Analysis and Modelling of the Balancing Energy Market in the Nordics and Finland

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Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 19.5.2023

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Abstract of the master's thesis

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Title Analysis and Modelling of the Balancing Energy Market in the Nordics and Finland

Degree programme Advanced Energy Solutions

Major Sustainable Energy Systems and Markets **Code of major** ELEC3048

Supervisor Prof. Mahdi Pourakbari Kasmaei

Advisor MSc Nikita Semkin

Date 19.5.2023 **Number of pages** 48 **Language** English

Abstract

The balancing energy market is the last of multiple markets that ensure the equilibrium of electricity production and demand. It is the mechanism through which mFRR activations are procured, and balances the power system within the operational hour.

This thesis analyses the market design and turnout to establish a description of the balancing energy market, how does its turnout behave, and how can it be modelled. First, a literature review establishes the market rules, main design parameters and key stakeholders in the Nordic balancing energy markets, as well as main future drivers of change. Then, the characteristics of the Finnish market turnout during 2018-2022 are described with statistical data analysis. Finally, a modelling methodology for volume and premium is proposed for long-term scenario generation purposes.

The balancing energy market is a real-time market with asymmetrical, marginal pricing. The Nordic synchronous grid has a common merit order with multiple market areas. The three main market actors are the System Operators, the Balancing Service Providers, and the Balancing Responsible Parties. Future drivers include planned market reforms, and increasing electricity demand and variable renewable energy.

The analysis shows a small market, with a growing trend in both volume and premium. Seasonality was detected at hourly and monthly level. Volume was found to be distributed consistent to a random variable. Correlations were discovered between volume and premium, but also to day-ahead price and interconnector usage, and a weak but increasing correlation to wind power. No significant increase in correlation was detected when comparing the Finnish versus Nordic level of variables.

The proposed model performs acceptably when compared to historic data, but does not capture all characteristics of the turnout. Further research is proposed to better capture the characteristics of the balancing energy market.

Keywords electricity markets, balancing energy, reserve markets, mFRR

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Diplomityön tiivistelmä

Tekijä Lionel Irrmann

Työn nimi Suomen ja Pohjoismaiden säätösähkömarkkinoiden analyysi ja mallinnus

Koulutusohjelma Advanced Energy Solutions

Pääaine Sustainable Energy Systems and Markets **Pääaineen koodi** ELEC3048

Työn valvoja Prof. Mahdi Pourakbari Kasmaei

Työn ohjaaja DI Nikita Semkin

Päivämäärä 19.5.2023 **Sivumäärä** 48 **Kieli** Englanti

Tiivistelmä

Säätösähkömarkkinat ovat mFRR:n hankintamekanismi, millä vastataan sähköjärjestelmän tasapainoittamisesta operatiivisen tunnin aikana. Se on näin ollen ajallisesti viimeinen osa sähkömarkkinoiden ketjua, jolla varmistetaan sähköntuotannon tasapaino kysynnän ja tuotannon välillä.

Diplomityö tutkii markkinan rakennetta ja toteumaa luodakseen kuvauksen säätösähkömarkkinoista, sen käyttäytymisestä ja mallinnusmahdollisuuksista. Kirjallisuuskatsaus määrittelee pohjoismaisten markkinoiden rakenteen ja säännöt, sidosryhmät ja tulevaisuuden ajurit. Tilastollisen analyysin avulla kuvataan vuosien 2018-2022 toteumaa Suomen markkina-alueella. Lopuksi markkinapreemiolle ja volyymille luodaan malli pitkän aikavälin skenaarioiden luomiseksi.

Säätösähkömarkkinat ovat reaaliaikaiset, asymmetrisesti ja marginaalisesti hinnoitellut markkinat. Pohjoismaisella synkronijärjestelmällä on yhteinen tarjouslista, mutta useita markkina-alueita. Markkinoilla operoi järjestelmäoperaattorit, reserviooperaattorit sekö tasetasevastaavat. Markkinoiden tulevaisuuden ajurit ovat markkinauudistukset sekä lisääntyvä kysyntä ja uusiutuva vaihteleva tuotanto.

Analyysin perusteella markkina on pieni mutta kasvava. Kausiluonteisuutta esiintyy tunti- ja kuukausitasolla. Volyymi on satunnaisesti jakautunutta. Volyymi ja preemio korreloivat keskenään, sekä vuorokausihintojen ja siirtoyhteyksien käyttöasteen kanssa. Tuulivoima korreloi heikosti mutta enenevin määrin toteuman kanssa. Pohjoismaiden tasoinen tarkastelu ei lisännyt korrelaatio verrattuna Suomen laajuiseen tarkasteluun.

Ehdotettu malli toimii tyydyttävällä tasolla, mutta ei mallinna kaikkia toteuman ominaisuuksia. Jatkotutkimukseksi ehdotetaankin mallin suoriutumisen parantamiseksi.

Avainsanat sähkömarkkinat, säätösähkö, reservimarkkinat, mFRR

Preface

I thank Professor Mahdi Pourakbari Kasmaei and my advisor Nikita Semkin for their guidance. I also thank my family and all my friends for the support, not only in the thesis process but across my studies.

Finally, a big thank you to Aalto for all the years of studying and personal growth, and AFRY for the opportunity to further develop myself towards a professional in the energy sector.

Otaniemi, 19.5.2023

Lionel Irrmann

Contents

Symbols and abbreviations

Symbols

MW	Megawatt, unit of power
MWh	Megawatt-hour, unit of energy
p	market price
q	market volume
δ	market premium
G	(total) electricity generation
W	wind electricity generation
D	electricity demand
IC	denotes Interconnector usage across two market areas
superscript F	forecast figure
superscript R	actual figure

Abbreviations

VRE	Variable Renewable Energy
BRP	Balance Responsible Party
BSP	Balance Service Provider
TSO	Transmission System Operator
SO	System Operator
SvK	Svenska Kraftnät, the Swedish TSO
ENTSO-E	the European Network of Transmission System Operators for Electricity, the association for the cooperation of the European TSOs
mFRR	manual Frequency Restoration Reserve
aFRR	automatic Frequency Restoration Reserve
FCR-N	Frequency Containment Reserve for Normal operations
FCR-D	Frequency Containment Reserve for Disturbances
SARIMA	Seasonal Autoregressive Integrated Moving Average mode, a family of time series models
ARMA	Autoregressive-moving-average models, a subset of SARIMA models

1 Introduction

Electricity as a commodity is unique due to its physical constraints. At every moment, demand and supply must perfectly match, since electricity cannot be stored at scale in an economical manner. If there is an imbalance, power quality decreases in the form of frequency deviations. These deviations may cause serious adverse effects on the electric infrastructure and damage the rotating machinery present in generators and motors. To minimise the risk of any damages, electricity is traded at many levels for ensuring equilibrium at all times.

The balancing market acts as the last link in the electricity market chain for real-time balancing of consumption and production. While the bulk of electricity is traded in day-ahead markets well before delivery, the balancing energy market is used to ensure equilibrium in real time. It is thus pivotal in enabling the stable operation of the power system. Balancing energy is either upregulating or downregulating. In upregulation, market participants increase their production or decrease consumption to provide additional energy. Downregulation is then the opposite, where market participants decrease their production or increase their consumption to reduce surplus energy from the power system. It is the TSOs, the entities operating the physical electricity transmission system, that are in charge of operating the balancing energy market in the Nordics.

Far from being a static and redundant market, pivotal changes such as the rapid growth of variable renewable energy (VRE), increased electricity demand from electrification, and integration of European energy markets may shape and change the balancing energy markets.

In the literature, there is relatively little research on the balancing energy markets, compared to the larger day-ahead and intraday markets. This is both in terms of market design [1] and on suitable forecasting methods [2]. Existing research includes, for example, Van der Veen and Hakvoort [1], who propose a framework to analyse the design of balancing markets. Market design and integration, with a concern on bidding and strategic behaviour has been analysed by, amongst others, Boomsma et al. [3], Poplavskaya et al, [4], and Farahmand and Doorman [5]. The impact of VRE on balancing markets has been debated, e.g., by Ocker and Ehrhart [6], Ivanova et al. [7] and Ortner and Totsching [8].

Forecasting balancing markets has also been researched, with most notably Klaeboe et al. [2] compiling and benchmarking forecasting methodologies from previous research. More recent works on forecasting balancing markets include Ortner and Totsching [8], Chazarra et al. [9] and Pavic et al. [10], with methods used ranging from long-term modelling to short-term time series forecasting.

One notable challenge in balancing market research is the wide range of different power systems, in terms of technologies used and size, and balancing market designs, as exemplified by an ENTSO-E survey on balancing markets [11]. It is of note that even in the Nordics, which has a long history of market integration, the balancing market rules differ across countries. This causes the balancing markets to differ in design and characteristics, both across geographies and time. As such, the research may or may not be directly applicable to other markets.

Fortunately, the Balancing Market structure is transparent and well-documented. In addition, the TSOs and ENTSO-E publish market documentation on their respective websites.

This thesis examines the implementation and behaviour of balancing energy markets in the Nordics through both quantitative and qualitative analysis. The motivation is to understand the design parameters and characteristics of the balancing energy markets, and possible future trends. During this analysis, the applicability of research in other areas is also assessed, as no specific research on Finnish markets was found.

The main research questions to be answered are:

- How are the balancing markets organized in the Nordics in general and Finland in particular?
- How can balancing market turnout, meaning traded volume and premium, be characterised and how does it depend on commonly acknowledged market fundamentals in Finland?
- Can the balancing energy market development be modelled based on the findings of the above two items?

This is achieved through a three-stage approach. First, a qualitative review of literature and documentation details how reserve and balancing markets are organised in the Nordics in general and Finland in particular, as well as what drivers may impact their development in the future. This qualitative review aims to lay out the physical, economic and regulative framework to understand the balancing market and its future development. Secondly, a descriptive statistical analysis of the Finnish balancing energy market turnout is carried out to quantitatively describe the turnout of the market in regards to both volume and price, as well as their correlation to other factors. Thirdly, a model is developed to simulate the turnout of the balancing energy market, providing the capability of simulating various scenarios based on the development of statistical turnout.

2 Literature review

2.1 Energy Markets in the Nordics

To better understand the balancing energy market, its context and role within the market structure of physical electricity delivery are reviewed to begin with. The Nordic electricity markets consist of multiple markets, with differing sizes and timelines. Currently, all physical markets operate on an hourly basis, i.e., the market time resolution is one hour. The Nordics are divided into 12 bidding zones, or separate market areas. Norway consists of 5 areas, Sweden of 4 areas, Denmark of 2 and Finland of one area. The main markets and their timelines are summarised in Figure 1.

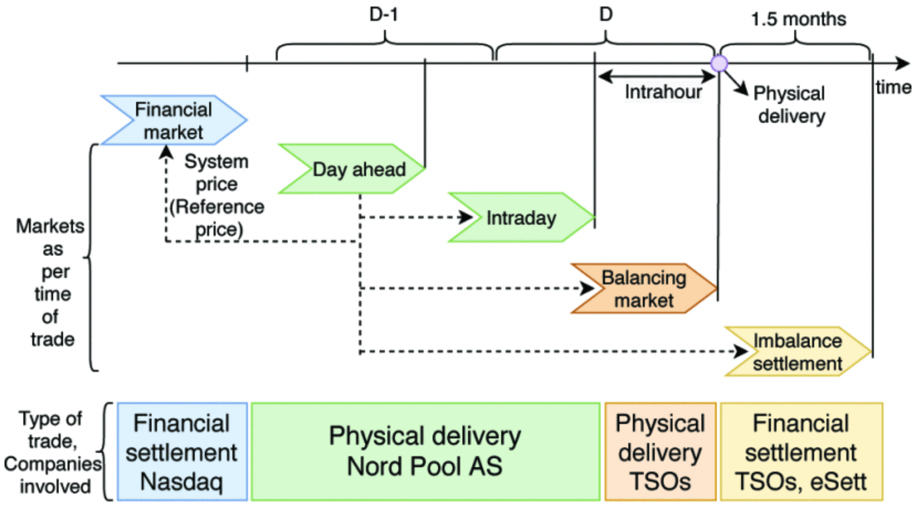

Figure 1: Timeline of main electricity markets in the Nordics.[12]

The first link in the physical markets chain is the Day-Ahead Market, followed by the Intraday market. Nord Pool is the nominated electricity market operator for these two markets. The day-ahead market is cleared the day before the delivery and represents the baseline for planning and delivery of electricity during the following day. Intraday is cleared one hour before the delivery and is used to account for changes in market conditions occurring during the trading period, such as loss of generation or transmission. [13]

Any potential changes at the real-time horizon from the forecasted situation at the time of Intraday closure are then addressed in the balancing process. This process is the responsibility of TSOs, and is carried through the use of reserves. In the Nordics, these reserves consist of Fast Frequency Reserves (FFR), Frequency Containment Reserves for Disturbancies and Normal operations (FCR-D and FCR-N), as well as manual and automatic Frequency Restoration Reserves (mFRR and aFRR). The reserve products are summarised in Figure 2.

The operation mechanism and interlink of the various reserve products are visualised in Figure 3 in terms of frequency and balancing power, exemplifying the

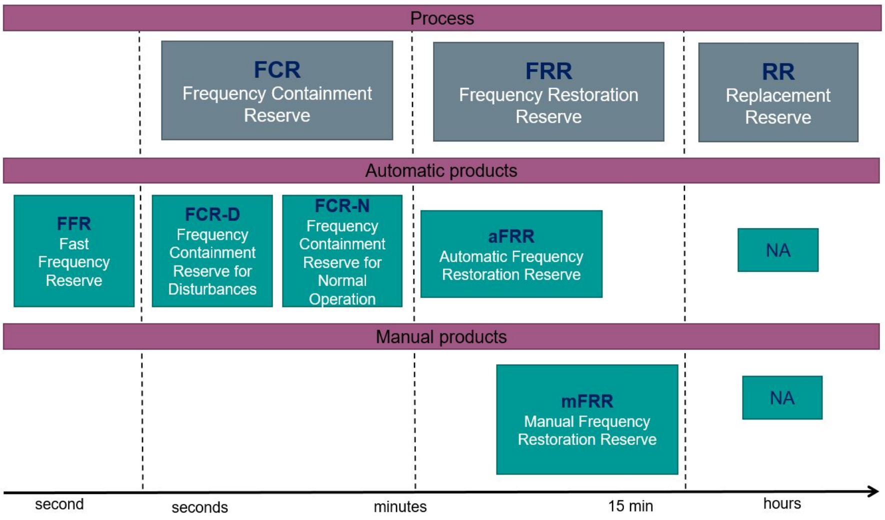

Figure 2: Reserve products in the Nordic power system. Source: [14]

time scale of different reserves. The FFR and FCR are used at the timescale of seconds to minutes to react to variations in the system frequency. The aFRR and mFRR are used to relieve these reserves and provide balancing energy to the system, at the timescale of minutes to up to an hour. Out of these reserves, the mFRR is the primary tool for balancing. This is due to its timescale. While the other reserves act from seconds to minutes, providing power, it is the mFRR activations, acting for longer periods of time, that provide the balancing energy needed to stabilise the power system.

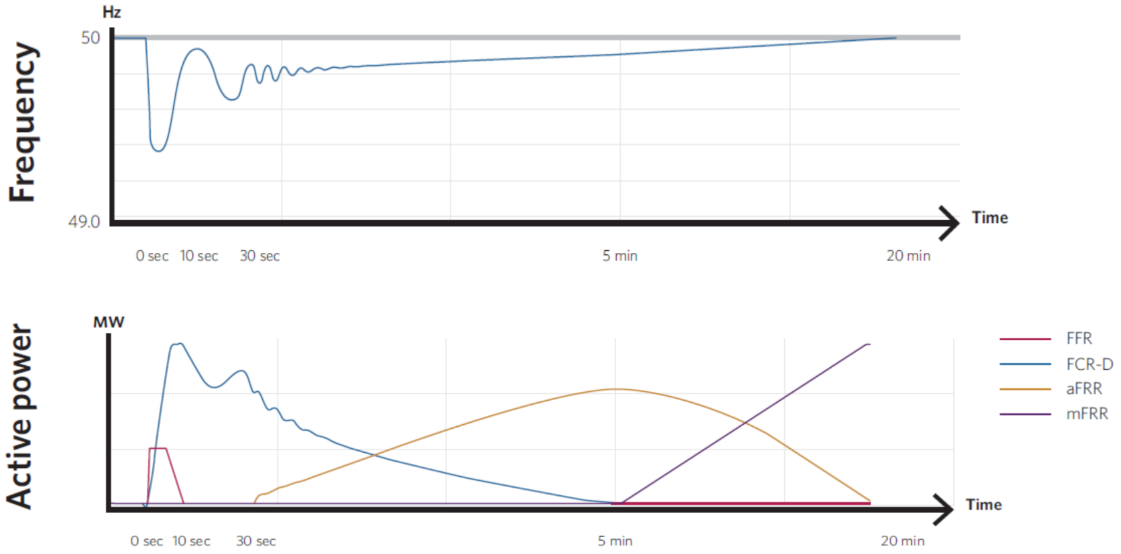

Figure 3: Example of frequency control and restoration.[15]

The balancing energy of mFRR activations are procured via a market mechanism,

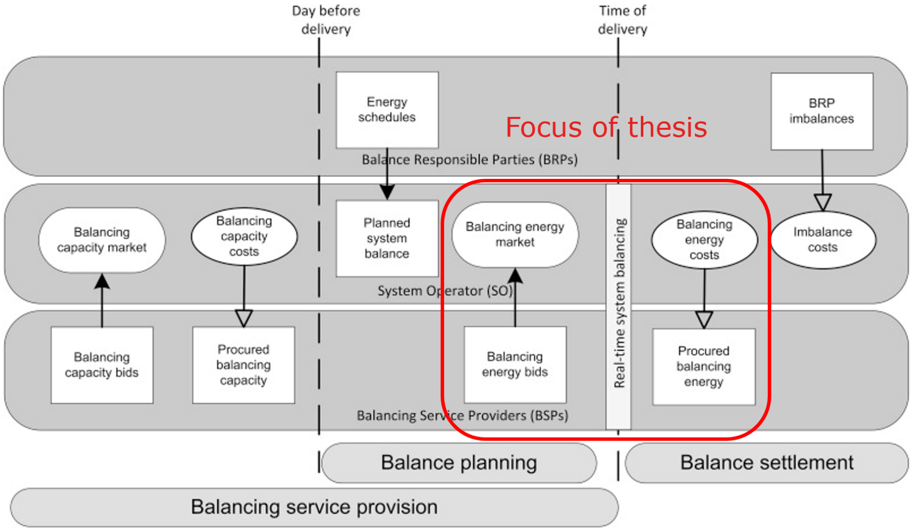

Figure 4: Framework of balancing market as proposed by Van der Veen and Hakvoort [1]. The focus of this thesis is indicated in red.

which is referred to as the Balancing Energy Market. It is this market for mFRR activations which is the topic of this work [16]. As reviewed, the purpose of the balancing energy market is to balance the power system within the operational hour by providing energy. It is a real-time market, meaning that it is cleared in real-time as capacity is dispatched, and it is settled only after delivery.

Due to its role as the last link in the electricity market chain, the Balancing Energy Market is relatively small. As a figure of scale for Finland in 2021, 57TWh were bought on the Nordpool day-ahead market, and Intraday saw 1TWh of bought volume [13]. The balancing market saw procurements 0.16TWh of upregulating energy and 0.2TWh of downregulating energy in the same period and area [17]. The balancing energy market is thus less than half the size of the Intraday market and less than 1% of the size of the day-ahead market.

2.2 Nordic Balancing Energy Market Design

The analysis of the Nordic and Finnish balancing energy market design is based on the framework proposed by Van der Veen and Hakvoort [1], which is summarized in Figure 4. Here, the market structure is described following the reference model they proposed, and relevant market parameters were identified from the design space of their work. Documentation on the Nordic market design is widely available at multiple levels of detail. The information here is sourced from the Nordic Balancing Philosophy document [16], describing the current Nordic principles and rules for balancing. For Finland specifically, Fingrid documentation was reviewed, such as the well-summarised "Reserve products and reserve market places" [14]. The framework was projected on the documentation to provide a structured analysis of the relevant structures and design parameters of the balancing energy markets.

There are three main actors involved in balancing: the system operator (SO), the Balance Responsible Parties (BRPs) and Balancing Service Providers (BSPs). The SO, which in the Nordics are the Transmission System Operators (TSOs), assesses the need for coordinates the balancing actions. BRPs are actors, such as utilities or major consumers, who are responsible for balancing their portfolios and carrying the costs of balancing. The BSPs are BRPs who operate balancing reserve assets in their portfolios, and offer balancing services on the market and dispatch the necessary balancing.

The process of balancing involves multiple phases. Firstly, balance planning involves the SO assessing the need for balancing, ensuring sufficient balancing availability, and coordinating information on production and consumption with the BRPs. Secondly, during the balancing service provision phase, BSPs offer balancing to the SO, who activates the necessary balancing according to the state of the power system. Finally, in the balance settlement phase, the imbalance price is discovered, BSPs are remunerated and BRPs are charged for the imbalances. When analysing the balancing energy market specifically, we focus on the balancing service provision phase, with also interest in the price formation process in the context of turnout.

In the Nordics, the current imbalance settlement period and balancing market time unit is one hour. However, a transition towards a 15-minute period is starting in the second quarter of 2023. This transition and its impacts are further detailed in Section 2.4. Balancing responsibility is zonal, where each BRP has to keep balance within the bidding zone. Market data is published, with data such as activated bid volume and price available on the ENTSO-E transparency platform [18]. In addition, the TSOs have additional available data on their websites. In Finland, Fingrid also publishes the sum of offered bids. However, information on, e.g., action at the level of individual BSPs is not available [17]. Also, information on the total Nordic bid curve for balancing energy is not available.

Each TSO is required to keep sufficient reserves to address the reference incident, i.e., the largest possible single disturbance in the TSO area. This could be for example the loss of the largest generating station or electricity consuming factory. In Finland, the reference incident for upregulation is 1300MW and 150MW for downregulation [19]. Balancing Energy is procured through both voluntary (energy-only bids) and contracted (capacity payments) reserves. All reserves bid on a common Nordic mFRR market, from where the activations are dispatched in merit order based on the bidded price, taking into account the technical limits of the power system. In Finland, there is a capacity market to contract upregulation reserve. Norway also has capacity markets for both upregulation and downregulation reserves. These capacity markets are not further analysed here. In addition, Fingrid owns and leases power plants to ensure the availability of upregulation to cover the reference incident at all times.

To submit bids, BSPs have to prequalify to ensure adequacy for providing balancing, with also bid requirements in terms of information provided and bid size. Bids to the Nordic mFRR market can be submitted up to 45 minutes before the operational hour. Bids are then centrally and manually ordered by the TSO, in practice by either phone calls or electronic messages.

Nordic balancing energy prices are determined only after the operational hour. The price is determined by the marginal accepted bid from the Nordic mFRR market. If there is congestion between two bidding zones, mutual regulation may not be possible, and balancing prices across areas separate, in a similar manner as seen in, for example, day-ahead markets.

Prices are asymmetrical, meaning there are separate prices for downregulation (reduction of generation or increase in consumption) and upregulation (increase in generation or reduction in consumption). The upregulation price has a minimum price of the spot price, and the downregulation price has a maximum price of the spot price in the ongoing hour. In practice, this sees that the BSP always receives a premium over the spot price. This is the premise for operating on balancing markets, as it provides additional revenue compared to operating on just the spot market.

Balancing reserves may be used for reasons other than balance management. These activations are designated as special regulation, and may be needed for, e.g., congestion management across network bottlenecks. These activations are paid-as-bid and occur outside the balancing energy market. Special regulation is not further analysed in this work.

Balancing Energy can also be traded from power systems outside the Nordic Synchronous system. Balancing Energy traded from the Nordics to other systems does not impact marginal pricing in the Nordics. However, there are different rules varying across TSOs on how balancing energy imports impacts the balancing energy price.

2.3 Organization and Key Stakeholders

As depicted in the framework in Figure 4, there are three distinct roles in the context of balancing energy market: The Transmission System Operators, the Balance Service Providers and the Balance Responsible Parties.

Within each country, the TSO is responsible for maintaining sufficient reserves. The respective TSOs are Fingrid in Finland, Svenska Kraftnät (SvK) in Sweden and Statnett in Norway. The Nordic TSOs coordinate their actions to a high degree, and operate a common Nordic Balancing Market.

SvK and Statnett, being responsible for about 75% of the load in the synchronous area, are the balance operators of the Nordic system. This means they jointly decide and execute the balancing actions. Denmark is balanced separately, and is not further analysed in this work [16]. After the decision-making of the balance operators, each TSO implements the actions and orders the activations in their respective areas.

The TSOs, monitoring and operating the transmission system, have the best information available for the need of balancing. Since energy is traded on an hourly schedule but consumption changes constantly, imbalances will occur even with perfect foresight. This is due to the difference between the discrete hourly dispatch of resources and the continuous nature of demand and VRE generation, causing inter-hourly imbalances. Other reasons for balancing include ramping of transmission links, disturbances such as the sudden loss of generation or consumption, and forecast inaccuracies both in scale and timing of demand and generation.

Since the frequency range targeted by the TSOs is 50Hz ± 0.1Hz, this gives the TSOs some leeway in the need for activations. In the case of the Nordic Synchronous System, 0.1Hz deviations translate to roughly a few hundreds of MW of margin, depending on the generation capacity online. This means that not all deviations require the activation of balancing energy. As activations are manual, it is up to the TSOs to assess whether balancing is needed.

Balance Responsible parties (BRPs) are the parties that are responsible for the imbalances. These are the commercial generation companies and major consumers, also including electricity retailers. BRPs are required to balance their portfolio before the operational hour through trades, mainly in the day-ahead and intra-day markets. The costs of balancing are then passed through by the TSO to the BRPs.

Balance Service Providers (BSPs) are the market participants providing balancing services to the TSOs. BSPs submit bids to the common Nordic mFRR market. The bids are placed in a common merit order, from which the activations are ordered. BSPs need to prequalify before participating in the market to ensure adequacy for balancing services. According to Fingrid, both up- and downregulating mFRR are mainly procured from hydro- and thermal power, with also some demand side response. Some wind power is also offered for downregulation, but has seen little activation, as visualised in Figure 5 [20].

The technologies of the Balance Service Providers make sense when assessing the nature of these technologies. Hydro and thermal generation can shift the use of energy between hours by withholding or increasing production, with the resource used – water or fuel – being stored for later use. As such, the cost of providing balancing energy is the price differential between the hours of the production shift. For wind power, such a shift is not possible due to the nature of the wind resource. Since wind energy cannot be shifted to another time, any downregulation provided has to be fully recouped to be profitable . As such, the price of balancing can be argued to be higher for wind than for hydro and thermal, explaining the low procurement amounts compared to offered bids in downregulation.

In Finland, the BSP has to enter a balancing market agreement with Fingrid in order to participate in the BEM. Technical requirements are imposed on the reserve unit. Activation of the reserve must be possible within 15 minutes, and the unit can sustain the activation for one full operating hour. The minimum bid is 1MW by electronic order or 5MW otherwise, imposing a minimum size to the unit. In addition, the capability to provide real-time information, with updates at least once a minute, is required. Aggregation is allowed, but the aggregated reserve resources have to be under the same BRP, and need to be in the same transmission area, in

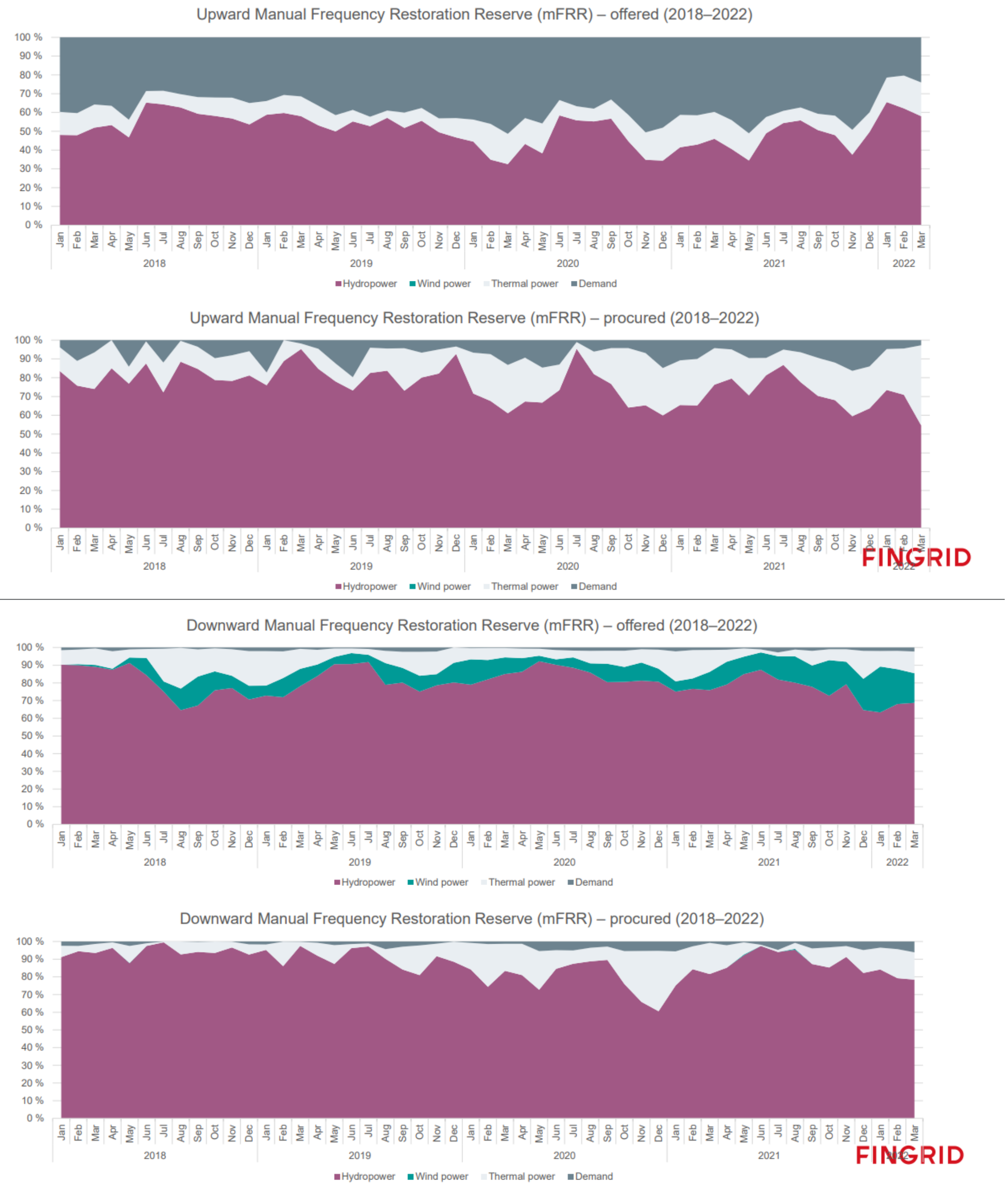

Figure 5: Offered and procured upregulation (upper) and downregulation (lower) by technology. [20]

Finland specifically either North or South of the P1 bottleneck line [21].

2.4 Future changes and drivers in the balancing energy market

Fingrid, the TSO in Finland, publishes its Network vision scenarios in order to prepare for probable future developments in the Finnish power system. Based on its climate-neutral growth scenario, Finland could see its wind power generation increase from 6TWh in 2018 to 94TWh in 2035, a growth of over 1400%. Meanwhile, electricity demand is expected to grow up from 87TWh in 2018 to 145TWh in 2035, for a growth of 60% [22]. These figures would be transformational for the Finnish power system.

The impact of variable renewable energy (VRE) such as wind and solar power on balancing energy needs has been studied multiple times, while changes in consumption have received perhaps less attention. Ortner and Totching [8] performed a large-scale modelling based on ENTSO-E's ten-year plans to derive insights into the role of the balancing market in 2030. They found that the largest sources of forecast error in the future are wind energy and consumption, with the forecast errors skewed towards a need for downregulation. However, they evaluated that the need for balancing in terms of volume does not increase significantly, and the balancing markets will remain at a fraction of the volume and monetary revenue compared to day-ahead markets. [8]

Hirth and Ziegenhagen [23] reviewed the channels through which VRE interact with balancing services. They argue that the weather-dependency of VREs, as stochastic behaviour, is a source of forecast errors which increase the need for balancing services. On the other hand, the VRE can also supply balancing services, provided that policies and markets are correctly designed. Contrary to a previous consensus in the literature, stipulating that increased VRE adoption increases the need for reserves, Hirth and Ziegenhagen found that the impact of VREs on the need for balancing is less dramatic than often thought. According to empirical evidence from Germany depicted in Figure 6, the period between 2008 and 2015 saw a near-tripling of VRE capacity, while the need for balancing reserve was reduced by about 15%, and balancing costs were halved. This would then suggest that other factors such as market redesigns had a larger impact on the balancing need, and the impact of VRE should not be assessed in isolation. [23]

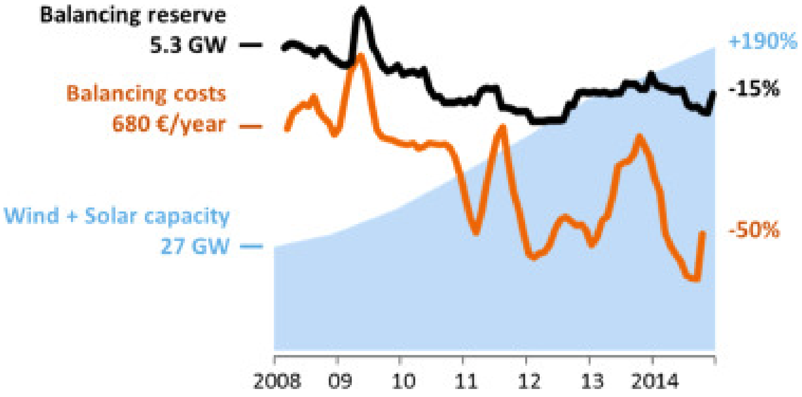

Figure 6: Development of balancing reserve, costs, and VRE development in Germany between 2008 and 2015. Source: [23]

Chazarra et al. [9] performed a statistical analysis of variables involved in mFRR provision in Spain. The results of their correlation analysis indicated that there is indeed a correlation between VRE and mFRR volumes, but many other factors also impact balancing, such that no single explanatory variable saw high levels of correlation with volumes.

From the perspective of an increase in consumption, the findings of Ortner and Totsching [8] would indicate that it is a major source of balancing needs in the future. This is also mentioned to be one significant source of balancing need in TSO documentation [16]. Although further research was lacking, it can be argued that increased consumption, in general, would increase the need for balancing. As electricity demand is stochastic and continuous, a growth in absolute size of demand should then also increase the absolute size of imbalances from demand, causing a growth in balancing energy needds. As seen in Figure 5, demand response is also a provider of balancing energy, and smart electrification could offer opportunities for aggregation and regulation service providing.

Based on the results of these research works, wind power is estimated to be a source of balancing needs due to its stochasticity, and is most likely a significant source of future balancing needs, as noted by both the analysis of Ortner and Totsching [8] and Chazarra et al. [9]. On the other hand, wind can and also does offer balancing services, as discussed by both Hirth and Ziegenhagen [23] and as seen from historical downregulation offering [20]. If the skewness of forecast errors is towards downregulation, as suggested by Ortner, this helps mitigate the need for increased reserves. Finally, both Chazarra and Hirth note that wind is only one factor impacting balancing needs. It is not deemed to be transformational for the relevance of the balancing energy market by Ortner. Hirth emphasises that wind should not be assessed in isolation, and for example, changes in market designs can counteract the impact of increases in wind power.

Indeed, multiple changes to the market design of the Nordic balancing model are planned. The Nordic TSOs are planning to implement changes in balancing and reserve markets, specifically in response to changes in the power system, such as more VRE and increased cross-border exchange. The aim is to facilitate trading closer to real-time and provide markets with increased time granularity. In practice, changes to be implemented include, most notably, a shift to the 15-minute imbalance settlement period and common European markets for balancing energy. [24]

The 15-minute settlement period will increase the market granularity from 60 minutes to 15 minutes, with stepwise implementation across all markets. First, a move to 15 minute settlement periods, with hourly pricing, is expected to be implemented in 2023. The remaining steps, being a 15-minute pricing scheme and enabling 15-minute cross-border Intraday trading, are expected in 2024 [25].The move to a 15-minute settlement period, especially the first step of the transition, is expected to reduce balancing energy needs according to the TSOs [16]. This is due to the higher granularity reducing the structural imbalance between the discrete market time unit and continuous demand, exemplified in Figure 7.

In addition, TSO cooperation through common markets for balancing energy is

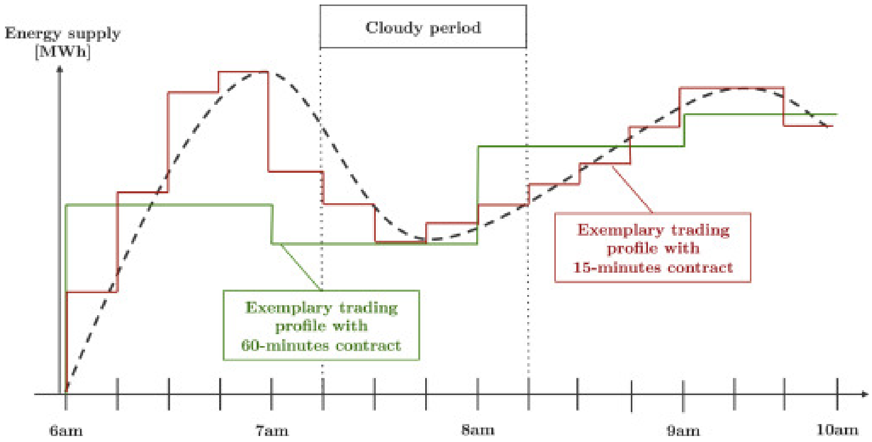

Figure 7: Example of trading profiles as 60-minute and 15-minute time resolution. [6]

planned as part of the Nordic Balancing Model [26]. First, a common Nordic market, with automated market clearing and activation, is planned to be implemented towards the end of 2023. As the Nordics already operate a common merit order, the main change from this phase is the introduction of automated processes. In the second phase, a common European market is planned for mid-2024. A common balancing energy market means that the reserve supplier is not anymore bound to the bidding zone, but rather can be procured across first the Nordics and then Europe, contingent on sufficient interconnector capacity. This is expected to reduce the cost of balancing energy and thus provide "huge economic gains" [26].

The impact of market design on balancing needs has also been studied in academic research. Notably, the findings of Ocker and Erhart[6] as well as Farahmand and Doorman [5] are of interest.

Farahmand and Doorman [5] analysed the integration of balancing markets in Northern Europe through modelling and comparison of a status quo and integrated market scenarios. This helps validate and quantify the claimed benefits of European market integration [26]. Integration of markets was demonstrated to bring savings due to fewer activations from imbalance netting, as well as the use of cheaper balancing resources through a system similar to the one used between Nordic TSOs currently. Based on their results, the integration of markets would provide significant potential for increased upregulation in the Nordics to cater for the continental area, while downward regulation saw the opposite happen. By providing access to cheaper balancing energy, Farahmand and Doorman find potential savings in activation costs of up to 50%. In addition, imbalance netting between the Nordic and Continental power systems was estimated to have the potential to reduce balancing volume by up to 30%. This would bring significant changes in market volumes and prices, while opening major opportunities for the most competitive regulating resources.

On the topic of the interaction of market design, VRE and balancing energy, Ocker and Ehrhart further investigated the "German Paradox" noted by Hirth and

Ziegenhagen [23]. They uncovered multiple factors related to market redesigns that reduced the need for balancing energy. One reason was the changes upstream of the market chain. The German Intraday transitioned from a gate closure time of 40 towards 30 minutes and switched from a 1-hour market time resolution to 15-minute windows. Intraday seemed to be the preferred flexible trading market for VRE, as intraday volume, not balancing volume, increased hand in hand with VRE installation rates. The second reason was efficiency savings from the cooperation between the TSOs operating in Germany starting in 2009, and across continental Europe in 2011. This was achieved through imbalance netting across balance areas, i.e., increasing the system size balanced, thereby seeing parts of imbalances cancelling each other out.

This body of research is in line with the expectations of the TSOs on the impact of the market reforms [16]. As demonstrated by Ocker and Erhart, increased market window resolution has reduced balancing needs in Germany. A flexible Intraday market has, at least in Germany, also captured the increased flexibility needs of VRE. Increased market integration is expected to reduce market prices and volumes as a whole. However, as can be derived from the findings of Farahmand and Doorman, this may also bring significant opportunities for the most competitive balancing energy providers.

When asked for further information on estimating reserve needs in [14], Fingrid commented that the need for additional balancing reserve is to grow slightly, with the main impacts being from increased unit size at Olkiluoto 3 and larger share of power exports from Finland in the future. They estimated wind power to slightly increase the need for balancing energy, but are also expecting wind power to increasingly participate in balancing. The 15-minute imbalance period was also estimated to reduce the need for balancing energy. Their view is then in line with the research, and would support the view that future drivers are likely to mitigate each other and keep balancing energy needs largely stable.

To conclude, a transformative increase in wind generation and consumption are likely to increase forecasting errors and can be expected to drive an increasing need for flexibility. However, the increased demand for balancing energy markets is likely mitigated by the upcoming market design changes planned in the Nordics. If previous evidence from Germany holds, the need for more flexible trading is likely captured by other markets in the electricity market chain. Based on the research analysed in this section, the impact of especially increasing wind power is likely smaller than previously anticipated. This would also be in line with the estimate of Fingrid that the need for mFRR is to remain largely stable. However, market integration does offer significant opportunities for the most competitive balancing service providers, as they can capture a larger market.

3 Research material and methods

The methodology used to assess the balancing energy market is two-staged. First, a quantitative analysis of the characteristics of the Finnish market turnout is assessed. The analysis is done through exploratory data analysis of the years 2018-2022. Second, a model to generate long-term scenario data replicating the characteristics of the Finnish balancing energy market is proposed. Finland was selected as the market area, as Nordics have slightly differing rules for the balancing energy market, and comprehensive market data is not available for the totality of the Nordics. It should however be noted that, as the Nordic markets operate jointly, a full picture of the power system and thus balancing needs cannot be formulated from inspecting the Finnish system only.

The purpose of the quantitative analysis is to produce insight into the behavior of the balancing energy market turnout. For the data analysis, market data was extracted mostly from the Fingrid data API [17], with the exception of day-ahead price and Nordic power system data, extracted from the ENTSO-E transparency platform [18]. The main variables analysed are the compensation premium δ and volume q of both up- and downregulating balancing energy (δ^{up}, δ^{down}, q^{up} and q^{down}, respectively). Balancing energy prices are tied to the day-ahead price of each hour, as described in Section 2.2. The compensation premium is defined as:

$$\delta = p^{BM} - p^{DA} \tag{1}$$

or in other words the difference between the balancing energy price and spot price, to characterize the incentive to provide balancing energy. From this definition, it follows that the minimum premium for upregulation and maximum premium for downregulation is 0 eur/MWh by definition. For compensation premium and volume, statistical measures analysed include distribution parameters, seasonality and trend.

In addition to univariate analysis, correlation to selected variables will be analysed. The starting point is the work of Chazarra et al. [9] analysing correction to variables related to generation, consumption and day-ahead price. As argued by Klaeboe et al. [2], the Balancing Energy Market is designed to handle unforeseen events. Any information available at day-ahead time should then be captured by the Day-Ahead and Intraday markets. As such, we further narrow the variables to those concerning the hour-ahead forecasts and actual values. Additional variables not presented by Chazarra et al. [9] are analysed, due to the interconnection of the balancing energy market to the Nordic system. Four additional variables are investigated : the imbalance trade to the Finnish system as a total, and the interconnector usages, calculated as scheduled commercial flows divided by the capacity of the link. As depicted in Figure 8, Finland is interconnected to Sweden, Estonia, Russia and Norway, with mFRR being traded from Sweden and Estonia. The links to each market area are identified by the two-character market area designations used by ENTSO-E.

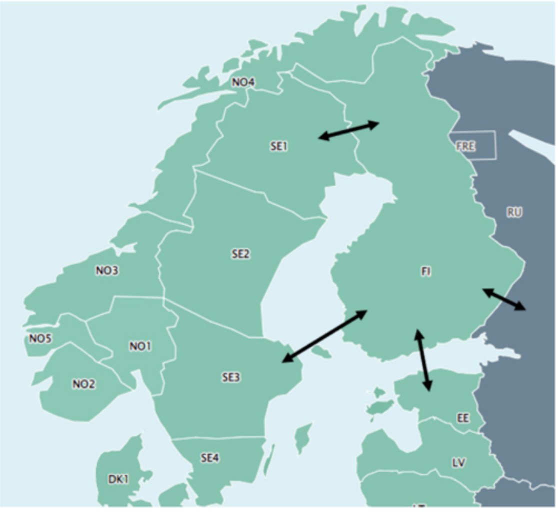

Figure 8: Interconnections of the Finnish market area and market area boundaries. Source: [13]

This leaves us with the following thirteen potential correlation variables:

- Actual hourly wind power production in the Finnish system (W^R)
- Predicted hourly wind power production in the Finnish system, as forecasted by Fingrid one hour prior (W^F)
- Hourly error between the actual and predicted wind power production ($W^F - W^R$)
- Hourly change between two consecutive hours of wind forecasted (sW^F)
- Actual hourly demand in the Finnish system (D^R)
- Predicted hourly demand in the Finnish system, as forecasted by Fingrid one hour prior (D^F)
- Hourly error between the actual and predicted demand ($D^F - D^R$)
- Hourly change between two consecutive hours of demand forecasted (sD^F)
- Hourly day-ahead energy market price (p^{DA})
- Imbalance trade (q^{trade})
- SE1-FI interconnector usage (IC^{SE1})
- SE3-FI interconnector usage (IC^{SE3})
- EE-FI interconnector usage (IC^{EE})

A correlation analysis is also performed to variables of the total Nordic system. Due to data availability, the variables and timespan differ from the list above. Data analysed spans January 1st 2021 to December 31st 2022. The variables investigated are:

- Actual hourly wind power production in the Finnish system (W^R_{FI})
- Actual hourly wind power production in the Nordic system (W^R_{SYS})
- Hourly error between the actual and predicted wind power production in the Finnish system ($(W^F - W^R)_{FI}$)
- Hourly error between the actual and predicted wind power production in the Finnish and Swedish system ($(W^F - W^R)_{SE,FI}$)
- Actual hourly total power production in the Finnish system (G^R_{FI})
- Actual hourly total power production in the Nordic system (G^R_{SYS})

Finally, modelling of the turnout, i.e. volume and premium, is performed. The goal is to generate time series data for scenario modelling in the long-term, for example for a one year period. Since the modelling methodology draws on the results of the data analysis, the modelling methodology is described in more detail in Section 5, after the results of the data analysis .

Both the data analysis and modelling are carried out using python [27] and its data manipulation, statistical, and visualisation libraries, namely pandas [28] for data manipulation, scipy.stats [29] for linear modelling, distfit [30] for distribution modelling, and seaborn [31] and matplotlib [32] for visualisation.

4 Results of the Statistical Analysis

The analysed sample, spanning January 1st 2018 through December 31st 2022, contained 43 464 hours of data. As data was joined with an inner join, hours missing one or more variable in the data has been excluded. As the time period spans 43800 hours, missing data represents 0.77% of the data set.

During the analysed period, upregulation occurred during 23.2% and downregulation during 34.4% of hours. An hour containing regulation in both directions only occurred during 0.9% of hours, meaning that up- and downregulation are mostly mutually exclusive. No regulation was needed during 41.4% of hours analysed, meaning a significant portion of time consists of non-demand, or time where no regulation is needed. In the physical sense, this refers to hours where the Nordic synchronous system remains within acceptable frequency range without Finnish balancing energy. This can be due to low imbalance, or that the imbalances across BRPs or market areas mitigate each other. It is also possible that all balancing energy is provided with more economic BSPs from other market areas, as the Nordics use a common merit order as described previously. Moreover, regulation is highly clustered, as approximately 80% of regulation hours followed a previous regulation hour.

The yearly volumes and average compensation premium in the balancing energy market are described in Table 1. Downregulation is represented by negative values. For volumes, this is due to the reason that downregulation reduces excess energy in the power system. The premium is negative as a result of equation 1, since downregulation prices are always below the spot price. Both up- and downregulation constitute very small markets, around 100-200GWh/a, in contrast to the yearly traded day-ahead electricity generation of about 57TWh [13]. As such, balancing energy constitutes under 1% of Finnish traded electricity.

Table 1: Yearly volumes and volume-weighted average compensation premium by year.

	Downregulation		Upregulation		Day-ahead
Year	Total Volume (GWh)	Premium (eur/MWh)	Total Volume (GWh)	Premium (eur/MWh)	Price (eur/MWh)
2018	-167	-16.96	122	67.69	46.79
2019	-200	-15.91	143	63.36	44.06
2020	-198	-26.51	185	94.91	28.10
2021	-197	-63.83	159	147.12	72.34
2022	-248	-127.80	183	215.53	154.10

Both up- and downregulation volumes have increased from 2018 to 2022, with downregulation consistently seeing greater volumes than upregulation. Upregulation has seen 20-30% smaller volume than downregulation, with the exception of 2020 with only a 7% smaller volume due to higher than usual upregulation. The average premium over the spot price has increased significantly, although so has the spot price itself. Upregulation has a consistently higher premium than downregulation. In relative terms, upregulation has been between 60%-300% higher than downregulation, with the proportional difference reducing across years. In absolute terms, upregulation premium has been 47-87 eur/MWh higher than downregulation, with the absolute difference increasing in recent years.

The key takeaway of the overview is that the balancing energy market is relatively small market. Demand is not constant and is highly clustered. Downregulation is more common and has a greater annual volume than upregulation. Upregulation sees constantly higher premium.

4.1 Trend

Due to the relatively small amount of years analysed, trends were identified on a monthly basis of the turnout. Based on Table 1 and analysis of the data at a monthly level, premiums of both regulations have had a growing trend, correlating to the development of the spot price. Volume saw high variance, but indicated a growing trend in both directions as well. It is due to this high variance that volume analysis is depicted below at the yearly level instead.

The growth in volume can be decomposed into the development of the share of hours with demand, and average volume of the hours with demand. From Figure 9, we notice that the share of non-demand has increased, reducing activation events. This is a significant decrease, with regulation hours dropping from 62% down to 55% of hours during the period analysed. The growth in yearly total volume originates from the larger volumes during demand hours for both regulation directions, with a near doubling of average upregulation volume from 54MWh to 100MWh in upregualtion and average downregulation volume rising from 53MWh to 84MWh.

The yearly growth in the standard deviation, and as such variance, is also notable and sustained. Upregulation sees its standard deviation rise from 62MWh to 103MWh, and downregulation from 54MWh to 97MWh.

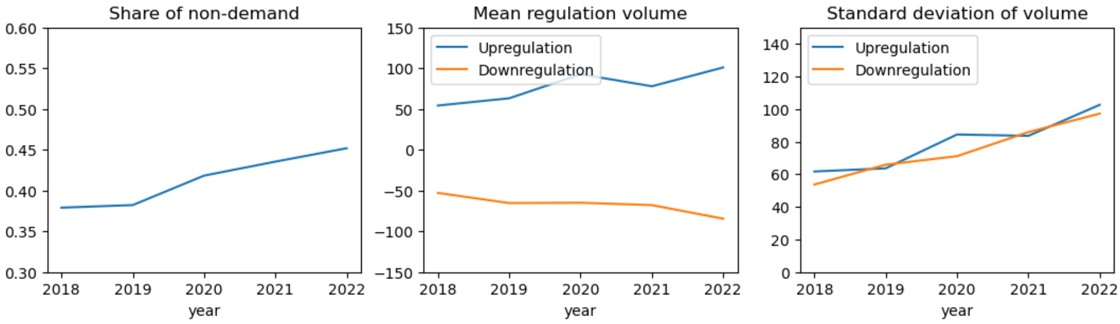

Figure 9: Yearly development of non-demand share (upper left, fraction), average volume (lower left, MWh) and volume standard deviation (lower right, MWh)

For regulation premium, we notice that the monthly average premium closely follows the day-ahead price levels. It can be posited that the development of regulation premium is mainly driven in the long-term by the spot price development. Upregulation can be seen to recurrently have price spikes, which correspond to individual regulation events within the month seeing a very high volume and premium of regulation.

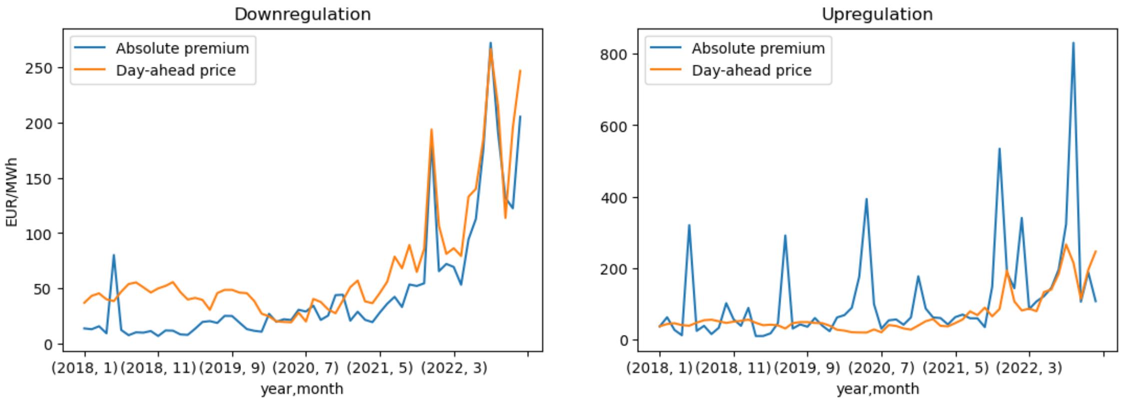

Figure 10: Monthly development of regulation premium and day-ahead price in Finland.

The development of volume does not show a clear long-term driver. Comparison is made challenging by the multiple concurrent development occurring during the analysis period: increasing wind production, the cutoff of Russian electricity imports, and the energy crisis of 2021-2022. No strong correlation could be established at the monthly level to volume turnout or share of demand.

The key takeaway of the trend analysis is the sustained growth of volume, its volatility, and premium, of both regulation types over the analysed period. The number of hours with demand fell, but was more than compensated by the volume of the remaining demand hours. The main driver of premium seems to be day-ahead prices. No similar driver could be identified for volume due to the large amount of concurrent changes in the power system.

4.2 Seasonality

Seasonality is commonly detected using methods such as autocorrelation detection and spectral analysis via Fourier Transforms. Due to a large number of non-demand hours introducing constant zero-values, the common methods did not provide satisfactory results. This is due to the fact that the zero-values, consisting of over 40% of the data and correlating with each other, overwhelm any other information on the correlation of the demand hours.

For this reason, seasonality is here analysed according to common seasonality patterns detected in other markets of the power system at the monthly, daily, and hourly levels. The seasonality is measured as the empirical conditional probability for each type of regulation (i.e., none, up, down or both). No seasonality was detected at the daily level, but monthly and hourly seasonality was detected. These are represented in Figure 11. On a monthly level, no regulation was most often needed in September and least in March. The opposite holds true for downregulation. Variation in upregulation probability was smaller, with the most probability during August and November. Monthly seasonality was verified on a per-year basis, and the above-mentioned patterns were consistent across years.

It would then seem that the need for no- and downregulation evolve in a complimentary manner, where the increase in downregulation probability reduces the probability of no regulation. Meanwhile, upregulation probability is much more stable. This is a surprising finding, with no clear explanation based on the reviewed literature.

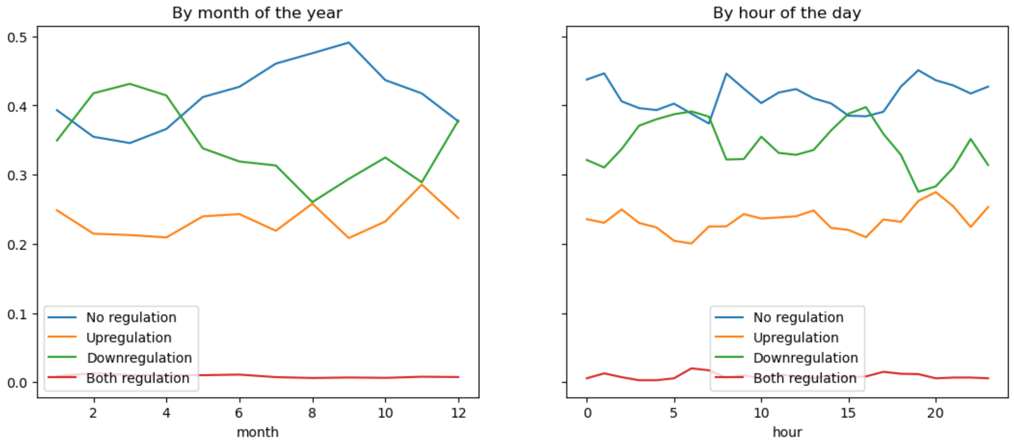

Figure 11: Empirical probabilities of regulation, conditional on the seasonal variables of the month (left) and hour (right).

On a daily level, the least likely hours to see regulation are at 00-01, 8, and 19 o'clock. Downregulation is most probably needed at 6 and 16 hours, both hours coinciding with the beginning of the morning and afternoon demand peak patterns. Upregulation sees the highest probability at 19-20 hours, coinciding with the end of the afternoon peak. As mentioned in Section 2.2, one cause of regulation is the inter-hourly fluctuation of demand. As such, strong ramping of demand such as at the beginning and end of a peak could be argued to explain the hourly seasonality patterns.

As such, it can be concluded that the balancing energy sees seasonal variation across months and hours, with the monthly variation being larger than the hourly one. On a monthly level, upregulation probability remains rather stable across the year, while downregulation and no regulation fluctuate.

4.3 Distribution of turnout

Distribution was analysed both visually through histograms and by fitting the data to statistical distributions. Both up- and downregulation volumes seem to follow a random variable distribution. Downregulation best fits a Beta distribution, while upregulation fits best a gamma distribution, as depicted in Figure 12. The fit for upregulation is almost equal for a gamma and beta distribution. The distribution fits the data well, and the Q-Q plot indicates that the proposed modelled distributions catch well the extreme values. The fitted distribution would indicate that balancing energy volumes behaves as a random variable around no balancing need, slightly skewed towards downregulation. In the light of the balancing principles [16] and the results of Klaeboe [2], the volume distribution confirms that balancing volume is needed for unforeseen events, hence the behaviour consistent of a random variable. Based on the empirical and fitted distributions, it is proposed that the balancing energy volume for hours with demand can be modelled using beta distributions.

Up- and downregulation could also be modelled jointly. This approach also provided acceptable fit, best fitting a weibull distribution. However, as the fit was not as good and some skewing towards downregulation not captured by the joint method, the separate fitting of up- and downregulation distribution was preferred.

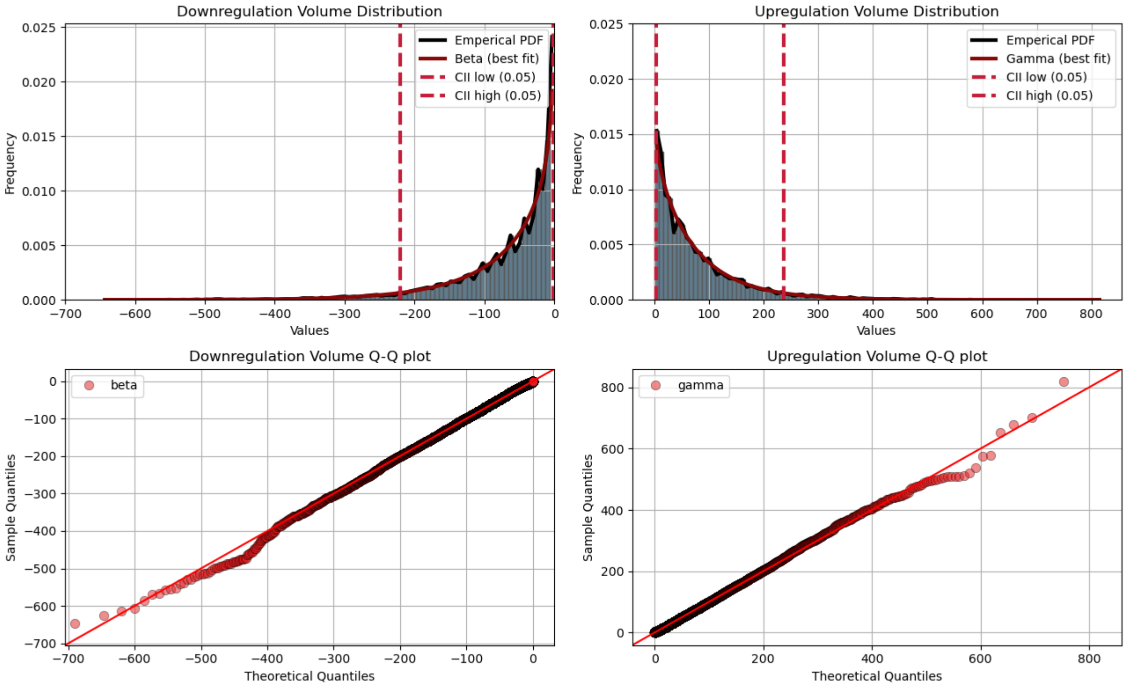

Figure 12: Modelled and empirical distribution of mFRR volumes

For balancing energy premiums, statistical distributions are less well fit. As can be observed from Figure 13, the best fits to empirical observation are the Weibull distribution for downregulation and Log-normal for upregulation. This is also well exemplified by the Q-Q plots. For downregulation, the modelled distribution underestimates the number of observations for almost all values. The fit for upregulation is much better, with a good fit up to about 900 eur/MWh levels, after which extreme values are underrepresented in the model distribution. This would imply that there is a more deterministic approach to describe the observed premiums.

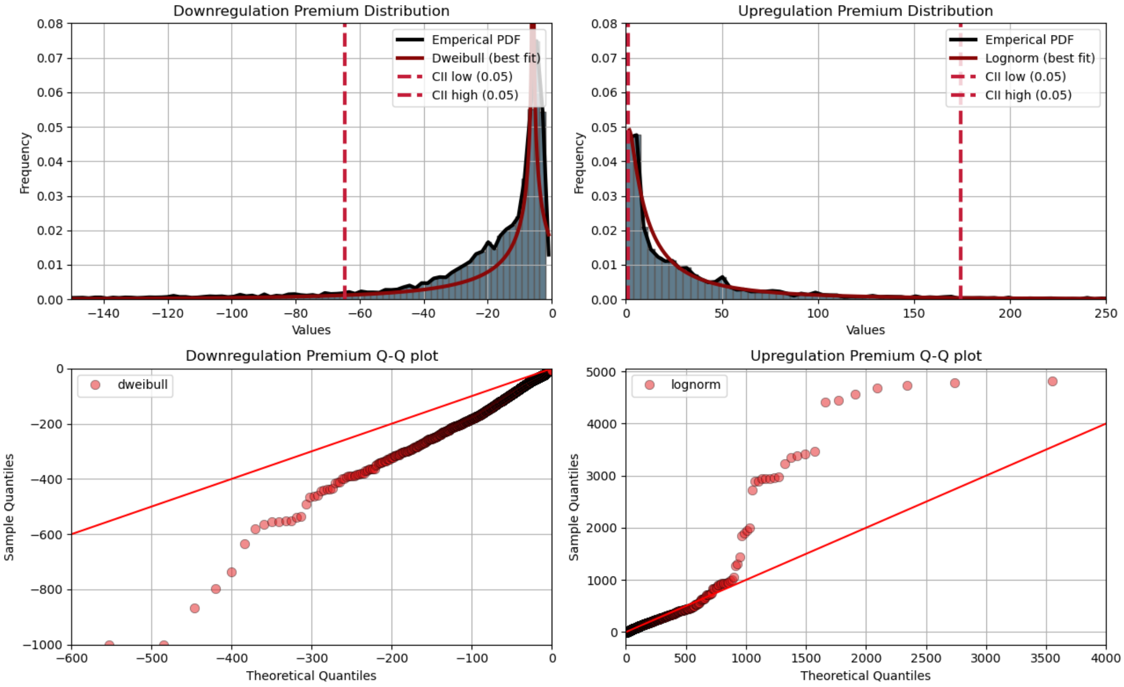

Figure 13: Modelled and the empirical distribution of mFRR premiums. Due to the range of data and distribution, x-axes vary.

Volume and premium are correlated in the Balancing Energy Market. Based on calculated Spearman correlation factors, downregulation volume and premium have a correlation of 0.48, and upregulation volume and premium have a correlation of 0.67. This indicates a moderate correlation with downregulation and a strong correlation with upregulation. This is visualised in Figure 14, where a linear regression is fitted on the data. The correlation is consistent with the merit order dispatch of the market. Larger volumes then typically see a higher premium, as more expensive bids are needed to cover the volume of demand. One possible cause for the higher correlation in upregulation is that the upregulation merit order more closely follows the marginal cost of reserve capacity, where high volumes see the activation of e.g. more costly reserve units. Downregulation premium may then be more influenced by other factors, such as hydropower generation conditions or spot prices.

The key takeaway from distribution analysis is the distribution of volume being consistent of the behavior of a random variable, that can be model with two beta distributions. Balancing premium is less well fit by any mathematical distribution. Premium and volume correlate, which can be expected from the use of merit order in activations. Based on the less than perfect correlation, this indicates that premium are also driven by other explaining variables than volume alone.

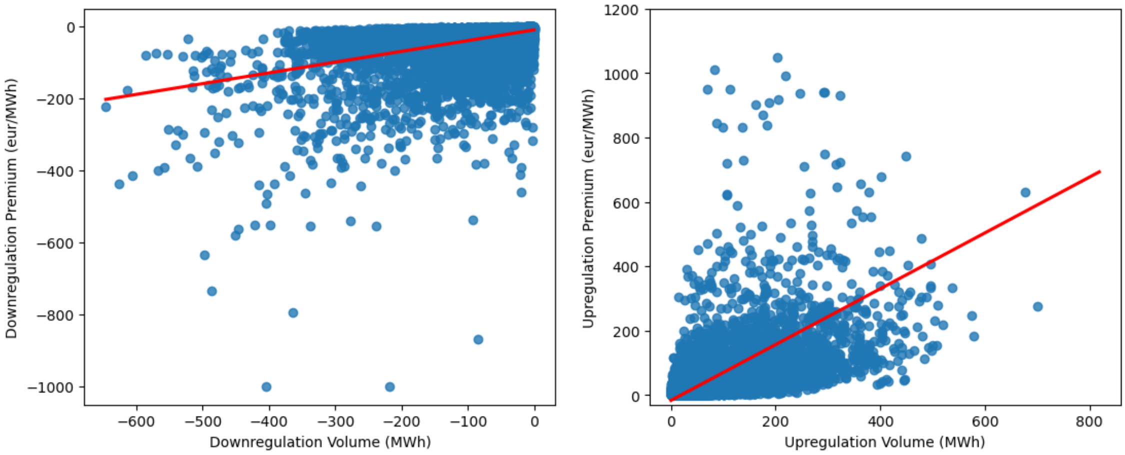

Figure 14: Relationship of price and volume in the balancing energy market. Note: Some extreme values for upregulation are not visualised for clarity purposes.

4.4 Correlation analysis

The correlation of variables is analysed through correlation coefficients. Chazarra et al. used the widely-used Pearson correlation coefficient [9]. However, based on statistics documentation reviewed [29], this method assumes a normal distribution of the underlying data. Since the variables are not all normally distributed, the Spearman correlation coefficient was used instead. The Spearman coefficient better captures nonlinear relationships and relationships between non-normally distributed data. We interpret the correlation figures as categorized in Figure 2. Positive values depict a positive correlation, and negative values in turn a negative correlation.

Table 2: Interpretation of correlation

Magnitude of correlation	Interpretation
0.0 - 0.2	No correlation
0.2 - 0.4	Low correlation
0.4 - 0.6	Moderate correlation
0.6 - 0.8	Strong correlation
0.8 - 1.0	Very strong correlation

Correlations are calculated on the full dataset, within the hours of similar regulation, separating up- and downregulation. The coefficients obtained are reported in Table 3.

The overall conclusion drawn from the Table is similar to that of Chazarra et al. [9] from the Spanish market: low correlation to balancing energy turnout is observed for most variables analysed. The results do however differ. In other words, variables have different relationships to turnout than in Spain. This confirms that insights from analysis are not directly applicable across markets. The most interesting results are the correlations with interconnector usage and day-ahead price.

Table 3: Spearman correlation factors to studied variables

	Downregulation		Upregulation	
	Volume	Premium	Volume	Premium
p^{DA}	-0.35	-0.62	0.15	0.33
W^R	0.13	-0.01	-0.05	-0.02
W^F	0.14	-0.02	-0.01	0.04
$W^F - W^R$	-0.02	-0.06	0.15	0.27
sW^F	-0.01	-0.03	-0.03	-0.03
D^R	-0.17	-0.01	0.09	-0.01
D^F	-0.18	-0.01	0.07	-0.01
$D^F - D^R$	-0.08	-0.01	-0.07	0.01
sD^F	-0.11	-0.09	0.02	0.07
q^{trade}	0.10	-0.13	0.13	0.08
IC^{SE1}	-0.28	-0.48	0.34	0.53
IC^{SE3}	-0.12	-0.15	0.32	0.37
IC^{EE}	-0.05	0.16	-0.07	-0.22

For interconnectors, IC^{SE1} sees a moderate correlation to premium and a low correlation to volume for both regulation types. IC^{SE3} also sees a weak correlation, especially towards upregulation volume and premium. IC^{EE} sees a low correlation to premiums.

The day-ahead price p^{DA} is negatively correlated to downregulation, strongly towards the premium and weakly towards volume. A positive but weaker correlation can be observed towards upregulation.

Another interesting insight is the relationship of regulation to generation and demand. Downregulation volume seems to be correlated, although very weakly, to absolute amounts of wind generation (W^R and W^F), positively, and demand (D^R and D^F), negatively. The downregulation premium does not correlate with these variables. Meanwhile, upregulation volume and premium both weakly correlate with the wind forecast error $W^F - W^R$, but do not correlate with variables related to demand.

The development of correlations across time was also analysed, by calculating the correlation for data from 2018 and 2022 separately. The results, the most notable of which are depicted in Table 4, indicate that the correlations observed are dynamic. The largest changes occurred in the correlations of spot price and wind variables against turnout.

It would seem that the hours with high wind forecast error are increasingly correlated with high upregulation volume, while the correlation to downregulation volume remains much weaker.

Interestingly, the development of absolute wind to correlate increasingly with both volume and premium would indicate a mitigating trend, as positive downregulation

Table 4: Main developments in variable correlations

Variables	Downregulation		Upregulation	
	2018	2022	2018	2022
q, W^R	0.08	0.21	0.01	-0.14
$q, W^F - W^R$	-0.04	0.11	0.03	0.20
q, D^R	-0.17	-0.22	0.20	-0.01
$q, D^F - D^R$	-0.19	-0.07	-0.14	-0.05
δ, p^{DA}	-0.29	-0.80	0.32	0.14
δ, W^R	0.04	0.34	-0.05	-0.24
$\delta, W^F - W^R$	-0.07	0.06	0.11	0.18

correlation and negative upregulation correlation mean values are increasingly closer to zero at times of high wind.

The correlation to p^{DA} strengthens the evidence of the day-ahead price driving the increase of downregulation volume. The sharp increase in correlation between δ^{down} and p^{DA} is likely caused by the high day-ahead price and volatility seen in 2022. Interestingly, δ^{up} has seen decreasing correlation to the spot price.

With the exception of p^{DA}, all correlation remained weak. The increasing trend does provide evidence that wind may become a more significant driver of the balancing energy market turnout in the future.

The relationship between variables is further analysed by visualization. Based on correlations, we further investigate the relationship of p^{DA}, IC^{SE1}, IC^{SE3}, IC^{EE}, $W^F - W^R$, and D^F to the market turnout.

Figure 15 depicts the linear relationships between p^{DA} and market turnout. The most interesting insight is the relationship between downregulation premium and p^{DA}. Not only is the correlation clearly identifiable, but there is a strong cut-off of observations below a line that corresponds the $\delta^{down} = -p^{DA}$ level, marked by a black dashed line on the figure. This is also observable from the downregulation prices ($p^{DA} + \delta^{down}$). This suggests that there is a soft lower limit to the bidded downregulation of 0 eur/MWh, although some observations can be observed in the negative bid area. This would then also explain the sharp increase in downregulation premium observed in Table 1, which coincides with high day-ahead prices. Similar linear patterns can be observed in upregulation premium, for example where $p^{DA} + \delta^{up}$ is equal to 700, 1000 and 1500 eur/MWh. Although not visible from the figure, a similar pattern can be observed at 200, 300 and 500 eur/MWh bid prices. This suggests that the total bid is either fixed or capped, at least for some market players, independent of other conditions. This illustrates that the bid price and premium have inflexible levels set by the market participant when bidding, providing further support to the claim that the balancing energy premium has deterministic components.

Figure 16 depicts the relationship between interconnector usage and market turnout. Here, positive values are usage where energy flows to Finland. We notice

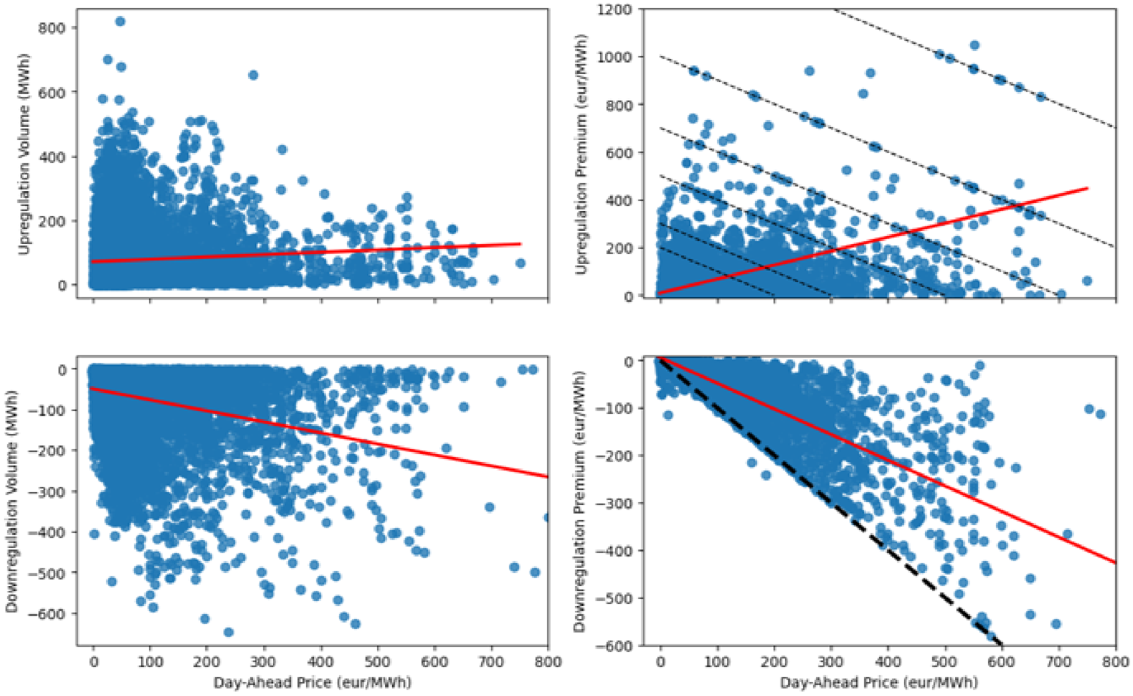

Figure 15: Correlation of market turnout to Day-Ahead price.

the correlation captured by the Spearman coefficient is highly nonlinear. It would seem, that for all connections, full utilisation of the interconnector is some sort of prerequisite for the highest prices and volumes observed. This makes sense in light of the market rules. Full utilization of interconnectors is when bottlenecks between bidding areas occur, and the areas may see separate regulations. This then sees higher volumes and prices in Finland. This strongly suggests that Finnish regulation prices are highly dependent on the wider Nordic state of the power system.

When analysing the relationship of $W^F - W^R$ and market turnout, some weak correlation can be detected visually as well. This is depicted in Figure 17. It can be observed that high volumes of upregulation are less likely with strongly negative wind forecasts, where there is more production than anticipated. However, the highest upregulation volumes occur when the forecast error is close to 0. This would support the findings of Hirth and Ziegenhagen, where the wind is only one factor in the Balancing Energy picture, and should not be assessed in isolation from other factors.

Finally, we analyse the link between Finnish market turnout and variables at the Nordic level during 2021-2022. Data at the Nordic level is more restricted and varied in quality. For example, Norway does not provide wind generation forecasts, and the data availability across market areas may differ. The data used was extracted from ENTSO-E and spans generation data and wind forecast at the hourly level. Performing a correlation analysis using Spearman factors, correlations depicted in Table 5 are obtained. It can be noted that adding a Nordic perspective to either absolute or forecast error of wind production, and total generation, failed to increase

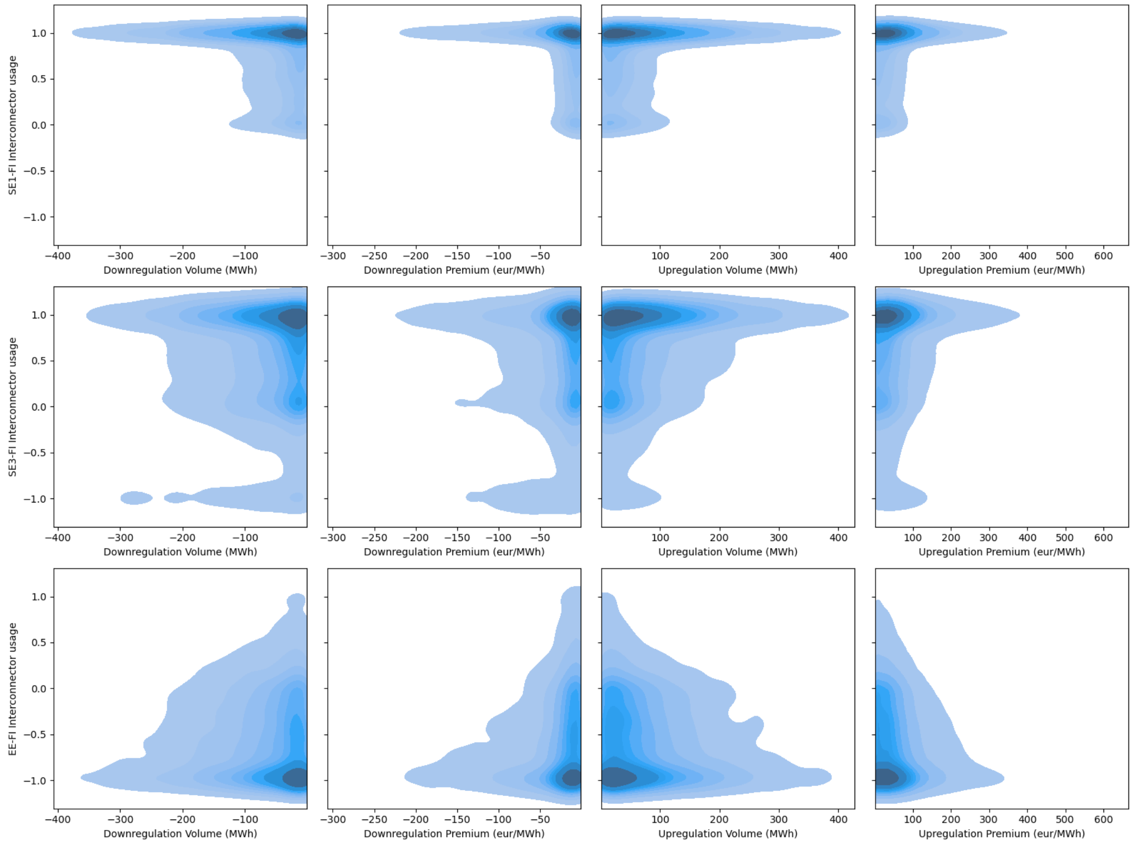

Figure 16: Correlation of market turnout to interconnector usage

the correlation of the variables to the Finnish market outturn.

Table 5: Correlation of Nordic variables to Finnish turnout

	Downregulation		Upregulation	
	Volume	Premium	Volume	Premium
W^R_{FI}	0.11	0.10	-0.07	-0.05
W^R_{SYS}	0.04	0.07	0.07	0.13
$(W^F - W^R)_{FI}$	0.07	0.06	0.19	0.20
$(W^F - W^R)_{SE,FI}$	0.09	0.10	0.11	0.08
G^R_{FI}	-0.12	-0.02	-0.03	-0.06
G^R_{SYS}	-0.21	-0.09	0.01	-0.03

It can be concluded from the correlation analysis that no single variable is a sole driver of the balancing energy market turnout. Highest correlations were established between turnout and day-ahead price and the use of the SE1-FI interconnection. Correlation to day-ahead price uncovered soft limits for bids in the market. In addition, the correlation of turnout to wind power generation has grown during the analysed period, although wind power and balancing energy turnout still remains only weakly correlated.

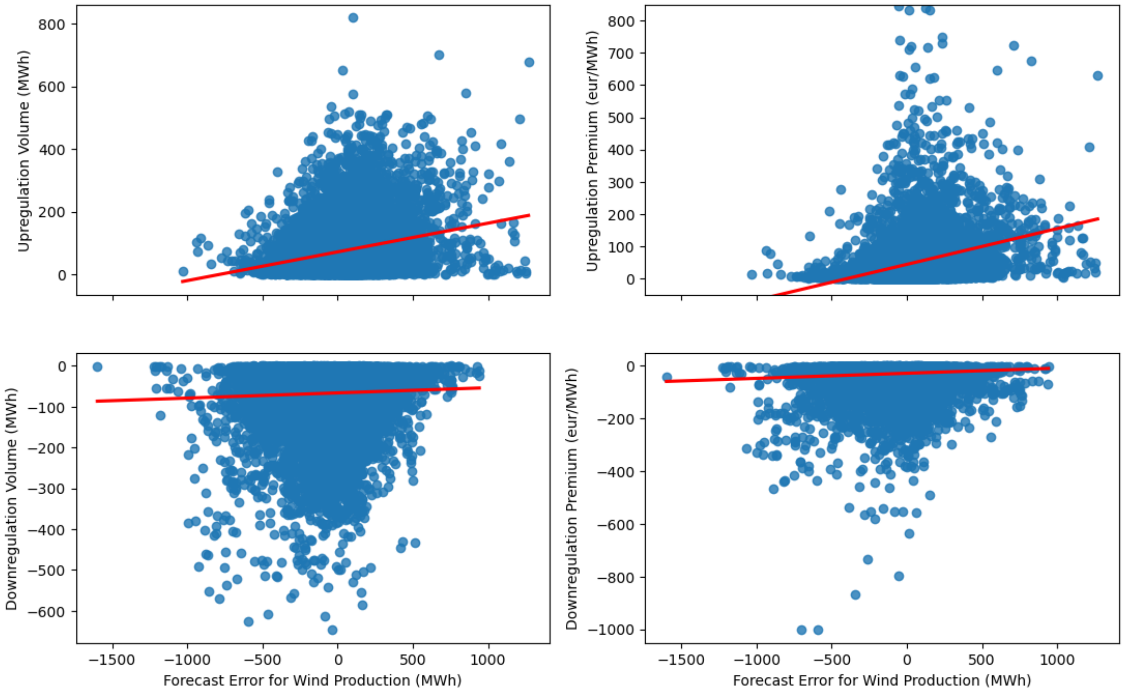

Figure 17: Correlation of market turnout to wind forecast error

5 Modelling

The aim of the modelling is to generate data that model hourly turnout of volume and premium at the longer term. The purpose is not to forecast multiple years ahead, but rather provide a tool to generate time series that follow scenario-building assumptions of the yearly turnout.

Modelling the market turnout consists of multiple steps. The first task is determining the regulation state (up, down, or non-demand). Second, the appropriate volume is determined. Finally, the market premium is estimated.

5.1 Methodology

In literature, modelling of balancing markets is almost exclusively done for the short-term, ranging from hour- to days ahead. Here, our purpose is to model the hourly turnout of the balancing energy market for the purpose of scenario generation at a longer term. As such, short-term models for forecasting steps ahead, such as those based on ARMA methods, are less suitable due to their mean-reverting properties. The basis of the long-term modelling work is based on Jaehnert et al. [33] and its further analysis by Klaeboe et al. [2].

Jaehnert et al. proposed a long-term model where balancing market premium is determined based on a linear relationship to an exogenous input of volumes for the NO2 market area in Norway. Klaeboe et al. replicated this model for NO1, with the addition of day-ahead price and power production as additional inputs. The additional inputs were implemented due to the lower correlation between volume and premium in NO1 compared to the original study in NO2. Here, this model is adapted to include balancing volume and day-ahead prices as explaining variables. This follows the results of the data analysis, where the correlation between volume and premium are closer to levels observed by Klaeboe, and day-ahead prices indicate correlation to volume too. This model can be formulated as:

$$\delta_{modelled} = \begin{cases} \eta_U + a_U \cdot q_{BM} + b_U \cdot p_{DA} & +\epsilon_U, \text{ if upregulation} \\ 0 & +\epsilon_0 \text{ , if no regulation} \\ \eta_D + a_D \cdot q_{BM} + b_D \cdot p_{DA} & +\epsilon_D \text{ , if downregulation} \end{cases} \tag{2}$$

Where η notes a constant, a and b coefficients, and ϵ a probabilistic component following a random variable. The model is fitted through linear regression to the data. The probabilistic component is modelled based on an appropriately fitting random distribution on the residuals of the linear regression.

For the use of this model, time series of balancing volumes are to be generated. For determining state, multiple different methods are available. Simple methods include sampling volume and regulation state from historic data. More refined models, especially in the domain of short-term forecasting, include determining balancing state using Markov, SARIMA, or arrival rate models. Literature on volume forecasting is more scarce, but Klaeboe describes approaches such as sampling from a modelled distribution fitted on historic data, or SARIMA forecasting. [2]

For generation of scenarios, a simple approach is preferred. Here, regulation state is drawn from historic probability. Volume is drawn from a modelled distribution, for example derived from historic data. The development of volume distribution parameters and state probabilities could further be modelled to follow changes in the broader power system. Since the data analysis did not produce identifiable causality between power system development and mFRR turnout, we will refrain to do so in the academic interest.

5.2 Modelling price

The starting point to develop the model depicted in Equation 2 are the findings of the data analysis. We note that the balancing premium correlates moderately with regulation volume and spot price. We develop the deterministic part of the model with linear regression using least squares method. As has been done by Jaehnert et al [5], the model is trained on data without outlier values. Jaehnert et al [33] defined outliers as those with either price or volume further than three standard deviations from the mean. Here, four times standard deviations is used as a limit due to the higher variance of the data. Even then, the removed values, representing only 2% of the regulation occurences, account for 10% of volume and 46% of revenue. This emphasises the importance of outliers in the turnout of the balancing energy market. The data selected is depicted in Figure 18

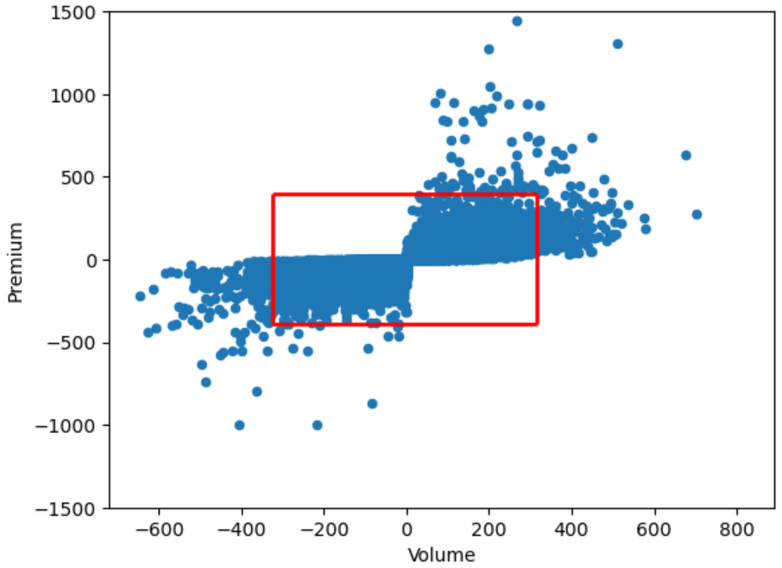

Figure 18: Data used for modelling. Red square indicates the threshold of 4 standard deviations

The fitted linear regression model obtained is then of form:

$$\delta_{deterministic} = \begin{cases} -11.6 + 0.42 \cdot q_{BM} + 0.25 \cdot p_{DA} & \text{, if upregulation} \\ 0 & \text{, if no regulation} \\ 10.3 + 0.14 \cdot q_{BM} - 0.45 \cdot p_{DA} & \text{, if downregulation} \end{cases} \tag{3}$$

The deterministic part has an R-squared of 0.47 for upregulation and 0.72 for downregulation, meaning it captures 47% and 72% of the respective variance in balancing premium. This score can be deemed as adequate for downregulation, but having a poor explanation power for upregulation.

The stochastic part is implemented to address the significant portion of variance not captured by the deterministic part. The stochastic components are described by distribution functions. Where Jaehnert found extreme value distributions to best fit the data in NO2, a T-distribution better describes the analysed data from Finnish markets. A T-distribution $T(\mu, \sigma, v)$ has three parameters: location μ, scale σ and shape v. The residuals, or the difference of the deterministic model and recorded market data, and the fitted distributions are presented in Figure 19.

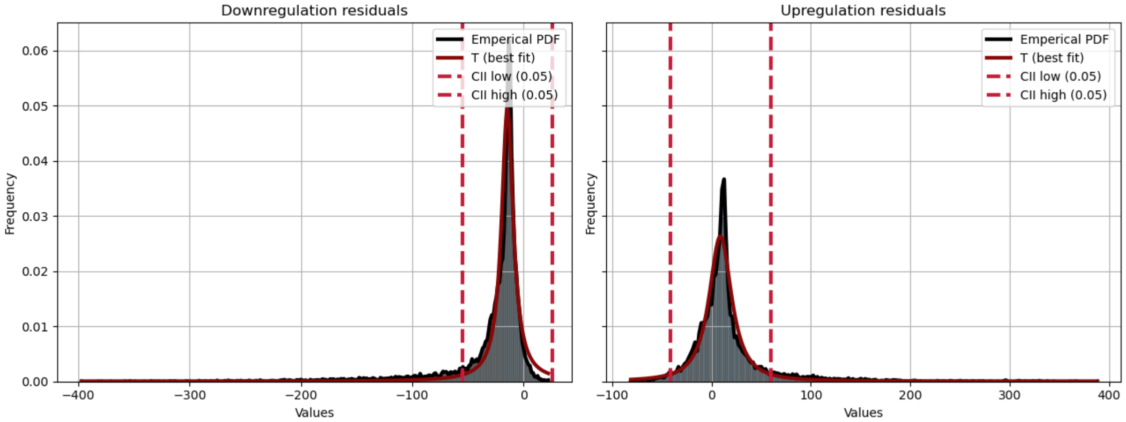

Figure 19: Residuals and fitted distributions

In addition, the premium at no regulation sees much less variance than in NO2, so much so that ϵ_0 is set to 0.

This results into a probabilistic model part in the form of

$$\delta_{probabilistic} = \begin{cases} T(8.9, 12.8, 1.4) & \text{, if upregulation} \\ 0 & \text{, if no regulation} \\ T(-14.4, 6.4, 1.0) & \text{, if downregulation} \end{cases} \tag{4}$$

Combining equations 3 and 4, we get a premium model of the following form, while enforcing the constraint that $\delta_{modelled}$ is positive in upregulation and negative in downregulation.

$$\delta_{modelled} = \begin{cases} -11.6 + 0.42 \cdot q_{BM} + 0.25 \cdot p_{DA} + T(8.9, 12.8, 1.4) & \text{, if upregulation} \\ 0 & \text{, if no regulation} \\ 10.3 + 0.14 \cdot q_{BM} - 0.45 \cdot p_{DA} + T(-14.4, 6.4, 1.0) & \text{, if downregulation} \end{cases} \tag{5}$$

5.3 Generating volume time series

For generating volume time series, we assume yearly probabilities of regulation conditional on the month. This method captures the monthly seasonality detected in the data analysis, and is relatively straightforward to implement. It will not however capture the clustering of regulation occurences detected in the data analysis. For the purpose of yearly scenario generation, this can be deemed as an appropriate tradeoff, where ease of implementation is selected over more advanced methods, such as Markov models. It is of note that, as discovered in the data analysis, yearly probabilities of regulation are not stationary, and any reference year should be selected with care for modelling purposes. As discovered in the data analysis, the relationship of turnout to notably wind power and day-ahead price have shifted in recent years.

Taking 2019 as an example, this gives us probabilities as displayed in Figure 20. For applying the methodology to scenario development, using a reference year or long-term average probabilities as in Figure 11 is proposed.

After the regulation state is drawn, the volume is sampled from a beta distribution. Beta distributions are of form $\beta(\alpha, \beta, \mu, \sigma)$, with α and β determining the distribution shape, and $\mu$and σ being the location-scale parameters. These can be fit according to historical years, or formulated to have interesting properties, such as doubling the variance compared to some reference year. As was discovered in the data analysis, volume mean has remained relatively stable. Variance however has increased during the sample period analysed, and as such yearly distributions are warranted in modelling. Taking again 2019 as a reference, modelled distributions are depicted in Figure 20

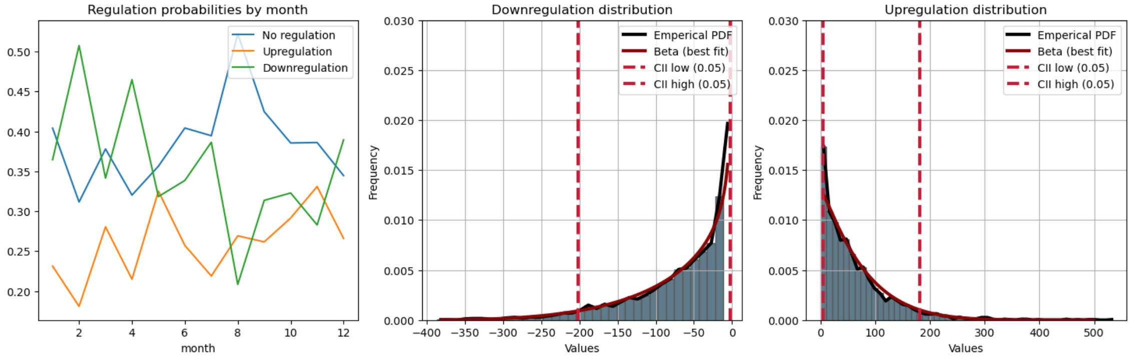

Figure 20: Regulation probabilities and fitted regulation distributions in 2019

5.4 Results

To exemplify the model developed, we benchmark its performance against a reference year, here 2019. Modelling is here scored by comparing mean and variance of the generated data to comparative real data. This approach is chosen, as metrics based on pairwise error between actual and observed instances (such as mean absolute error or root mean square error) are not meaningful due to the probabilistic model part introduced.

The benchmarking of the data is visualised through distributions in Figure 21. It can be noted that the model does not properly capture the distribution of actual prices, with an upregulation mean of 31EUR/MWh and standard deviation of 47EUR/MWh (actual: 18EUR/MWh and 27EUR/MWh) and for downregulation -31EUR/MWh and a standard deviation of 270EUR/MWh (actual: -11EUR/MWh and 11EUR/MWh). As such, the variance and mean are larger in the modelled values than in actual historical values. This can be seen to be due to two factors. First, the varying dynamic of volume and premium across years may result in a model trained with the full sample to be less well adapted to the dynamics within any specific year. Secondly, the uniform distribution of the random variable residual can be seen to impact results as well.

It would then seem the model of Jaehnert et al. [33] is not particularly suitable for modelling the Finnish balancing energy market. Indeed, the dynamics of the market premium seem to follow different fundamentals as in NO2, with a less clear correlation of volume and premium. Furthermore, the Finnish balancing energy market seems to be ongoing a transition, with shifting correlation to different variables, particularly spot price, but also e.g. wind power production, as discovered in the data analysis.

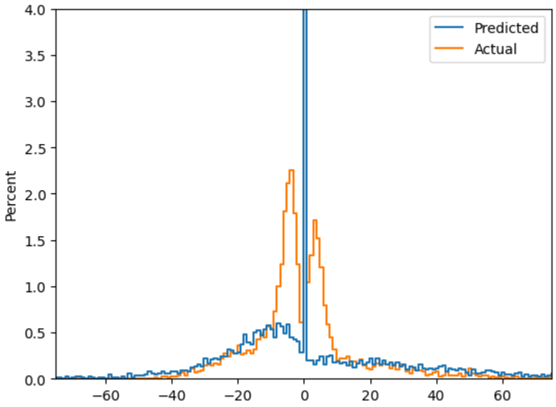

Figure 21: Modelled and actual premium for 2019 input data

For generation of volumes, the regulation state is drawn according to a selected historic probability, conditional on the month of year. Then, volumes are drawn based on the fitted beta distribution to the according yearly distribution. Taking again 2019 as a reference year, this method obtains us synthetic volume data as visualised in Figure 22. We note that, unsurprisingly, this method fits well the distribution of

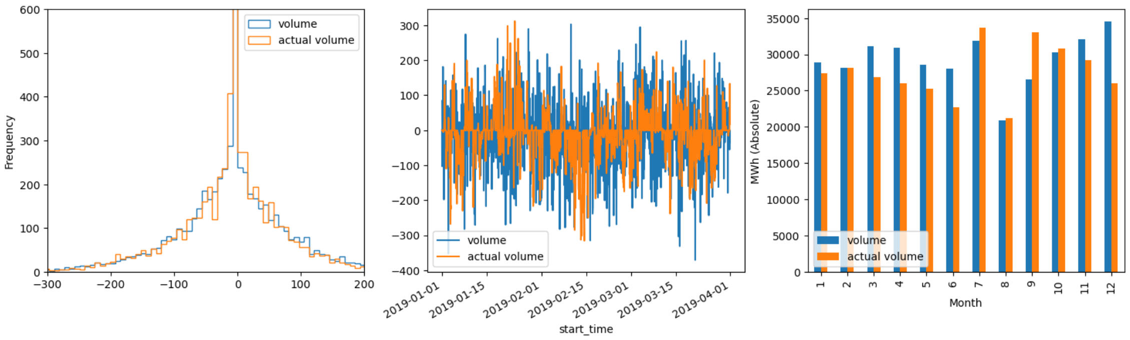

Figure 22: Synthetic and actual volumes for 2019 as histogram (left), time series (center), and monthly absolute sum of all regulation. Time series depicts January through March.

volume at the yearly level. Observing the time series however indicates that this method does not capture the clustering and dynamics of the regulation states at the hourly and daily level. Furthermore, it would seem that monthly volumes are slightly overestimated during most months. This is likely due to months with outlier events distorting the distribution on one hand, and intra-yearly develpment of the volume distribution not captured by the method, on the other hand. As such, while not perfect, this method produces figures that are suitable for long-term modelling, but should not be used for forecasting purposes.

The volume model can be combined with a projection of spot prices for generating balancing premium using the premium model. Together, balancing turnout can be modelled for long-term scenario projections. Based on the results of these models on historic data, volume modelling performs adequately, but does not capture the clustering dynamics, and slightly overestimates turnout.

The premium model, does not perform as well, with significant overestimation of variance and mean premium. As such, more advanced modelling methods may be needed to properly capture the characteristics of the Finnish balancing energy markets.

6 Discussion

The literature review reveals a market of marginal size but of great importance. The balancing energy market is characterised by its fundamental link to the physical state of the electricity system and its real-time mechanism. It is likely due to this physical link to the power system that there is such a heterogeinity in market rules and design across countries, even within the Nordics. Thankfully, the market design is well-documented, and data is consistently available, especially in Finland through the Fingrid data portal [17]. Also academic literature and industry documentation commonly useas the same terms, such as the reserve product nomenclature and market roles of BRP, BSP and SO presented by Van der Veen and Hakvoort [1]. This eased the projection of the presented framework onto market documentation such as the Nordic Balancing Philosophy [16].

Based on both literature and data analysis, it is clear the balancing market is dynamic, with multiple concurrent changes, with volumes, premiums and correlation to power system variables evolving across the analysed years and market design changes in the upcoming years. The power system has also been in transition, with the analysed period seeing increased renewable production, the energy crisis of 2021-2022, and the closing of Russian imports. Neither previous literature nor statistical methods had a consensus on the exact causalities for the changes, with notably the role of wind power production being contested in driving balancing volumes. It would seem, however, that interconnectedness, spot prices and market design are central factors in the development of the balancing energy market. Due to the multiple parallel changes, it was not possible to determine causalities and whether any single driver is impacting the balancing market.

Due to this dynamic transition, it is good to remind the old adage that historical results are not proof of future performance, and caution is advised if the historical turnout characteristics are applied in long-term outlook analyses. Instead, the analysis should be seen as an investigation into the recent historical behavior of the market and a complement to the body of literature on other balancing energy markets across Europe. No similar studies have been performed on the Finnish market, and comparison to research in other balancing markets are needed to account for the unique characteristics of each power system and the heterogenous rules for balancing across countries.

One interesting comparison is to the analysis of Chazarra et al. [9], with a consensus that balancing markets cannot be explained by any single power system variable. This strengthens the perhaps surprising conclusion that especially the role of wind forecast errors are likely overestimated.

From balancing actions at a scale smaller than the market time unit to the manual activation decisions and frequency band allowed by operators, it is challenging to establish any exact rules or relationships from large resolution market data to balancing actions. However, data at the level used for decision-making by TSOs is not publicly available. This makes the balancing energy market a hard case to analyse.

The difficulty of modelling the balancing energy market is further accentuated by the tight interlink across Nordic market areas.

Furthermore, the role of outliers in the balancing energy market proved to be central. As concluded during modelling, the 2% of outlier values further than 4 standard deviations from the mean accounted for 46% of the revenue during the outlook period. As the outliers often correspond to exceptional events, capturing these outliers in modelling is challenging to say the least.

One major limitation in analysing the full Nordic perspective was the availability of data. Fingrid has an excellent open data portal. Similar portals were not available from SvK and Statnett. Additionally, the reporting of data on the ENTSO-E Transparency platform was heterogenous for the Nordic market areas. Further research encompassing the full Nordic outlook, if the data becomes better available, is proposed, and would prove beneficial to expand the understanding of Nordic balancing energy markets. No such research was identified.

The balancing energy market is tightly interlinked to other markets and reserve products. From the linkage of day-ahead and balancing prices to the large suit of resrve products, further interesting topics for further research could investigate how the mFRR market is interlinked to other markets and reserves. Some research on the topic does already exist in the Nordics, such as the analysis of the interplay of day-ahead and balancing energy markets by Boomsma et al. [3].

Literature for long-term analysis of balancing markets proved to be very scarce, with only one presented long-term model [33], further reused in subsequent literature [2]. For the purpose of this work, this model was adapted to the Finnish market. A tradeoff of more simple modelling methods to allow for lighter implementation was chosen against better accuracy resolution, due to the objective of providing a scenario generation tool. Further research could improve on the modelling accuracy using more sophisticated tools and more complex algorithms. Also the distribution modelling may be revisited, as scaled beta distributions are not as intuitive to scale across i.e. variance than normal distribution, for example, due to the parametrization.

Overall, the market description and design have been well documented and relatively straightforward to identify. However, the behaviour of the market revealed to be relatively opaque. Further research is proposed to understand the context of the balancing energy market as a piece in the larger energy market ensemble, how Nordic markets interact as a whole and whether more complex modelling tools would better capture characteristics of balancing energy markets.

7 Conclusion

The balancing energy market is the mechanism through which mFRR activations are procured. It acts as the last of multiple markets used to trade electricity and ensure equilibrium of electricity production and consumption. First, documentation and literature was reviewed to establish a description of the market. Second, a statistical analysis was performed to characterise the market turnout in Finland during 2018-2022. Thirdly, a model was developed to generate market turnout timeseries for the purpose of scenario generation.

The Nordics, as a synchronised area, operate a common balancing energy market, divided into multiple market areas. The balancing energy market sees three main actors. The Nordic TSOs coordinate actions in their respective market areas, while ensuring sufficient reserve availability. BRPs are the electricity producers, retailers and industrial customers that cause imbalances and carry the costs of balancing. BSPs are the actors providing balancing reserves and bidding on the balancing markets. The market design is characterised by the hourly market resolution, real-time market clearing, a common Nordic bid curve and zonal, asymmetrical pricing. The market design is characteristic of balancing energy markets, with strong Nordic integration. The linkage of the balancing energy prices to the day-ahead reference price is also of note. The qualitative key drivers of change for the balancing energy markets are the expected increase in VRE and demand, the transition to a 15-minute imbalance settlement period and the integration of European balancing markets. Increase in VRE and demand are expected to increase the need for balancing, while market design changes are expected to reduce the need for balancing. Based on empirical evidence from Germany, balancing needs can be reduced by market design changes even while experiencing substantial increases in VRE production. The identified key drivers are then expected to mitigate each other, with the need for balancing in Finland expected to remain largely stable.

Analysis of the historical turnout paint the picture of a small market, with growing volumes and premium from 2018 to 2022. Yearly volumes have grown in downregulation from 170GWh to 250GWh and in upregulation from 120GWh to 180GWh. Similarly, the average premium has increased in downregulation from 17EUR/MWh up to 128EUR/MWh and in upregulation from 68EUR/MWh up to 215EUR/MWh. The development in premium seems to be driven by the increasing day-ahead prices during the period. During the period, an upward trend in volume mean and variance, as well as in the number of hours without demand, can be observed. This means the market has grown in both volume and premium, while becoming increasingly volatile. Correlation analysis reveals that up- and downregulation follow different drivers, with no single explaining variable. Volume and premium correlate, with a correlation of 0.67 in upregulation and 0.48 in downregulation. Downregulation premium also correlates strongly with day-ahead prices, with a correlation of -0.67. Beyond these, no other strong correlation were found. Low to moderate correlations were found with the usage of interconnectors, especially between Finland and the SE1 area. Wind power sees a low but growing correlation. Taking into account variables at the Nordic level did not increase correlation when compared to Finnish variables. This means that on one hand, the increase in wind power generation did not correlate with any large increase in balancing volumes. On the other hand, no clear drivers, especially for volume, were identified. As such, volume seems to follow a largely stochastic pattern. Premium could then be seen as being impacted by, at least, volume and day-ahead prices.

For modelling turnout, volume and premium modelling was performed separately. Volume was adequately modelled by a month-conditional regulation state probability, combined to a Beta-distributed volume fitted to historical patterns. This method did not however capture the observed clustering of regulation. Premium was modelled as a function of volume and day-ahead prices, with an additional residual random variable. This model did not properly capture the large amount of low-premium hours, resulting in overly large variance and mean for both regulation directions. When modelling based on 2019 actual data, the model overestimated premium by 13 EUR/MWh for upregulation and 20 EUR/MWh for downregulation when compared to actual historical values. Standard deviation was overestimated by 20EUR/MWh for upregulation and 259EUR/MWh for downregulation. Balancing energy markets are inherently hard to model in the long term due to the stochastic and real-time nature of the market. As such, the performance of the model is in line with previous understanding on the complexity of the modelling task. Modelling also highlighted the importance of outlier values in providing revenue for the market, further complicating the modelling task.

The Balancing Energy Markets are an interlinked piece of the wider energy market and power system puzzle. Based on previous literature, the balancing energy market has been a less well-understood piece of that puzzle. All of the above insights set to provide a synthesis of the market design and behaviour in the Nordic context. This hopefully provides a sturdy springboard for further research in the interlinkages of electricity markets, be it with other geographic markets or other markets such as day-ahead and intraday.

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