020). *D3.5 - Market design for a reliable ~100% renewable electricity system*. Retrieved from https://traderes.eu/wp-content/uploads/2021/04/D3.5_MarketDesignOptions_H2020.pdf

Tuulivoimayhdistys. (2022a, 9). *Rakenteilla olevat hankkeet*. Retrieved 9 14, 2022, from https://tuulivoimayhdistys.fi/tuulivoima-suomessa/rakenteilla-olevat-hankkeet

Tuulivoimayhdistys. (2022b, 9). *Tuulivoimahankkeet Suomessa*. Retrieved 9 14, 2022, from https://tuulivoimayhdistys.fi/tuulivoima-suomessa/kartta

Vehviläinen, I. (2020). Lecture 2, Electricity markets. Energy and environmental economics. Aalto University. Retrieved from Energy and environmental economics.

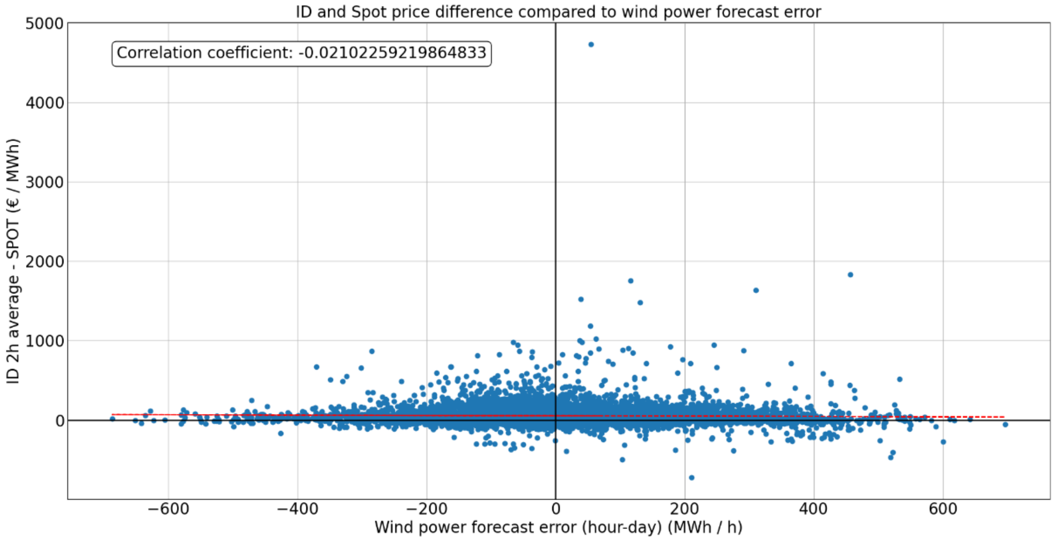
Xiao Hu, J. J. (2021). The effects of wind power on electricity markets: A case study of the Swedish intraday market. *Energy Economics, 96*. doi:https://doi.org/10.1016/j.eneco.2021.105159

YLE. (2022, 6 19). *Defence Forces: Few wind power locations available*. Retrieved 12 8, 2022, from Defence Forces: Few wind power locations available

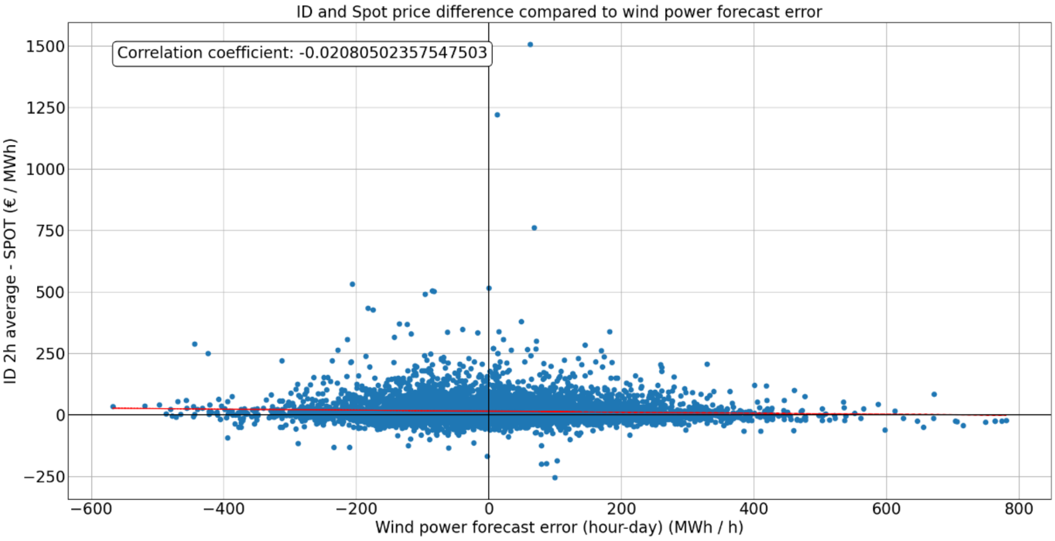
Appendix A. Other wind power forecast error results

1. ID-DA no filter

2021

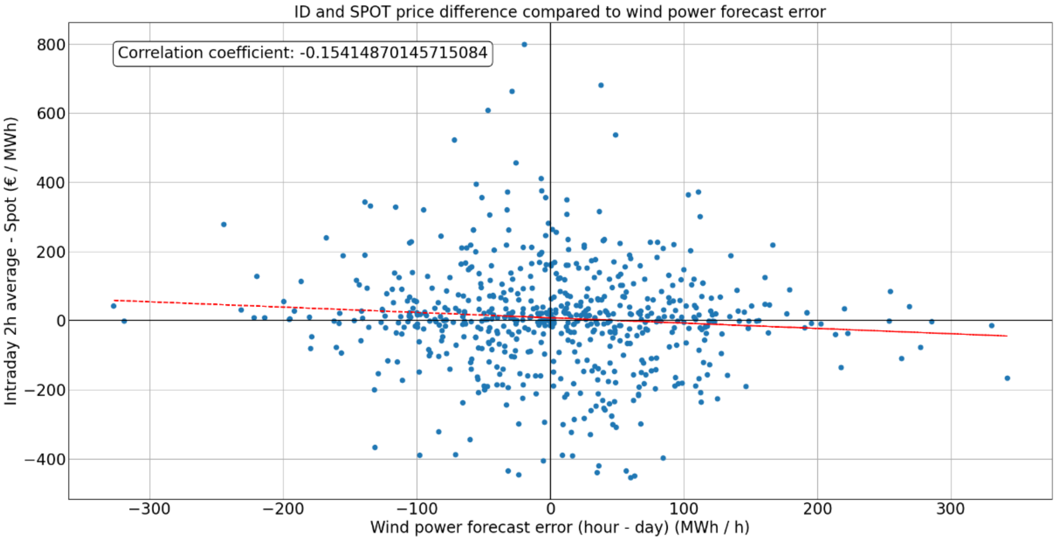


2020

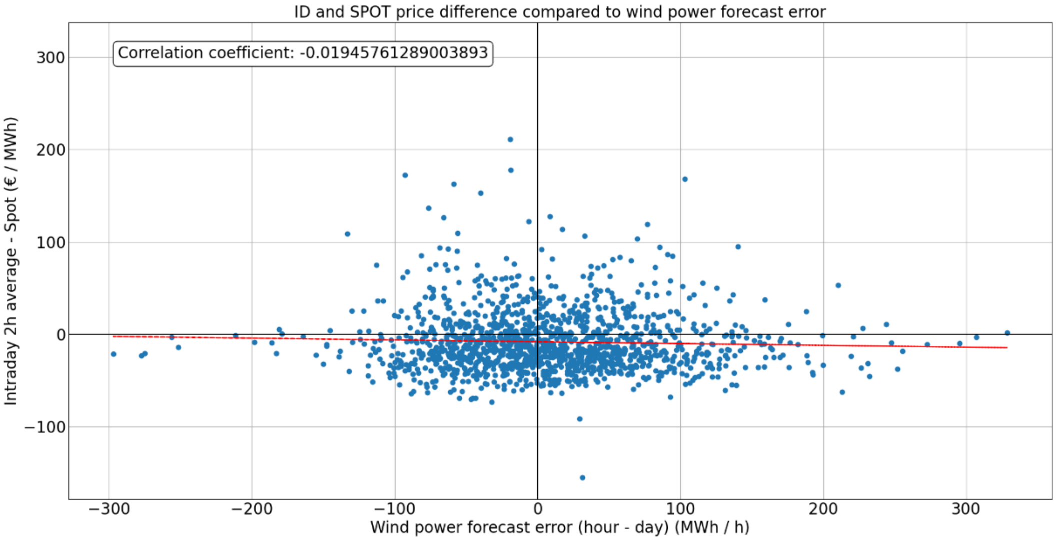


2. ID-DA ConEr filter

2022 H1

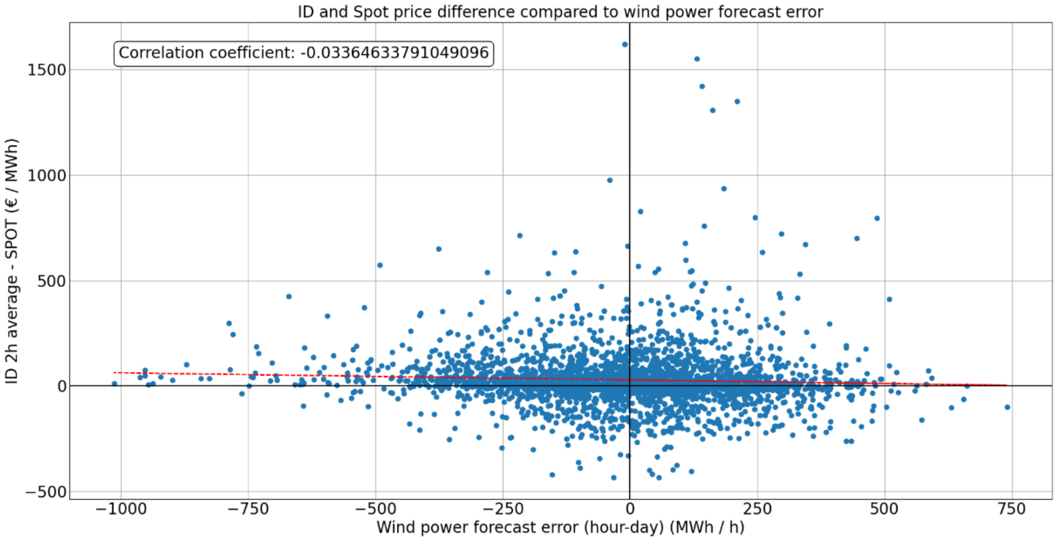


2019

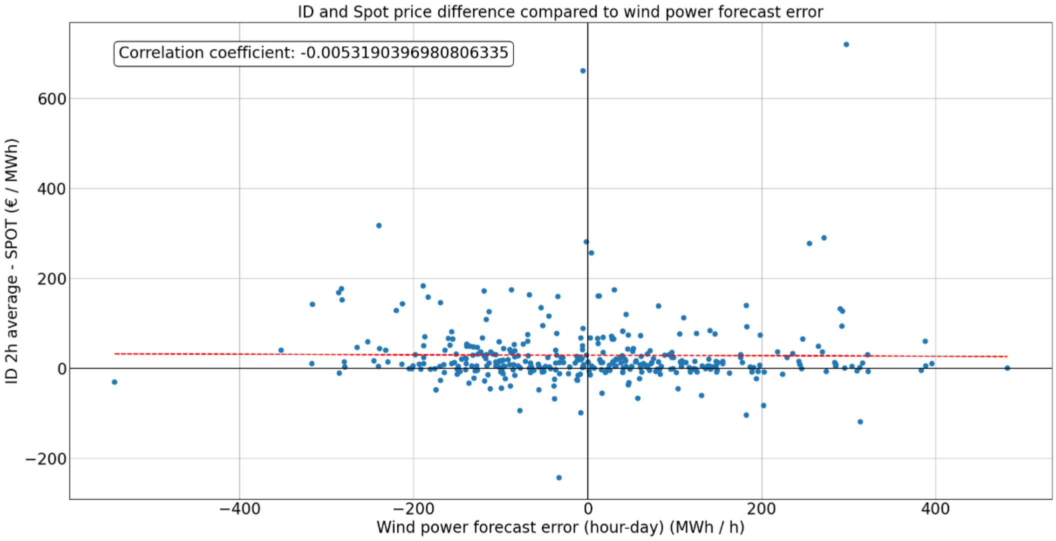


3. ID-DA threshold percents 2022 H1

10 %

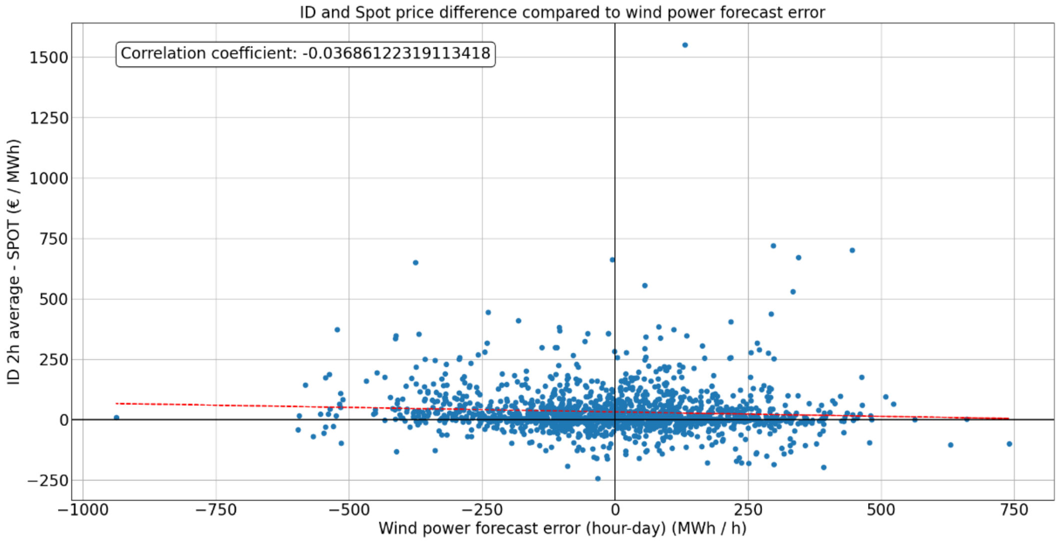


30 %

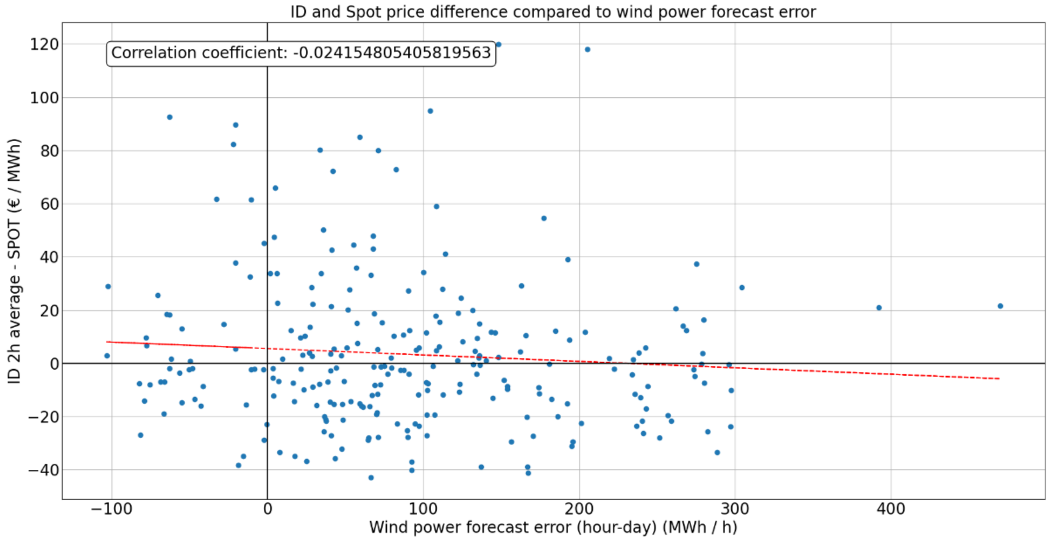


4. ID-DA threshold filter

2022 H1

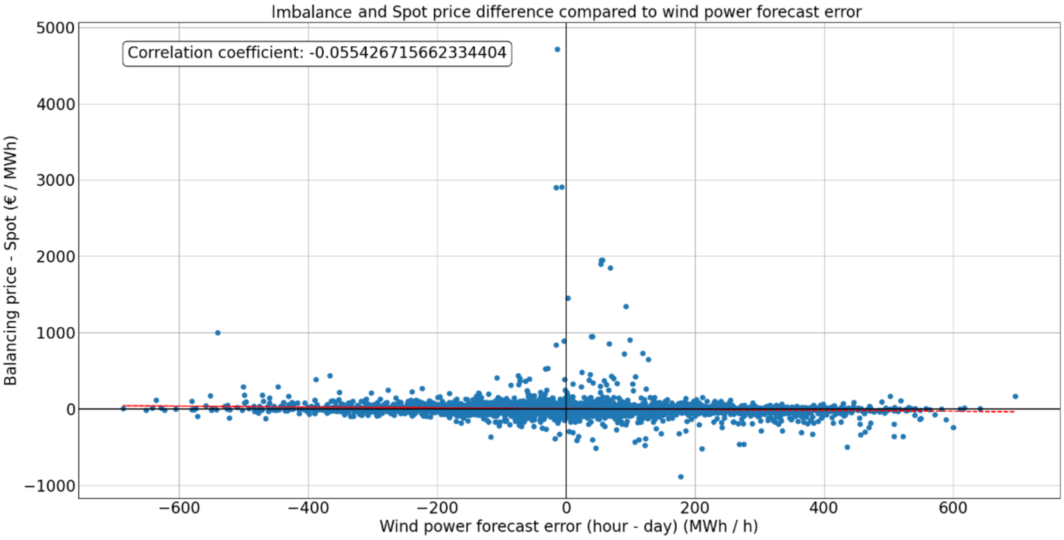


2019

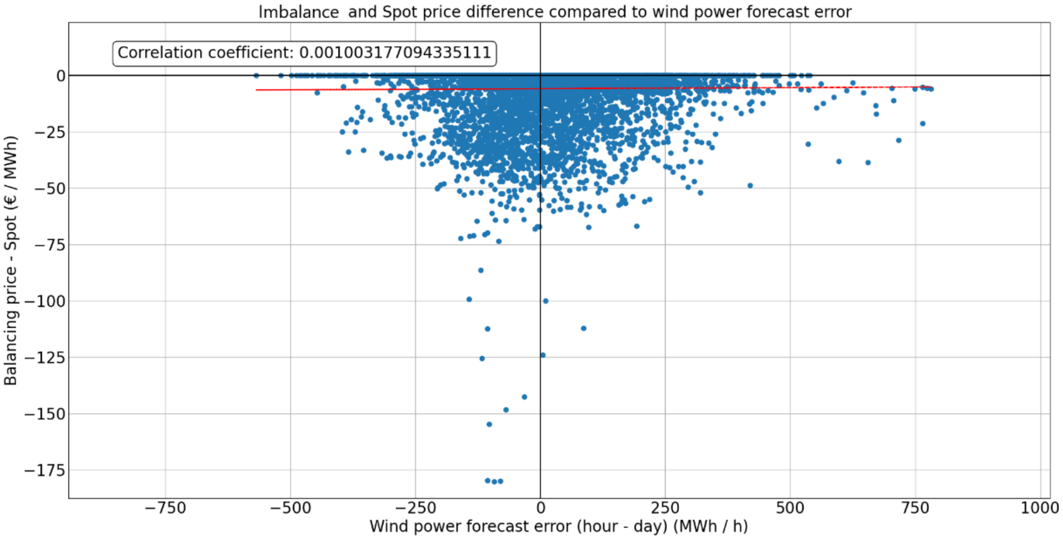


5. DA-Balancing price no filter

2021

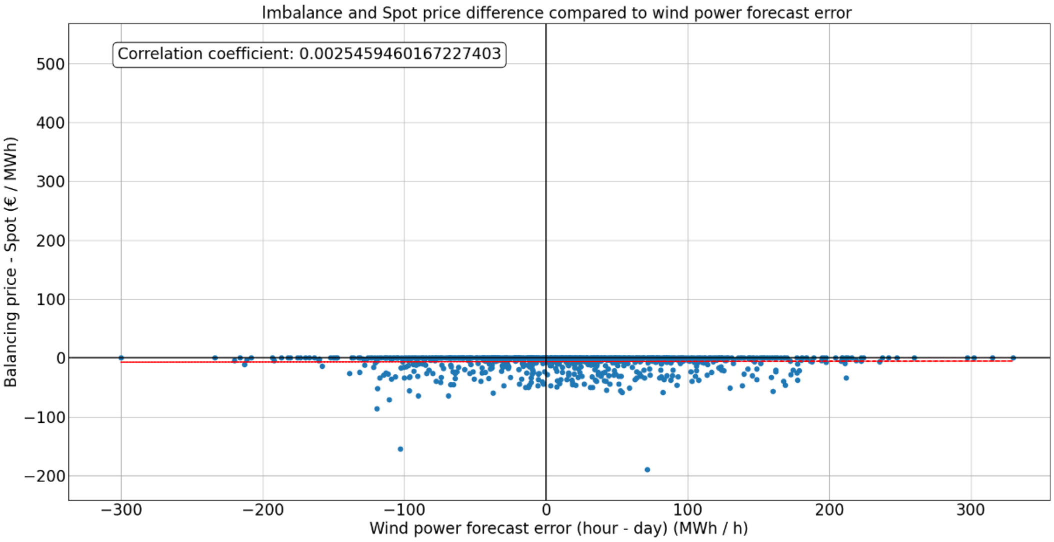


2020

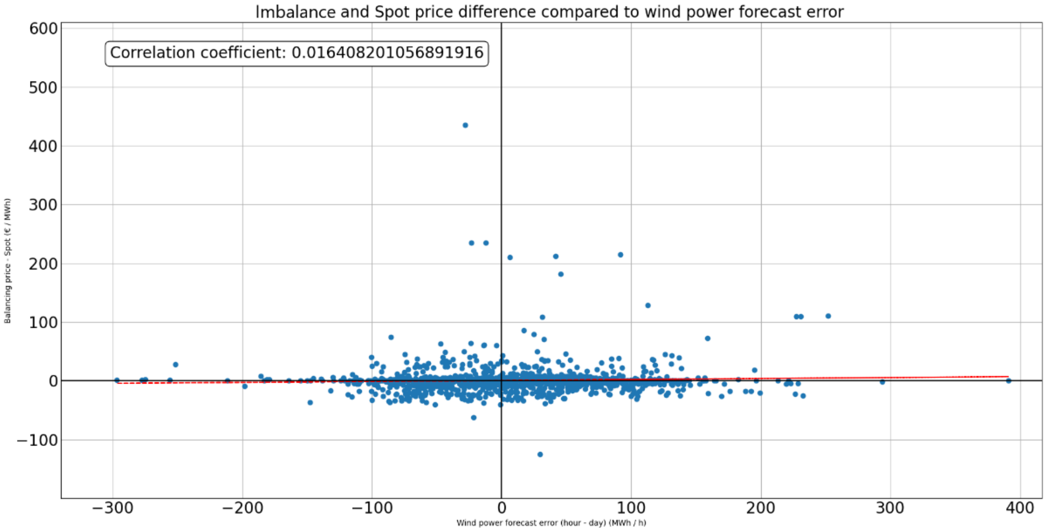


6. DA-Balancing price ConEr filter

2020

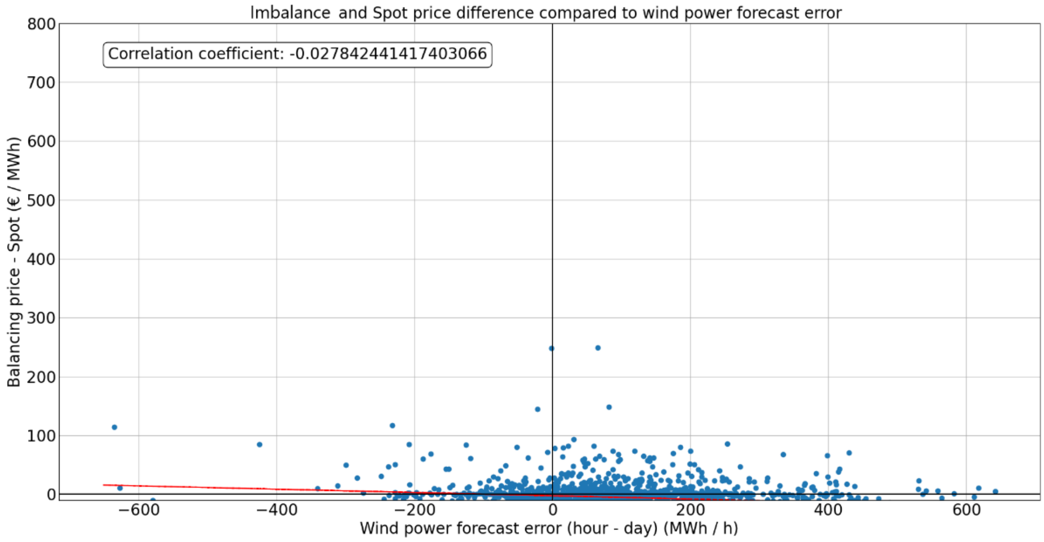


2019



7. DA-Balancing Threshold filter

2021



2019