Design of Electricity Markets for Efficient Balancing of Wind Power Generation

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Abstract

Deploying wind power to a larger extent is one solution to reduce negative environmental impacts of electric power supply. However, various challenges are connected with increasing wind power penetration levels. From the perspective of transmission system operators, this includes balancing of varying as well as – to some extent – uncertain generation levels. From the perspective of power generating companies, changes in the generation mix will affect the market's merit order and, hence, their profits. This thesis focuses on provision and use of flexibility in the Nordic electricity market.

First, this thesis studies wind power variations and accuracy of wind power forecasts in Sweden using statistical methods. Even though today's wind penetration levels are still low in Sweden, power systems and electricity markets have to cope with these characteristics of variations and forecast errors to a larger extent in future.

Second, it investigates to which extent an increased exchange and use of flexibility that is available in the intraday time-frame could efficiently facilitate system balancing and whether this would also be profitable from the power generating companies' perspective. Here, a simulation model is developed that reflects important aspects of production planning and trading decisions in the intraday time-frame. In a first case study, it is shown that the benefits of internal rescheduling strongly depend on the costs to adjust production plans in the intraday time-frame as compared to real-time. In a second case study, it becomes evident that trading flexibility in the intraday time-frame can reduce the need for system balancing more efficiently than internal rescheduling within each balance responsible party.

Motivated by the positive gains of intraday trading and the challenge of appropriately modelling continuous intraday markets, trading activity and price development on ELBAS is investigated. The results provide insights into trading behaviour on a continuous intraday market and show that trading is not always in accordance to the power system's physical situation. To the extent to which better information and adaptations in the market design could improve the market participants' base for trading decisions, policy recommendations and further research questions areas suggested.

Sammanfattning

Att använda vindkraft i en större utsträckning är en möjlighet att minska elproduktionens negativa miljöpåverkan. Det finns dock också olika utmaningar med stora mängder vindkraft. Från ett systemperspektiv gäller det till exempel att hålla balansen mellan tillförsel och konsumtion av el. Från elproducenternas perspektiv bör vindkraftens påverkan på elmarknaden nämnas eftersom det påverka aktörernas vinster. Avhandlingen titta närmare in i hur man kan få tillgång till mer flexibilitet på produktionssidan.

Avhandlingen består av tre delar. För det första undersöks variationer och prognosfel av vindkraft i Sverige med hjälp av statistiska metoder. Även om andel vindkraft hittills är låg i Sverige, behöver elsystemet och elmarknader i framtiden hantera samma egenskaper av själva variationer och prognosfel som idag men i en större utsträckning.

För det andra undersöks hur den flexibiliteten som finns i tidshorisonten några timmar innan leveranstimmen kan utnyttjas för att integrera vindkraften på ett sätt som är både fördelaktigt från systemets och från aktörernas perspektiv. Undersökningen sker med hjälp av en simuleringsmodell som omfattar viktiga delar i produktionsplanering och intradayhandel. I en fallstudie uppvisas att vinster av intern omplanering är i högsta grad beroende på kostnadsskillnaden mellan omplanering några timmar innan leveranstimmen och anpassning av körscheman under själva leveranstimmen. Resultat av ytterligare en fallstudie uppvisar att det är betydligt billigare och mer effektivt att använda intradayhandel istället för intern omplanering för att utnyttja den befintliga flexibiliteten och för att reducera obalanser som systemoperatörer annars behöver ta hand om under leveranstimmen.

Detta är en anledning till att undersöka handelsmönster på Elbas som är en intradaymarknad med kontinuerlig handel. En annan anledning till den här tredje delen är utmaningarna i att modellera kontinuerlig intradayhandel. Studien beskriver handelsaktiviteten på Elbas och hur priserna utvecklas under handelstiden. Ett resultat är att handeln inte alltid återspeglar den fysiska situationen i elsystemet. I den utsträckningen som ett snabbare informationsflöde och förändringar i marknadsdesignen kunde förbättrar aktörernas underlag för intradayhandel, föreslås förbättringar och öppna forskningsfrågor.

Tack!

First of all, I would like to thank Mikael Amelin and Lennart Söder for their help and support during the project as well as for acquiring funding for it. The financial support from the ELEKTRA programme and the feed-back from the reference group are gratefully acknowledged. I am also very grateful to Mikael and Lennart that they did not bother to take our discussions in Swedish which was a perfect chance for me to practice this language!

Second, I would like to thank several external persons for taking their time to comment on draft versions of manuscripts, to discuss questions that I had and to share parts of their practical knowledge; especially Mia Westerlund, Mattias Linell, Gabriel Asphult and Pontus Thorsson. In this context, I also want to include the YEEES seminars which provided an excellent possibility to discuss work-in-progress and where I received many constructive comments. Finally, special thanks to Oskar Sämfors and Jesper Storebjerg for data provision.

During course work, a winter school on uncertainty organised by NTNU and NHH was an outstanding chance not only to learn a bit more but also to meet other PhD students in the field of production planning and electricity markets. Some of these contacts have been really helpful, especially Jonas Egerer. Thanks!

Together with Camille, I really enjoyed organising our wind power course. Here, I would like to thank Lennart for giving us a lot of freedom to further improve the course as well as the chance to lecture on topics related to our projects which was an outstanding possibility to test both pedagogics and own understanding.

I also want to thank my colleagues for sharing many nice discussions, fika and lunch breaks. I guess I will always remember Magnus Brolin's happy "Tjenare!", Karin and Robert knocking on our door every day at 9:30 and 14:30, Yelena's most beautifully decorated cakes and Rujiroj frying ice-cream for all of us. Special thanks to Camille, Lars and Yuwa! I also want thank Nathaniel, Peter and Camille for helping me to "manage" my computer as well as Andreas, Gunder, Jesper and Per for all our innebandy matches which I enjoyed a lot!

It is many of these "small" things that made me feeling comfortable and "a bit home" at KTH and in Sweden. I am very glad to have met many new, nice people that added a lot to my positive experiences of both Swedes and Sweden. Finally, many warm thanks to my parents for their steady support and for taking part in my journey in such a nice way.

Contents

Chapter 1

Introduction

This chapter introduces to the thesis, outlines addressed research questions and states achieved contributions. It also lists those publications that are part of the thesis and guides through the structure of the remaining chapters.

1.1 Integration of wind power generation

Nowadays, supply of electric energy is essential for our society: for competitive industries as well as for public services such as transportation, healthcare and communication infrastructures. Even though the political goals regarding electricity supply vary in their formulation, countries have adopted the same basic aims: security and quality of supply as well as cost efficiency. Security of supply includes both long-term and short-term components to guarantee a reliable electricity supply, e.g. by access to primary energy sources, adequate generation and transmission/ distribution infrastructures as well as an adequate market framework [1]. Quality of supply can be seen as the short-term component of supply security that guarantees at a reliable continuous supply of electricity at stable voltage levels. It can even include quality regarding consumer services such as grid connection and customer support [2].

According to [3], focus was changing between these goals: back in the time of vertically integrated monopolies, long-term security of supply and reliability of supply in the short-term were the most important goals in Europe. Later, restructuring electricity markets and exposing market participants in the areas of generation, trading and retail to competition was seen as an appropriate instrument to increase cost efficiency. But with the liberalisation of the electricity sector also quality issues became once more important in order to prevent market participants from reducing their costs by lowering quality of supply.

In the last years, the reduction of the power supply's environmental footprint became another objective; one example are EU's Energy 2020 goals with regard to renewable energy sources [4, Article 3], energy efficiency [5, Article 3] and carbon

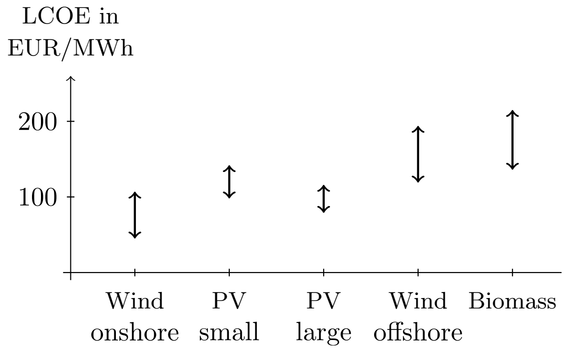


Figure 1.1: Range of levelised costs of electricity (LCOE) for renewable energy sources as estimated by FRAUNHOFER IES in 2013 for locations in Germany [10].

dioxide emissions [6, Article 1]. In Sweden, goals for an increased deployment of renewable energy sources are stated by parliament in a law on electricity certificates [7]. Here, it is set to which extent Sweden's electricity demand (with exception of energy-intensive industry) should be covered by renewable energy sources that are eligible to receive certificates. In 2020, the quota will reach its maximum amounting to 19.5 % [7]. Because only those renewable power plants that have been commissioned after May 2003 are eligible for these certificates from the beginning of 2014 [8], the quota in 2020 translates to approximately 25 TWh/year of newly installed capacity with respect to 2003, see [9] for more details.

Comparing the average generation costs of different renewable energy sources, onshore wind power tends to be one of the cheapest renewable options; in Figure 1.1, selected results of study for locations in Germany [10] are presented. The plot shows the estimated *levelised costs of electricity.* These costs reflect average generation costs considering capital cost, fixed and variable operation costs as well as maintenance and fuel costs. However, they do neither reflect that the value of supplied electricity varies from hour to hour nor the possibility of generation technologies to supply balancing services. However, the estimates indicate that – also from a economic perspective – wind power will play a more important role in the deployment of renewable energy sources, especially as the potential for new hydro power plants (which are in a study from 2010 estimated to be even cheaper than onshore wind [11]) is limited [12].

The characteristics of wind power generation differ from those of conventional power plants. At first glance, wind power generation differs in two manners: it is exposed to changing wind speeds and to uncertainty regarding these wind speeds. Therefore, it is a *variable renewable energy source* (vRES). Its characteristics pose challenges to electric power systems, especially regarding the task to continuously balance generation and consumption. This will be discussed in the following.

On the generation side, unplanned variations have been experienced by power systems only with regard to outages in power plants and transmission lines as well as with regard to run-of-the-river hydro power plants that do not have any storage possibility. Hydro power plants along river systems with hydro reservoirs are also exposed to inflow uncertainty, but due to the possibility to store water for later use, this uncertainty does not translate to generation uncertainty to the same extent as wind power forecast errors affect generation of wind power plants.

On the demand side, consumption has always been uncertain to some degree, but forecast errors tend to be smaller than those for wind power plants [13]. Hence, even though power systems are used to handle variations and uncertainty, wind power – as well as other vRES, for example, solar power – significantly complicate balancing tasks.

At the same time, wind resources are free of charge. The absence of fuel costs for wind does not only offer advantages, e.g. by reducing total variable generation costs in the power system, but poses a second type of challenges: it will in the long run affect profitability of competing conventional power plants. Having negligible variable generation cost, wind power generation can be offered on the market at low prices which decreases the number of hours where power plants with larger variable generation costs will be demanded. In the long run, this will lead to a technology shift [14]. To a certain extent, this transition towards power generation technologies with less negative environmental effects is a political goal. However, as many conventional power plants provide balancing services, this function needs to be considered as well.

At second glance, there are several more technical issues connected to wind power integration: sites for wind power generation tend to be more geographically dispersed than those of conventional power plants. At the same time, capacity of individual wind power plants is significantly smaller than the one of standard-sized conventional power plants. Therefore, integration of wind power also needs to handle issues that affect the grid in similar ways as other distributed generation; the possibility of reversed power flows from local/regional grids to transmission grids is one example. Also deviations from nominal voltage levels close to the connection point of wind parks have to be handled, e.g. in case of induction generators due to reactive power consumption. Other issues include power quality due to the use of power electronics that distort the waveform of the output, e.g. in case of doubly-fed induction generators and synchronous generators with full-scale power converters.

The broad range of challenges connected to integration of wind power is illustrated in Figure 1.2. Especially with regard to balancing, market and grid issues, the way we operate and plan electric power systems – this includes the design of electricity as an instrument for efficient system operation – will need to be adjusted in order to efficiently accommodate generation from wind power, other vRES as well as distributed generation.

To handle some of the technical challenges, so-called *grid codes* or *network codes* are enforced by the transmission system operators (TSOs). These codes specify requirements that power plants have to fulfil in order to get connected to the grid, for example, reactive power compensation, active power control, fault-ride-through

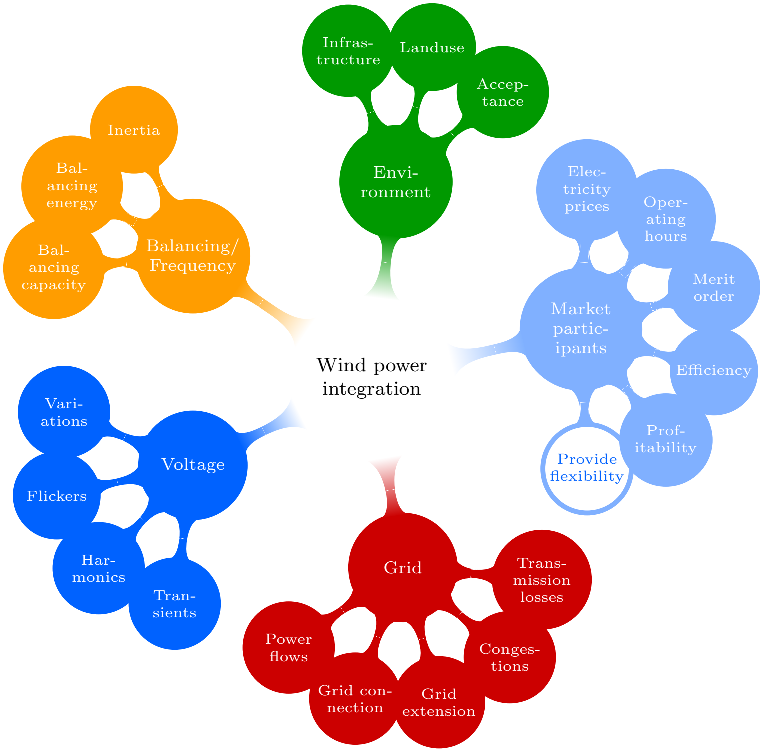
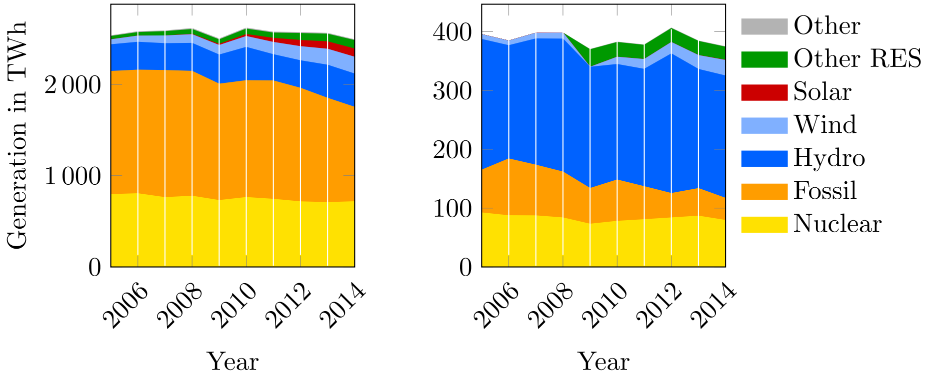


Figure 1.2: Issues regarding wind power integration. Exchange and provision of flexibility are in the focus of this thesis.

and black-start capabilities; see [15] for a comprehensive overview.

Others challenges can be handled by the instrument of electricity markets, for example balancing of wind power forecast errors. Here, market participants can be stimulated to reduce their expected imbalances before the period of delivery. This can be facilitated by trading possibilities in the intraday time-frame. However, there will always be variations within the period of delivery; therefore, balancing services have to be procured to keep the system stable.

As generation from vRES is increasing and reaching considerable levels, also the issues mentioned above become more noticeable. Figure 1.3 illustrates the increase of vRES in two synchronous areas of the European electric power system. In 2014, already 26 TWh out of 374 TWh have been generated by wind power plants within the Nordic synchronous area plus western Denmark. This yields a wind energy penetration level of 7.0 %. The situation for the Continental European synchronous area without western Denmark is similar; here, 184 TWh out of 2 489 TWh have been generated by wind power plants in 2014; the corresponding penetration level



(a) Continental European synchronous area without western Denmark. Data from [16, 17].

(b) Nordic synchronous area and western Denmark. For 2009, no details have been available on generation from RES. Data from [16–18].

Figure 1.3: Generation mix in selected parts of the European electric power system. Before 2005, concise data on generation from renewable energy sources (RES) is not available due to different accounting of these by European TSOs [18].

is 7.4 %. Due to the general trend towards increased deployment of wind power, an efficient integration of wind power generation will become a more and more pressing issue.

1.2 Research questions and scope

This thesis deals with one aspect of an efficient wind power integration: *how market participants can use available flexibility in their own power plants in a way that is profitable for them and – at the same time – facilitating system operations, especially the TSO's task to balance generation and consumption during real-time.*

From the overall system's perspective, it is important to guarantee supply of electricity in a reliable and cost efficient manner. To continuously balance generation and consumption, balancing services are procured and activated in real-time. The volume that is necessary to keep the balance depends on the accuracy with which all market participants stick to their production/consumption plans as well as on variations of generation and consumption during the period of delivery.

If market participants would have more accurate generation/consumption plans, balancing during real-time could be facilitated and less costly. Of course, some of the saved costs will be compensated by increased rescheduling costs of the market participants. However, in total, balancing and rescheduling costs decrease because parts of the balancing services can be delivered by power generation units with different technical and economical characteristics, e.g. lower ramp rates and longer minimum activation time. In addition, the risk of power shortages could be reduced if fewer reserves have to be used to balance deviations in real-time that have already been expected ex-ante, i.e. before the period of delivery.

One central incentive for market participants to trade on electricity markets in such a way that they fulfil their commitments as precisely as possible during the period of delivery is to expose market participants to imbalance costs in case their generation/consumption deviates from their scheduled generation/consumption. According to a recent overview in [19], all countries within the European Network of Transmission System Operators for Electricity (ENTSO-E) except Hungary have implemented some form of an imbalance cost component. Currently, implementations differ widely which results in stronger or weaker incentives.

It is therefore investigated in this thesis to which extent market participants can beneficially (from the perspective of market participant's) and efficiently (from a system-wide perspective) facilitate balancing of wind power forecast errors. Here, market design choices are of importance because electricity markets are used as an instrument to steer market participants towards scheduling solutions that are operationally feasible and cost-efficient.

As two "side-products" of this research question, wind power forecast errors and hourly variations of wind power generation in Sweden have been analysed to get a better understanding of their magnitudes. Both affect the need for balancing services during real-time; the central difference in context of this thesis is that sub-hourly variations cannot be reduced by trading on electricity markets with hourly trading periods, as it is the case with day-ahead and intraday markets in the Nordic countries.

Even though this thesis aims at contributing to the question in which way changes in current market design can facilitate an efficient integration of significant wind power capacity, many areas remain outside the scope of this thesis. This includes handling of sub-hourly variations, balancing services other than those procured on the Nordic balancing market, market coupling, long-term transition effects of changed merit orders, support schemes for vRES, priority feed-in and central control of vRES, locational pricing, capacity markets, and last but not least the question whether markets with competitive elements are an appropriate instrument to handle an infrastructure that is technically complex, essential to economy and society as well as to a large extent a natural monopoly.

1.3 List of publications

The following published articles and submitted manuscripts are appended and form part of this thesis:

[P1]: R. Scharff and M. Amelin. 'A Study of Electricity Market Design for Systems with High Wind Power Penetration'. In: *8th International Conference on the European Energy Market (EEM).* 2011, pp. 614–621.
This article was the starting point of the project. It describes selected electricity markets and provides an overview of challenges of wind power integration for electricity markets. I outlined, performed and wrote the review under the supervision of Mikael Amelin.

[P2]: B.-M. Hodge, D. Lew, M. Milligan, H. Holttinen, S. Sillanpää, E. Gómez-Lázaro, R. Scharff, L. Söder, X. G. Larsén, G. Giebel, D. Flynn and J. Dobschinski. 'Wind Power Forecast Error Distribution: An International Comparison'. In: *International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants Conference.* 2012.
To get a better understanding for forecast errors, e.g. their frequency of occurrence and their magnitude, day-ahead wind power forecasts of the Swedish transmission system operator have been analysed. In collaboration with the IEA Wind Task 25 working group, the results have been compared with those of other countries and presented in this article. The article was outlined by the working group, the analysis was based on a script by Bri-Mathias Hodge. For Sweden, I collected, analysed and interpreted data under the supervision of Lennart Söder.

[P3]: R. Scharff, M. Amelin and L. Söder. 'Approaching wind power forecast deviations with internal ex-ante self-balancing'. In: *Energy* 57 (2013), pp. 106–115.
In this article, a model is described that was developed to study effects of internal ex-ante self-balancing, i.e. when power generating companies reschedule their own production according to their latest wind power forecasts shortly before the period of delivery. This article is an improved version of [20]; the latter one is therefore not included in this thesis. I sketched, build and described the model as well as an application on a test system under the supervision of Mikael Amelin and Lennart Söder.

[P4]: R. Scharff and M. Amelin. 'Distributed Balancing of Wind Power Forecast Deviations by Intraday Trading and Internal Ex-ante Self-Balancing – A Modelling Approach'. In: *Database and Expert Systems Applications (DEXA), 2013 24th International Workshop on.* Aug. 2013, pp. 176–183.
This article describes an extended set up of the model applied in article [P3]. Here, two trading steps that represent intraday auctions are included. I expanded the model and discussed the results of another application on a test system under the supervision of Mikael Amelin.

[P5]: R. Scharff, J. Egerer and L. Söder. ‘A description of the operative decision-making process of a power generating company on the Nordic electricity market’. In: *Energy Systems* 5.2 (2014), pp. 349–369.
This article is a joint work with Jonas Egerer (TU Berlin, DIW Berlin) where we provide an overview of the production planning and trading process of power generating companies along with a review of optimisation models that optimise some of the planning and bidding decisions. The article was drafted, discussed and written together by Jonas Egerer and me under the supervision of Lennart Söder.

[P6]: J. Kiviluoma, H. Holttinen, R. Scharff, D. E. Weir, N. Cutululis, M. Litong-Palima and M. Milligan. ‘Index for wind power variability’. In: *International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants Conference.* 2014.
The article is a side result of another project of the IEA Wind Task 25 working group and describes the variability index that we apply in [P7]. The manuscript was outlined by the working group and the main work was done by Juha Kiviluoma. I contributed under the supervision of Lennart Söder to the introduction and by collecting, analysing and interpreting data for Sweden that were input to [P7].

[P7]: J. Kiviluoma, H. Holttinen, D. E. Weir, R. Scharff, L. Söder, N. Menemenlis, N. A. Cutululis, I. D. Lopez, E. Lannoye, A. Estanqueiro, E. Gómez-Lázaro, Q. Zhang, J. Bai, Y.-H. Wan and M. Milligan. ‘Wind power variability’. In: *submitted to Wind Energy* (submitted October 2014).
To get better knowledge about variability of wind power generation, generation data from the Swedish transmission system operator has been analysed. In collaboration with the IEA Task 25 working group, the results have been compared with those of other countries and presented in this manuscript. The manuscript was outlined by the working group, the analysis was based on a script by Juha Kiviluoma. For Sweden, I collected, analysed and interpreted data under the supervision of Lennart Söder. I was not involved in the presented regression model.

[P8]: R. Scharff and M. Amelin. ‘Trading behaviour on the continuous intraday market Elbas’. In: *submitted to Energy Policy* (submitted March 2015).
This manuscript describes trading activity and price development on Elbas. It is based on an analysis of market data of Elbas, Elspot and the Nordic balancing market. I conducted the work as well as outlined and wrote the article under the supervision of Mikael Amelin.

During the following parts of the thesis, the symbol ☞ is used to highlight where a publication that is part of this thesis is discussed. Where appropriate, also individual sections, table or figures are specified. All other references to chapters, sections, figures and tables that are not introduced by that symbol refer to the main text part of this thesis. I hope this will facilitate reading!

1.4 Contributions

The contributions of the thesis include:

- Study of the decision making process of power generating companies on the Nordic electricity market. Power generating companies optimise both production planning and trading decisions. These comprise various decision steps that consider different time horizons and uncertainties. All decisions affect each other which makes the process rather complex. The contribution of ☞[P5] is to map all operative decision steps and their interrelations. In addition, the article gives an overview on models developed to determine optimal production planning and trading decisions. Here, emphasis is on the extent to which these models include different decision steps in their problem formulation.
- Analysis of wind power forecast errors in Sweden. Wind power forecasts errors result in balancing needs which can be reduced if market participants have possibilities to reach balanced positions according to updated forecasts. Studying wind power forecasts from the Swedish TSO, insights into magnitude and frequency of forecast errors have been gained. In combination with ☞[P2] which is based on similar studies for different countries, the study contributes to a deeper understanding of the statistical properties of wind power forecast errors.
- Analysis of wind power variations in Sweden. From a power system's perspective, not only frequently occurring variations are important; power systems also have to handle rarely occurring large variations. Therefore, distributions of hourly wind power ramp rates have been studied. The results in ☞[P7] are based on similar studies for different countries. Variability of wind power generation is described and it is investigated by which factors (e.g. geographical dispersion) it is affected.
- Development of a simulation model to assess effects of ex-ante self-balancing. Here, a model was build that reflects important aspects of ex-ante self-balancing decisions, which can include production planning and trading decisions. Rescheduling costs, limited liquidity on intraday markets and different levels to which flexibility can be provided have been implemented. The model is described in ☞[P3, P4].
- Simulation of effects of ex-ante self-balancing. The contribution is the application of the before mentioned simulation model to study effects of ex-ante self-balancing. In ☞[P3], market participants use rescheduling (referred to as *internal* ex-ante self-balancing) and in ☞[P4] also intraday trading (referred to as *external* ex-ante self-balancing). The findings stress the positive value of intraday trading and under which conditions ex-ante self-balancing can be beneficial. If intraday trading is assumed to be impossible, it is found that rescheduling needs to have access to significantly cheaper flexibility than the balancing market in order to be beneficial from the systems's perspective as well as from the power generating companies' point-of-view.

- Analysis of trading activity and price development on Elbas. So far, no detailed study on trading behaviour on Elbas has been published. However, such a study is important to understand complexity and uncertainty which market participants experience on continuous intraday markets. This is of relevance because intraday trading can facilitate system balancing. The study presented in ☞[P8] contributes also by identifying some possible improvements. In addition, it explains the imbalance settlement rules in the Nordic countries and their characteristic that imbalances on the production side can be moved to the consumption imbalance.

1.5 Outline of the thesis

The included articles and manuscripts are a central part of this thesis. In the following chapters, the work presented in those publications is discussed and connected to each other.

Chapter 2 offers a brief description of the relevant background. Here, ☞[P1, P5] are included.

The following three chapters summarise the main areas of the presented work: Chapter 3 addresses variability and uncertainty of wind power generation. Here, ☞[P2, P6, P7] are connected.

Chapter 4 studies one answer to the question how to efficiently handle forecast errors. This is based on applications of a model presented in ☞[P3, P4]. In addition, practical implications of the Nordic imbalance settlement are discussed here based on the corresponding section in ☞[P8].

Chapter 5 summarises the analysis of trading behaviour on Elbas which is described in ☞[P8].

All three chapters that describe the main work close with a description of open research questions in each respective area.

Finally, Chapter 6 summarises the main findings and focuses on a discussion of policy recommendations with regard to improvements in the current market design in order to both facilitate an efficient integration of vRES.

Chapter 2

Background

This chapter discusses the relevant background for the thesis. For stable operation of electric power systems, production planning and system balancing are of central importance. While the latter task is within the responsibility of the TSO, production planning as well as corresponding scheduling of consumption is the sole responsibility of market participants including power generating companies, retailers and large consumers. Electricity markets can then be used to couple both tasks in order to coordinate and to optimise schedules for power generation and consumption and to provide flexibility for cost-efficient system balancing.

2.1 Terminology

Before describing production planning, system balancing and electricity markets, several terms might need to be clarified. In this thesis, many issues are discussed from a Nordic perspective. With the term *Nordic countries*, I refer to Norway, Sweden, Finland and Denmark. Regarding system operation and electricity markets, some terms are used differently in the Nordic countries than in continental Europe because operational guidelines, for example [21, 22], used to be developed separately for each synchronous area. Nowadays, there are large efforts in Europe to harmonise rules governing system operation and electricity markets. As a nice side-product of harmonisation, also terminology will become more similar.

While terminology in the text part of this thesis tries to follow ENTSO-E's drafted network codes [23], some of the publications that are part of this thesis tend to use different terms that have been (or still are) more common in the Nordic or the Continental European synchronous area. The use of following terms should be clarified based on ENTSO-E's definitions:

- *Balanced position*: denotes the state of market participants that have its planned generation/generation in accordance with their sales and purchases. The term is used in [24] to describe the role of balance responsible parties.

- *Balancing*: includes "all actions and processes, on all timelines, through which TSOs ensure [...] to maintain the system frequency within a predefined stability range [...] and to comply with the amount of reserves needed [...]" [24]. In this thesis, the TSO's efforts to balance the system during the period of delivery is sometimes referred to as *real-time balancing* in order to emphasise the difference to *ex-ante self-balancing* which aims at achieving balanced positions based on latest generation/consumption forecasts. Ex-ante self-balancing is done by BRPs, not by TSOs.
- *Balancing services*: refer to balancing capacity and balancing energy used or procured to balance the system during the period of delivery [24]. Balancing services are provided by the following reserves:
  - *Frequency containment reserves*: reserves that are procured and used to stabilise system frequency [25]. In the Nordic countries, these are called *frequency controlled normal operation reserve* and *frequency controlled disturbance reserve*, both are part of the so-called *automatic active reserve* [22, Appendix 2]. In the Continental European system, these reserves are called *primary control reserves* [21].
  - *Frequency restoration reserves*: reserves that are procured and used to restore system frequency to its nominal level; can be automatically or manually activated [25]. In the Continental European system, these reserves are automatically activated and called *secondary control reserves* [21]. However, in the Nordic countries, mainly manually activated reserves are used to restore grid frequency to its nominal level [26]; these manual reserves are, for example, in Sweden, often called *secondary reserves* [27].
  - *Replacement reserves*: reserves that are procured and used to replace and to support frequency restoration reserves; activation times can be significantly longer than those of frequency restoration reserves [25]. In the Continental European system, these reserves are called *tertiary control reserves* and are mainly available by rescheduling [21]. In the Nordic countries, these reserves correspond to reserves procured through the Nordic *regulating power market* [26] which mainly consist of *fast active countertrading reserves* and *fast active forecast reserves*, but also include *fast* and *slow active disturbance reserves* used to replace frequency controlled disturbance reserves [22]. Observe that the reserves procured on the Nordic regulating power market are manually activated and also commonly referred to as *secondary reserves* [27].
- *Balancing market*: refers to "all institutional, commercial and operational arrangements" for market-based procurement of balancing services [24]. In this thesis, the term is used for markets where TSOs procure manually activated reserves for frequency restoration and reserve replacement. In the Nordic countries, this market is called *regulating power market*.

2.2 Production planning

Assuming that power generating companies behave rational, they will try to maximise their profits [28, p. 53]. Therefore, they try to optimally schedule their power plants. As many factors have to be considered, the planning process includes both scheduling stages that occur long before the period of delivery as well as those that are close to it. According to the time horizon of the scheduling stages, long-term and short-term production planning can be distinguished. The length of the planning horizon differs from fractions of hours up to several years.

As described in ☞[P5, Section 3.1], long-term production planning tackles several questions. The goal is to compute production levels for a longer period in future that guarantee highest profits. Long-term planning is subjected to various sources of uncertainties that affect the availability of generation capacity, for example, inflow to hydro power reservoirs. In addition, also the consumers' demand for electricity is uncertain. Therefore, both the electricity prices that consumers are willing to pay to cover their demand as well as the total electricity demand have to be estimated.

One important area of long-term planning that is common to all types of power plants is to schedule maintenance in an optimal way. Here, periods of planned down-times should be moved to periods of delivery with low expected electricity prices. For all power plants that are dependent on fossil fuel, long-term planning needs to consider fuel supply, especially fuel prices. Then, one result of long-term planning is at what time how much fuel should be ordered.

Hydro power plants that are down-stream of reservoirs in which water can be stored can have considerable long planning horizons of up to five years depending on the size of the reservoir [29]. In general, the aim is to distribute the available water resources in a way that maximises profits from generation. Ideally, water should be available for use in hours of high electricity prices and any spillage (i.e. releasing water without generating electricity, e.g. due to full reservoirs) should be avoided. In reality, significant uncertainties exist with regard to future inflow (precipitation, discharge from other hydro power plants further upstream in the river system) and future value of stored water.

Short-term production planning has significantly shorter planning horizons. Relevant forecast horizon and level of detail depend on the purpose of the planning as described in ☞[P5, Sections 3.3, 3.7 and 3.10]. Purposes are, for example, to compute optimal production plans as basis for providing bids to a day-ahead market, participating in tender processes for balancing services, trading on an intraday market and as basis for optimising own generation closer to the period of delivery. In other words, this implies that short-term planning is a planning *process* rather than one single distinct planning step.

Uncertainties during the short-term planning process are reduced as compared to long-term planning. However, there are still significant uncertainties, for example, regarding wind power generation, intraday and imbalance prices.

2.3 System balancing

At a certain point before the period of delivery, market participants are supposed to closely follow their production and consumption plans, which implies that from this moment, the TSO (or an independent system operator) has full responsibility to keep generation and consumption in balance without grid frequency (which indicates that inertia from rotating machines has been used to maintain system balance) deviating noticeably from its nominal level.

To acquire information about production and consumption plans as well as stimulate market participants to compute accurate plans, TSOs use the concept of balance responsible parties. This is based upon that every energy imbalance, i.e. the difference between commitment and actual generation/consumption, is priced after the period of delivery between the TSOs and so-called *balance responsible parties* (BRPs). All generation and consumption has to be assigned to a BRP and each BRP aggregates the units for which it is balance responsible.

The responsibilities of a BRP include aggregation of generation/consumption plans, financial settlement of imbalances and in several countries also a legal obligation to reduce expected imbalances [19]. According to the drafted network code for electricity balancing in Europe [24], each BRP should have a *balanced position* before the period of delivery, where its planned generation/consumption is in accordance with the corresponding sales and purchases both on power exchanges and bilaterally.

Because BRPs can aggregate generation/consumption from several market participants, imbalances on the level of individual units might be partly compensated by other units within the BRP's responsibility; it is the net imbalance of a BRP that has to be settled financially; depending on the imbalance settlement rules, this net imbalance might need to be calculated separately for generation and consumption as well as separately per price area.

In order to balance variations in generation/consumption that arise within the period of delivery as well as deviations between planed and actual generation/ consumption, TSOs procure balancing capacity and balancing energy from other market participants because they usually do not have own balancing reserves. As outlined in ENTSO-E's drafted network code on load-frequency control and reserves [25] these resources include:

- Frequency containment reserves: used to stabilise system frequency; technical requirements include that these reserves have to be fully available within fractions of a minute after frequency deviations are observed which requires automatic activation controlled by frequency deviations.
- Frequency restoration reserves: used to restore frequency to its nominal level; one distinguishes between automatic and manual frequency restoration reserves regarding their activation; required maximum time for full activation differs between TSOs, but is typically below 15 minutes [30].
- Replacement reserves: used to restore and to support frequency restoration reserves; activated manually based on a set-point received from the TSO; re-

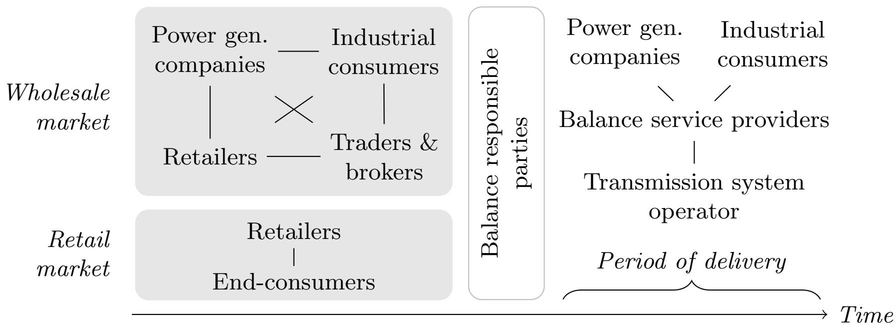


Figure 2.1: Market participants and their interaction. Figure also used in ☞[P5, Figure 1].

quired maximum time for full activation differs between TSOs, but is typically above ten minutes [30].

During the period of delivery, i.e. during real-time, the TSOs ensure uninterrupted supply of electricity in a cost-efficient manner. To fulfil this task which also includes handling of congested transmission lines, they can, for example, activate some of the procured balancing services, use countertrading (i.e. TSO-initiated trade, e.g. through balancing markets) or redispatch which implies that they order market participants to change their generation/consumption levels [31].

2.4 Competitive electricity markets

2.4.1 Design

As [32, Chapter 4] explains, electricity markets are "inevitable organised in some way or another". Competitive electricity markets differ from regulated, vertically integrated monopolies and single-buyer markets by having several competing companies on both generation and retail sides. If, in addition, individual consumers also have the option to choose from which retailer they want to buy, one talks about an electricity market with competition on wholesale and retail market. This is the relevant electricity market model for this thesis.

The interaction of market participants on competitive electricity market is illustrated in Figure 2.1. On the left hand-side, trading relations before the period of delivery are depicted, while the right hand-side shows the use of balancing services by the TSO during the period of delivery. BRPs – which play an important role in the overall balancing process, but not in providing balancing services in real-time [24] – are positioned on the time line right before the period of delivery starts.

Competitive electricity markets offer different trading opportunities that should be designed to reflect the different needs of market participants at different points in time. These needs stem to a large extent from the market participants' attempts to maximise their profits which includes strategies for risk management, for example with respect to production planning as described in the preceding section. Trading opportunities include:

- Financial trading: used to hedge price risks; commitments are not settled by physical delivery/withdrawal of energy, but by financial payments.
- Day-ahead trading: used to find market participants that want to buy/sell the own generation/consumption; here, market participants commit themselves to supply/consume energy during a specified period of delivery; deviations from these commitments will be settled financially.
- Intraday trading: as day-ahead trading, but closer before the period of delivery; used to obtain balanced positions based on updated information.
- Procurement of balancing services: used to offer different kinds of balancing services to the TSO; therefore, this is a single-buyer market without competition on the buyer's side.

Besides bilateral trading possibilities where market participants agree on individual trades directly between each other, there are various organised markets where standardised products can be traded including a market for financial trading, a day-ahead market, an intraday market as well as a balancing market. Because financial trades are not settled by physical delivery/withdrawal of energy, financial trading is not relevant for this thesis. Therefore, only designs of day-ahead, intraday and balancing markets as well as imbalance settlement rules are outlined in the following.

Day-ahead markets

A common way to organise day-ahead markets is to implement power exchanges that offer one day-ahead auction per day. In this auction, *bids* to supply energy and *offers* to consume energy both during a fixed period of delivery are gathered and allocated. These periods of delivery cover the whole following day; therefore, this market is called day-ahead market.

Allocation on day-ahead markets basically[1] implies that all bids are sorted by ascending price; this yields the so-called *merit order*. In addition, all offers are sorted by descending price. Next, the offer that shows the highest willingness-to-pay is matched with the respective quantity of those bids that state the lowest willingness-to-sell. This is repeated with all remaining offers until their willingness-to-pay does not any longer exceed or equal the willingness-to-sell of yet unmatched bids. All remaining bids and offers cannot be allocated because the stated willingness-to-sell does not exceed the stated willingness-to-buy.

A common form of pricing is the combination of uniform and marginal pricing. Here, the price of last bid that gets matched represents the market clearing price. Therefore, power generation bids at the beginning of the merit order, i.e. the cheap-

[1] In reality, also more complex types of orders, e.g. block bids, are traded.

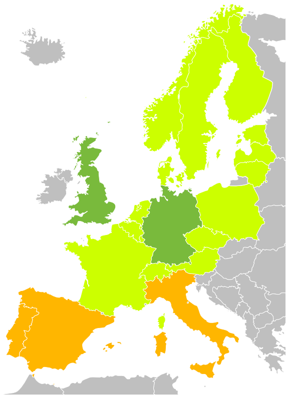


Figure 2.2: Different designs of intraday markets in Europe in 2015: discrete auctions (■), continuous trading (■), mixture of continuous trading and discrete auctions (■), no information (■). Based on information from the market operators: TGE for Poland [33], OTE for Czech Republic [34], EpexSpot for France, Germany/Austria, Switzerland [35], OMIE for Spain/Portugal [36], APX for the United Kingdom [37] and GME for Italy [38]. Political map based on [39]. Figure also used in ☞[P8, Figure 1].

est bids, will receive the same payment as the bid that is setting the market clearing price. The advantage of uniform marginal pricing is that market participants have an incentive to state their real willingness-to-sell and -buy [28].

Physical supply and withdrawal of electricity also requires that sufficient transmission capacity is available between seller and buyer. Between price zones or price nodes, this capacity can be implicitly auctioned in day-ahead markets to reduce the risk of congestion during the period of delivery.

Intraday markets

Intraday markets allow market participants to trade energy for delivery or withdrawal during a specified period much closer towards this period than on day-ahead markets. Therefore, market participants can use new information that is relevant for their short-term planning process, e.g. updated wind power forecasts.

In Europe, there are two common ways to design organised intraday markets: as auction or sequence of auctions and as continuous trading. Figure 2.2 provides an overview about chosen designs at the time of writing.

The working principle of intraday auctions does not differ from the one of day-ahead auctions. In order to move trading closer to the period of delivery, auctions for each period of delivery can be cleared at different times unlike day-ahead markets where all auctions (one auction per period of delivery) are cleared at the same time.

It is also possible to have multiple auctions for the same period of delivery, as, for example, on the Spanish/Portuguese intraday market [36].

Organising intraday trading as platforms for continuous trading differs substantially from the auction approach. On continuous intraday trading platforms, bids and offers are not matched at a specified time, but as soon as a bid and an offer at corresponding price levels exist, they are matched in first-come-first-serve order. Therefore, prices deviate from trade to trade. Formally, continuous trading can be regarded as one auction per *trade*. To better distinguish it from intraday auctions organised in the same way as day-ahead auction, one can use the term *discrete* to emphasise that discrete intraday auctions aggregate all bids and offers for the same trading period in one discrete intraday auction per *trading period*.

Some countries, for example Germany and the United Kingdom, combine continuous trading with a supplementary discrete auction [35, 37].

Balancing markets

In Europe, day-ahead markets are usually designed with time resolutions of one hour, i.e. energy can be traded for delivery in one of the hours of the next day[2]. Hence all day-ahead commitments focus on energy supply/consumption within the hour of delivery; how generation/consumption levels are varying during this hour is not set by the market. This implies that even if all market participants would fully follow their day-ahead commitments, the TSOs would still face uncertainties regarding how generation and consumption varies within the period of delivery. This is one reason why balancing services always have to be procured. Regarding intraday markets, several countries have already implemented sub-hourly periods of delivery for intraday trading, e.g. Germany [35, 40]. However, to increase the incentive for more precise scheduling, also the imbalance settlement would, in general, need to follow shorter time periods.

The second reason is due to those uncertainties that are connected to day-ahead decisions. These include forecast errors of generation as well as consumption levels, outages of power plants and individual generation units, failures in the transmission system that lead to decreased supply or decreased consumption, and failures in distribution grids that affect not only the consumption side but also distributed generation and smaller power plants that are not directly connected to the transmission grid.

Balancing services can be procured in different ways: TSOs might oblige certain grid users to provide balancing services; TSOs can contract balancing services bilaterally; and TSOs can establish a market where market participants [41], the so-called *balancing service providers*, can offer standardised *balancing services*, e.g. positive or negative balancing power or balancing energy. Here, details of those standard services, for example, maximum time to full activation, maximum ramp

[2] One contrasting example is the United Kingdom where two consecutive day-ahead auctions are settled: one with one-hour time periods (cleared at 11:00) and a second one with half-hour time periods (cleared at 15:30) [37].

rates and maximum time of use have to be specified. Positive balancing power means that a balancing service provider commits itself to increase generation if this is demanded by the TSO; offering negative balancing power, generation would be decreased. Also on the demand side, balancing services can be provided; here, positive balancing power corresponds to a decrease of consumption and negative balancing power to an increase of consumption.

Advantages of balancing markets for standardised balancing services include that a TSO can activate the cheapest offers within its balancing area (as long as their are no congestions that force the TSO to use more expensive offers in other parts of the balancing area instead) and that standardised balancing services can be easily exchanged with other TSOs. The latter one might play a more important role in future according to Entso-E [24].

Pricing on balancing markets differs. Some countries use pay-as-bid pricing, others use uniform pricing; uniform prices can in turn, for example, be based on marginal or on average prices. An overview on balancing markets in European countries is presented in [19, 41].

Imbalance settlement

Imbalance settlement approaches are always based on some form of generation/consumption plan. Deviations from these plans can then be accounted for and penalised. The exposure of BRPs to cost if they deviate from their committed generation/consumption levels is an important element of the design of electricity market. However, especially here, the level of harmonisation within the European countries is low as a recent survey from Entso-E shows [19]. Common differences include the following:

- Time resolution of imbalance settlement, currently varying between 15 min and $\leq$ 1 h.
- Exemptions from imbalance costs for certain types of generation, e.g. renewable energy sources or power plants that also provide balancing services. Exemptions can also apply to power plants with installed capacity below a specified level.
- Some countries calculate separate imbalances for generation and consumption, others one combined imbalance per BRP.
- Production/consumption plans differ in their level of aggregation. In some countries BRPs are required to submit one plan while other countries require BRPs to disaggregate the schedules, for example, depending on the type of power plant.
- Not all countries require all consumption to be included in consumption plans. This is, for example, the case in the Nordic countries as it will be briefly described in Section 2.4.3 and discussed more in detail in Section 4.2.
- Pricing of imbalances is based on different underlying prices, for example, on marginal or average prices of day-ahead, intraday or balancing markets.

Table 2.1: Example: Imbalance costs of a market participant in the Nordic countries. Here, either the day-ahead price p_{da}, the up-regulation price p_{up} or the down-regulation price p_{down} is applied to financially settle the imbalance energy E. Prices in red are less beneficial to the market participant while prices in green are more beneficial than the day-ahead price. Table also used in ☞[P8, Table 4].

(a) Two-price system.

	System: up-regulation	System: no regulation	System: down-regulation
Own deficit	Pay $p_{\mathrm{up}} \cdot E_{\mathrm{deficit}}$	Pay $p_{\mathrm{da}} \cdot E_{\mathrm{deficit}}$	Pay $p_{\mathrm{da}} \cdot E_{\mathrm{deficit}}$
Own excess	Receive $p_{\mathrm{da}} \cdot E_{\mathrm{excess}}$	Receive $p_{\mathrm{da}} \cdot E_{\mathrm{excess}}$	Receive $p_{\mathrm{down}} \cdot E_{\mathrm{excess}}$

(b) One-price system.

	System: up-regulation	System: no regulation	System: down-regulation
Own deficit	Pay $p_{\mathrm{up}} \cdot E_{\mathrm{deficit}}$	Pay $p_{\mathrm{da}} \cdot E_{\mathrm{deficit}}$	Pay $p_{\mathrm{down}} \cdot E_{\mathrm{deficit}}$
Own excess	Receive $p_{\mathrm{up}} \cdot E_{\mathrm{excess}}$	Receive $p_{\mathrm{da}} \cdot E_{\mathrm{excess}}$	Receive $p_{\mathrm{down}} \cdot E_{\mathrm{excess}}$

- Application of one- or two-price imbalance settlement systems. In one-price systems, the price at which imbalances are settled usually differs if the BRP has a positive (more supply or less demand than planned) or a negative imbalance (less supply or more demand than planned). In two-price systems, the price also depends on whether a BRP's imbalance has – on average and with respect to time resolution of the imbalance settlement - facilitated or hampered system balancing. Table 2.1 shows the one- and two-price systems that are applied for imbalance settlement in the Nordic countries. Two price systems offer an incentive for market participants to submit production/consumption plans according to their expected generation/consumption because they can never profit from having imbalances. In contrast to that, market participants under a two-price system can realise profits from having imbalances that mitigated the system's need for balancing services. Therefore, these can offer room for strategic behaviour. In [42], it is illustrated that a rational behaving wind power producer would submit different production plans depending on the applied pricing system: in a the two-price system, these plans would reflect the expected generation, but in a one price system the plans would either differ from the expected levels in order to sell the own imbalance volume at a price higher than the day-ahead market price if the system is needs positive balancing power and to buy the own imbalance volume at a price below the day-ahead market price if the system needs negative balancing power (highlighted in green in Table 2.1(b)).

In total, these differences explain why incentives from imbalance settlement rules can be larger or smaller. In [19, page 113], it is also mapped in which countries there is at least a small incentives for BRPs to achieve balanced positions; only in about two thirds of all ENTSO-E member countries, the answer was positive. This indicates room for improvement. To get more insights into how BRP facilitate system balancing, it would be interesting to also pose the question whether there is an incentive for BRPs to minimise deviations from their binding generation/ consumption plans.

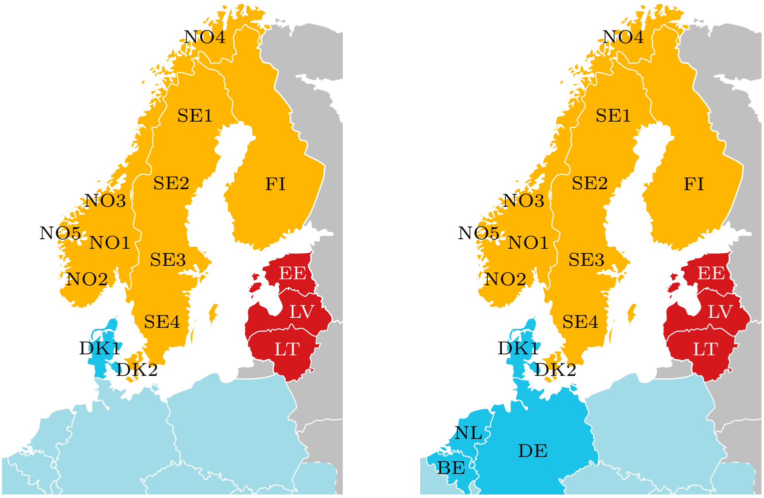
2.4.2 Functions

Markets can fulfil different functions; however, their central function is to yield a cost-efficient allocation of resources. This intrinsic characteristic of perfect markets results from the allocation process as outlined before in in the section on day-ahead markets. It is a way of taking advantage of the market participants' ambition to maximise their profits: market participants that state a price that differs from their true willingness-to-sell/-buy risk not to get their energy sold or purchased, respectively. As a result, all market participants state prices very close to their true willingness-to-sell/-buy and social welfare, i.e. the sum of the products of each traded volume and the difference between market clearing price and willingness-to-sell/-buy, is maximised. Adam Smith described this phenomenon already in the 18^{th} century as the *invisible hand* of a market [43]; it holds, however, only for markets that are regarded as *perfect* markets, i.e. as markets with perfect competition. Abuse of market power, entry and exit barriers, cost characteristics of natural monopolies etc. will hamper the function of the market's invisible hand, see [32, Section 3.2.1] for a very concise discussion to which extent electricity markets qualify/disqualify as perfect markets.

In addition to its allocative function, all market participants have an incentive to reduce their decision relevant costs, i.e. those costs that are variable with regard to the trading decision; in case of sellers on day-ahead markets for electricity, that would be the variable generation cost or, more specific, the marginal generation cost which shows the additional cost to also generate the volume of the bid. This way, markets also incentivise efficiency in production [28].

Besides their allocative and cost-reducing functions regarding energy, day-ahead and intraday markets can also be designed to allocate transmission capacity. However, this requires that day-ahead and intraday markets are divided into different price zones or price nodes. The reasons is that only transmission limits between price zones or price nodes can be included because the market uses price differences to prevent congestion. Other possibilities to allocate scarce transmission capacity include explicit auctions for transmission capacity, but implicit auctioning of transmission capacity (i.e. along with day-ahead and intraday energy trading) is regarded as more efficient and should be applied for day-ahead and intraday trading [31, Article 1(1)].

Finally, day-ahead and intraday electricity markets are also an important instrument to facilitate system operation because the market results provide information about the power system's situation for the coming day; for example, total expected generation and consumption levels for each trading period. The same holds for



(a) Day-ahead market ELSPOT (b) Intraday market ELBAS

Figure 2.3: Price zones and participating countries on ELSPOT and ELBAS within the Nordic (■), Baltic (■), and Continental European (■) synchronous area of the European electric power system as of April 2015. Political map based on [39]. Figure (b) also used in ☞[P8, Figure 2].

production/consumption plans which allow the TSO to estimate to which degree balancing resources are already utilised [44].

2.4.3 Nordic countries, especially Sweden

The day-ahead market ELSPOT comprises all countries within the Nordic synchronous area of the European power system plus the countries in the Baltic synchronous area. Also western Denmark, which is part of the Continental European synchronous area, uses ELSPOT, see Figure 2.3(a). The market is cleared at 12:00, trading periods have hourly resolution, prices for bids and offers are currently allowed to range between −500 EUR/MWh and 3 000 EUR/MWh [45]. Available transmission capacity between the price zones is auctioned implicitly. More details are described in ☞[P5, Section 2].

For intraday trading, market participants in the Nordic as well as the Baltic countries plus the Netherlands and Belgium use ELBAS. It is also open to market participants in Germany, see Figure 2.3(b). ELBAS is organised as a platform for continuous trading; trading is done for hourly periods of delivery and trading is possible until one hour before the start of the each hour of delivery [46]. Transmission capacity that is still available after closure of the day-ahead market ELSPOT is implicitly auctioned on ELBAS.

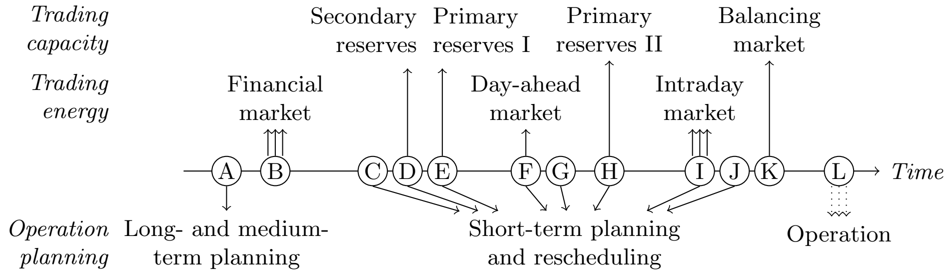


Figure 2.4: Decision points of power generating companies in the Nordic electricity market. Single arrows mark points where discrete decisions are taken, while several arrows represent a continuous decision process. Figure also used in ☞[P5, Figure 3].

The procurement of balancing services differs slightly between the Nordic countries. Regarding restoration reserves, all Nordic TSOs have merged their balancing areas into one where they use a joint balancing market. This includes western Denmark, but none of the other countries participating in ELSPOT or ELBAS. In contrast to several other countries, offers to the balancing market can be submitted until 45 min before the hour of delivery.

The resulting sequence of decision steps for a market participant on the Nordic electricity market is illustrated in Figure 2.4. In addition, also bilateral financial trading as well as bilateral day-ahead and intraday trading are possible, For details on the procurement of frequency containment reserves and frequency restoration reserves, see ☞[P5, Section 2].

The imbalance settlement is done separately for production and consumption imbalances of each BRP. BRPs can update their plans until 45 min before the start of the hour of delivery. In Sweden, these plans are submitted by the BRPs for each individual large and medium sized power plant, while small power plants that are of the same type (hydro power, wind power, combined heat and power etc.) and within the same price zone can be aggregated in one plan. Total installed capacity of power plants in such an aggregated plan may be up to 250 MW. Generation plans for large and medium sized power plants have a resolution of 15 min while those of smaller power plants are in hourly resolution [44, 47].

For consumption, aggregated plans are only required for larger industry consumers ($>$ 50 MW rated power) and consumption units where the owner has agreed that these units can be disconnected from the grid. Consumption plans have hourly time resolution [44, 47].

According to the balance agreement with the Swedish TSO [47], BRPs are neither allowed to deliberately deviate from their binding production plans nor to systematically have large imbalances. This adds a legal obligation to the imbalance settlement system and implies that BRPs should follow the binding generation/

consumption plans. In other words, from 45 min before the hour of delivery until the end of the hour of delivery, BRPs have no possibility of balancing generation except for those smaller power plants for which production plans have been reported in an aggregated manner.

2.5 Summary and outlook

Central elements of electricity market design (day-ahead, intraday and balancing markets as well as the imbalance settlement) fulfil allocative and cost-reducing functions and are important instruments to keep generation and consumption balanced in power systems. This chapter focused on describing how electricity markets coordinate production planning of power generating companies with balancing actions of TSOs. Of course, electricity markets fulfil similar functions also for the consumption side.

The following three chapters will first introduce to wind power variability and uncertainty as important sources of balancing needs. Then, it is investigated to which extent the role of BRPs can facilitate system balancing focusing on central decision steps of power generating companies on the Nordic electricity market.

Chapter 3

Wind power generation in Sweden

Market participants on competitive electricity markets use various tools and methods to optimise their production plans, to forecast wind power generation, to determine optimal bidding strategies etc. In a similar manner, TSOs use tools and methods, for example to procure a sufficient amount of balancing reserves. Many of those models and tools represent uncertainty and variability of wind power generation in the one or the other way. This holds also for studies on electricity markets and power systems as such, for example, studies on wind power integration costs.

It can appear tempting to represent wind power characteristics in different countries in similar ways. But to which extent is this appropriate? I.e. to which extent differ characteristics such as wind power variations and forecast accuracy between regions? Here, this chapter tries to contribute. First, by some studies on wind power generation in Sweden that have been done together with the IEA Wind Task 25 *working group and which investigate the following characteristics: geographic dispersion, hourly variations of wind generation, impact of wind generation levels on net-load, accuracy of wind power forecasts as well as characteristics of the distribution of wind power forecast errors. Second, the findings are discussed in context with results from other countries in order to compare characteristics of wind power generation ☞[P2, P6, P7].*

3.1 Overview of the studies

Three different studies with the IEA Wind Task 25 working group have been done in this PhD project. At first, wind power forecast errors have been studied. Input were hourly wind power forecasts from Svenska kraftnät, the Swedish TSO. Svenska kraftnät calculated these forecasts in a day-ahead time-frame. In the analysis, these forecasts have been compared to observed generation. Then, forecast errors were normalised by installed wind capacity to allow comparisons between different price zones in Sweden as well as between different countries. The results contributed to ☞[P2] which shows that wind power forecast errors are not well described by normal/Gaussian distributions. This analysis has been described in my licentiate thesis [48, Section 3.2].

Next, variations between wind generation levels in preceding hours – so-called *ramps* or *ramp rates* – have been analysed. Input were hourly levels of wind generation and load. They were normalised by installed wind capacity and peak load, respectively. Results for the year 2011 are presented in my licentiate thesis [48, Section 3.1].

Finally, for ☞[P6, P7], data series on ramp rates have been extended to cover the years 2007–2013.

In the following sections, central areas of all three analyses are briefly presented and discussed.

3.2 Installed capacity

In all three studies, observed and forecast wind power generation has been normalised by installed wind power capacity in order to be able to compare both ramp rates and forecast errors between different countries or in different price zones as, for example, in case of Sweden. In practice, that means that hourly wind power generation *levels* (wind power generation in % of installed wind power capacity), hourly normalised ramp rates in % of installed wind power capacity and hourly normalised forecast errors in % of installed wind power capacity have been calculated. However, the installed capacity can only be estimated. This holds both on an hourly basis as well as on a yearly basis. Overestimation of installed capacity implies smaller generation levels, smaller normalised ramp rates and smaller normalised forecast errors than in reality. Underestimation will artificially increase generation levels, normalised ramp rates and normalised forecast errors.

In Sweden, there are two available sources for data on installed wind capacity: information from Energimyndigheten on the Swedish/Norwegian certificate system for renewable energy and information from the industry association Svensk Vindenergi[1]. Differences between estimations based on these two sources are in the magnitude of 10 %.

While data from Svensk Vindenergi is based on the order books of manufacturers of wind power plants [49], data from Energimyndigheten includes those wind power plants that are registered in the certificate system. Because not all power plants that have been sold have already been commissioned, Svensk Vindenergi overestimated installed capacity. However, estimating installed capacity based on power plants registered in the certificate system is neither fully accurate. The certificate system tends to underestimate installed wind power capacity due to the following reasons:

- It is not mandatory to register wind power plants in the certificate system. However, all owners have a financial benefit from participating in that system.

[1] Svensk Vindenergi is providing its data to the European Wind Energy Association (EWEA) and the Global Wind Energy Council (GWEC).

Table 3.1: Estimated installed wind power capacity in Sweden. All values in MW. Data from ENERGIMYNDIGHETEN's statistics on the certificate system [50, 51]. The values on old power plants phased out from the certificate system in 2015 are preliminary. SE1–SE4 refer to the Swedish price zones, see Figure 2.3 for a map.

Price zone	Registered 18 Apr, 2015	Phased out 1 Jan, 2013	Phased out 1 Jan, 2015	Sum
SE1	482	1	7	489
SE2	1 608	3	20	1 631
SE3	1 712	67	79	1 858
SE4	1 252	56	120	1 428
Sum	5 054	127	226	5 406

Therefore, it is assumed that owners strive to registered their wind power plants in the certificate system.

- Some power plants might not fulfil the necessary requirements, e.g. wind power plants without hourly measurement of generated energy are excluded from the certificate system [9]. Their number cannot be quantified here, but it is assumed to be negligible.
- There is no register of wind power plants that stopped receiving certificates because they have been dismantled. They simply do not appear in future updates of the list of power plants that receive certificates, but these missing entries can hardly be identified.

In all three studies, it was chosen to base the estimation on those wind power plants that receive certificates for renewable energy generation within the Swedish/Norwegian green certificate system or that have received those certificates in the past, see Table 3.1 Power plants that existed already before introduction of the certificate system in May 2003 have been phased out at the beginnings of 2013 and 2015 [8]. Therefore, these values are added to the currently registered capacity. By April 2015, installed wind power capacity is expected to amount to approximately 5 400 MW in Sweden. Compared with the beginning of 2012, this is an increase by 100 %.

As mentioned before, capacity time series had to be estimated. This implies that newly installed capacity had to be accounted for during each year. Here, the certificate system's information on installed capacity per new wind park as well as its first day and last day of commissioning has been used. While some wind parks have been commissioned during a single day, others have been commissioned during a period of time. Accounting of newly installed capacity is simplified: in my licentiate thesis [48], total installed capacity was simply assumed to rise linearly between 1 January, 2011 and 31 December, 2011. To reduce the risk of over- and underestimation in the analysis presented in publications ☞[P6, P7], new generation was accounted for more in detail: here, 50 % of the newly installed

Table 3.2: Estimates of installed generation (all values in MW) based on information on the Swedish/Norwegian certificate system [50] and according to industry associations [52]. To the values marked by an asterisk, 127 MW of capacity should be added due to phase-out from the certificate system, cf. Table 3.1.

Time	Energimyndigheten		Used in	Industri
	100 % at start	50 % at start, then linear	☞[P6, P7]	associations
End 2006	480	459	559	571
End 2007	717	704	804	788
End 2008	977	970	1 070	1 021
End 2009	1 346	1 339	1 439	1 560
End 2010	1 887	1 875	1 975	2 163
End 2011	2 640	2 632	2 732	2 899
End 2012	3 514	3 470	3 570	3 746
End 2013	*4 069	*4 052	4 152	4 470

capacity of power plants which were commissioned during a period of time was assumed to be installed on the first day; then, installed capacity is increased linearly day-by-day until 100 % is reached on the last day. Also other ways, for example, 100 % at start, have been tested; the differences were only small, see Table 3.2. Even when accounting for capacity that was phased out from the certificate system – which was neither accounted for in the licentiate thesis [P5], nor in publications ☞[P6, P7] – installed capacity is lower than the one stated by the Swedish wind energy association Svensk Vindenergi. Therefore and due to harmonisation with a similar study of Norwegian wind variations, we increased the start estimate for the capacity time series at the end of 2006 by 100 MW. This might lead to possible overestimations until 2009 and possible underestimation after 2009 instead of a possible underestimation in all years.

3.3 Geographic dispersion

Variability and forecast accuracy of wind power generation exhibit different magnitudes depending on the extent to which wind power plants are distributed over a geographic area as well as the total size of that area. Within a larger area, it is more likely that weather regimes vary than in a small area. If wind power plants are more dispersed, it is more likely that turbines at different sites are simultaneously experiencing different wind conditions. In other words, correlation of wind generation at different sites decreases the more these sites are distributed over a larger geographic area [54]. For balancing, this implies that wind variations tends to be less challenging to handle the same wind power penetration level. This is a central argument in favour of large balancing areas.

Because this important characteristic is clearly observed when studying variations and forecast errors of wind power generation in Sweden geographical dispersion is illustrated in Figure 3.1. On that map, installed wind power capacity is shown in relation to the land area of each municipality; that means on a more detailed level than per price zone. Here, municipalities are the most detailed level to which data on the Swedish/Norwegian certificate system could be disaggregated in a reliable manner[2]. For comparison, the average of installed wind power capacity for the whole country is $12\,\mathrm{kW/km^2}$, for Denmark and Germany around $110\,\mathrm{kW/km^2}$, for the Netherlands and Belgium around $65\,\mathrm{kW/m^2}$ and for Estonia, Norway and Finland around $5\,\mathrm{kW/km^2}$; all these values are based on total area including inland waters; data from [55, Code tgs00002] and [56].

Even though the map shows several areas of more intense wind power deployment as well as areas of little wind power deployment, installed capacity can be regarded as well dispersed, which is also done in ☞[P2, P6, P7].

3.4 Wind power ramp rates

Magnitude and frequency of wind power ramp rates directly affect system operation. Here, it should be recalled that variations in time scales which are smaller than the periods of delivery for which electricity is traded have to be handled by the TSO in real-time; for example, market participants cannot reduce expected sub-hourly variations by trading on markets with hourly time resolution.

Figure 3.2 shows the size of hourly ramps in relation to installed wind power capacity as presented in the licentiate thesis [48]. Here, it can be seen that the spread between maximum up- and down-ramp is strongly reduced when aggregating variations over the whole country. The same holds for standard deviation σ. Therefore, tails of the distribution for the whole country are shorter and less pronounced as compared to the distributions for each individual price zone.

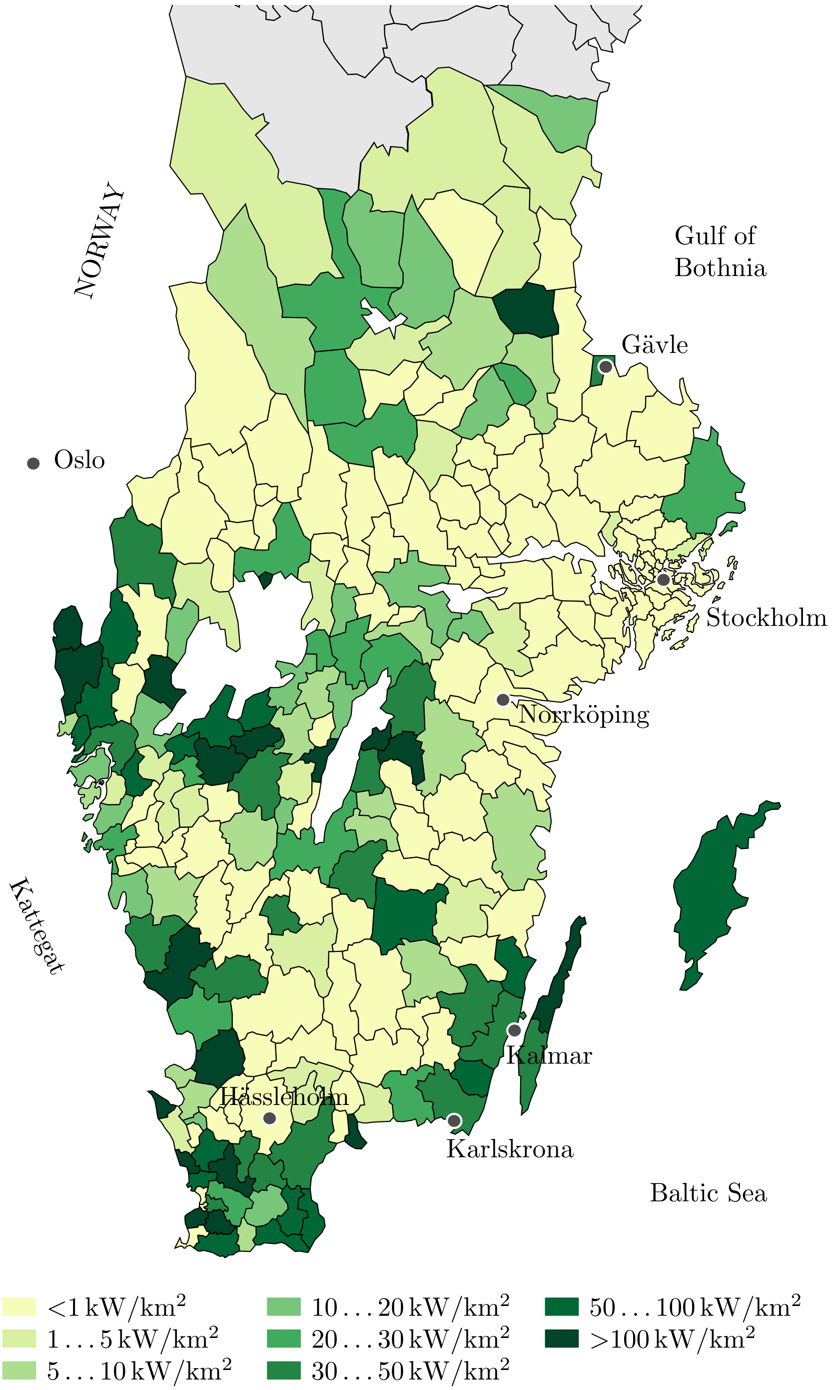
For Sweden, most ramp rates are small (half of all observed variations are within the intra-quartile range of $\pm$ 1.15 %). In comparison with other Nordic countries, also the number of larger hourly variations (tails of the distributions) is comparatively small which is explained by a high level of geographic dispersion over a large area ☞[P7].

In order to quickly assess variability and to test several factors that might be correlated to variability, we suggest an index in manuscript ☞[P7]. This index $I_{\text{variability}}$ is meant to serve as an estimate as contrasted to thorough wind integration studies. It is calculated in the following way:

$$I_{\text{variability}} = \frac{\sum_{\delta \in \{1\text{h},4\text{h},12\text{h}\}} \sum_{\alpha \in \{1\sigma, 0.96, 4\sigma\}} w(\delta,\alpha)\, Q_{\alpha,\delta}}{\sum_{\delta \in \{1\text{h},4\text{h},12\text{h}\}} \sum_{\alpha \in \{1\sigma, 0.96, 4\sigma\}} w(\delta,\alpha)}, \tag{3.1}$$

where $w(\delta,\alpha)$ are weights, σ is the standard deviation of the frequency distribution of ramp rates with time resolution δ and $Q_{\alpha,\delta}$ is the α-quantile of that frequency

[2]Data sources [50, 51] also specify locations, e.g. villages or towns, but this is not done in a concise manner. For example, locations are often set equal to municipalities which does not provide any additional value. In addition, typos in names of locations obstruct automatised geocoding.


NORWAY
Gulf of
Bothnia
Gävle
Oslo
Stockholm
Norrköping
Kattegat
Kalmar
Hässleholm
Karlskrona
Baltic Sea
<1 kW/km²
1 . . . 5 kW/km²
5 . . . 10 kW/km²
10 . . . 20 kW/km²
20 . . . 30 kW/km²
30 . . . 50 kW/km²
50 . . . 100 kW/km²
>100 kW/km²

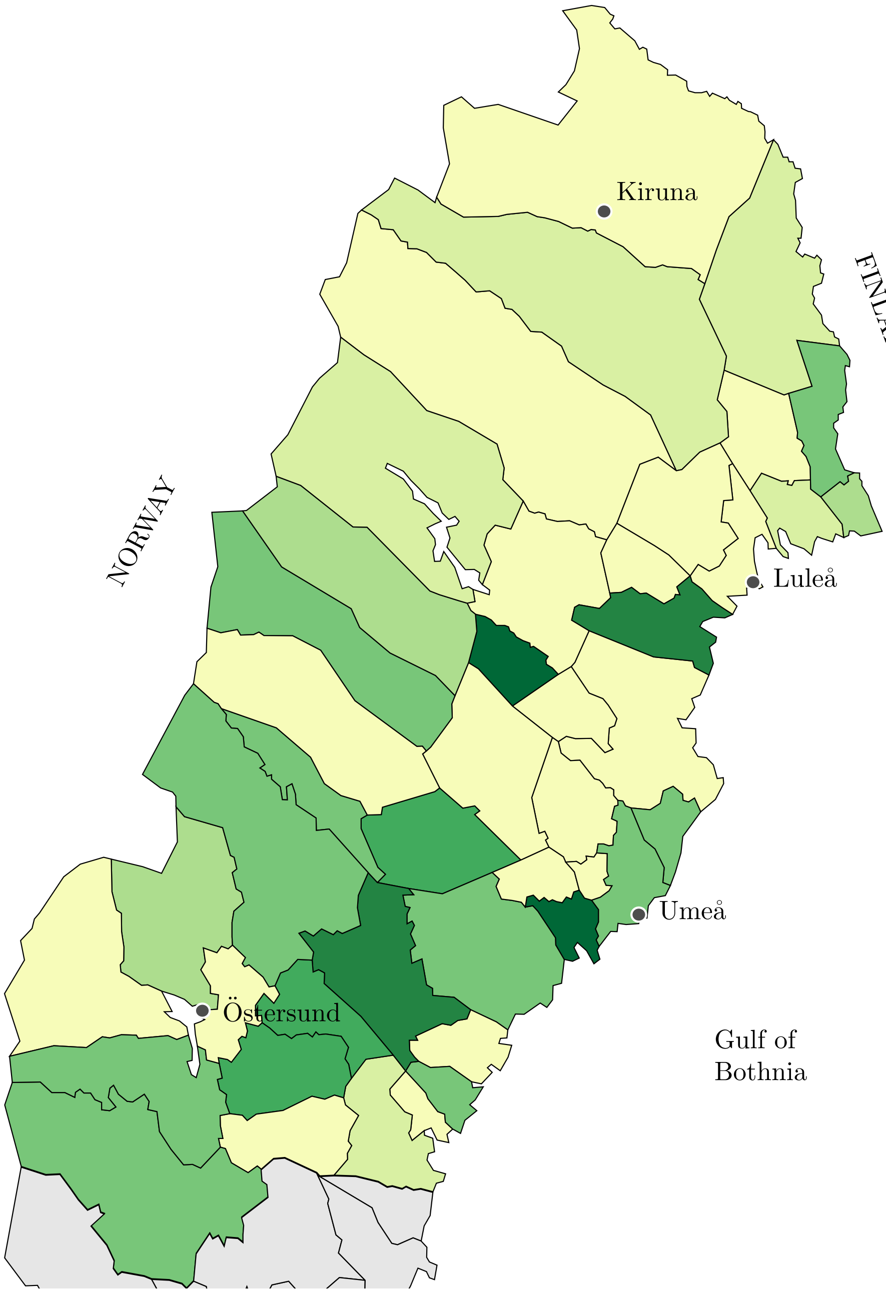
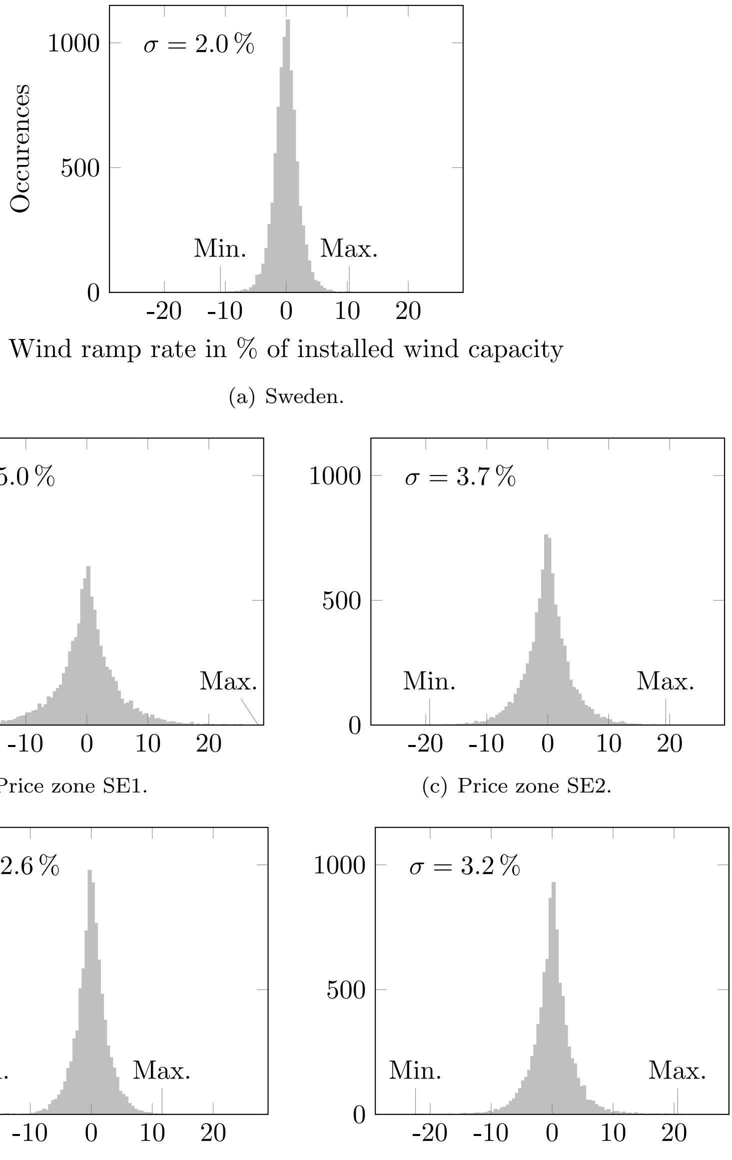


Figure 3.1: Geographical distribution of installed wind power capacity in Sweden by 18 April, 2015. The map shows installed capacity per land area for each municipality. Intervals as $[a, b)$, i.e. including the first value and excluding the last. Data compiled from [50]. Map of administrative borders based on [53].



(a) Sweden.

(b) Price zone SE1.

(c) Price zone SE2.

(d) Price zone SE3.

(e) Price zone SE4.

Figure 3.2: Frequency distribution of normalised wind power ramp rates in Sweden and their standard deviation σ. Figure also used in my licentiate thesis [48, Figure 3.3].

distribution. Differently said, $Q_{\alpha,\delta}$ equals the number of δ-ramps, e.g. one hour ramps, that do not exceed the chosen level α. For example, a 96 % quantile shows the level that 96 % of all ramps do not exceed. In article ☞[P6], different weights $w_{\alpha,\delta}$ and different sets for α and δ have been tested in order to test how sensitive the index behaves to these weights and sets. As a result, it was found that most tested combinations lead to similar values of the index. Therefore, it was chosen for ☞[P7], to include ramp durations of one, four and twelve hours and exceedance levels of one standard deviation, 96 % and four standard deviations as well as to weight all quantiles uniformly with $w(\delta, \alpha) = 1$. Uniform weights are a practical choice in connection with sets of exceedance levels and duration of ramp rates that both can be regarded as meaningful from the perspective of system operation.

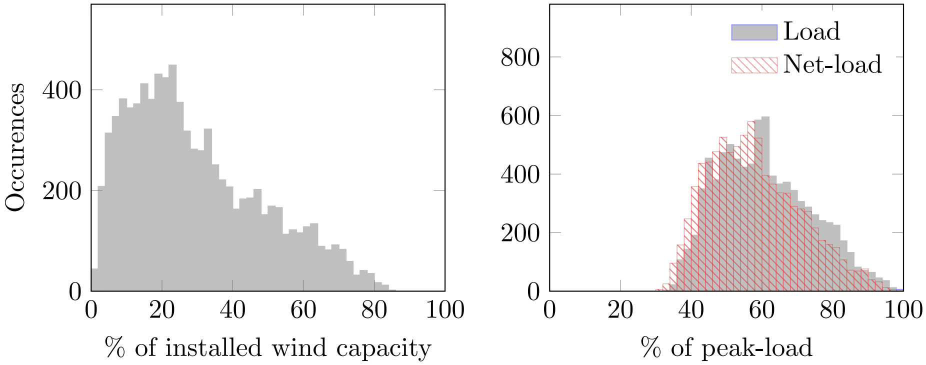
As seen before, most hourly variations in Sweden are small and large variations do not occur often. However, for system balancing, both types are important because the system has to be able to handle large variations also if they only rarely occur. In addition, different lengths of time periods are considered because short-term variations and long-term variations can be handled by different forms of balancing services. Regarding the Nordic countries, the variability index is highest for Denmark and Norway and lowest for Sweden.

Finally, it is investigated to which extent the suggested variability index is correlated to energy penetration levels of wind power (no correlation observed), to annual wind generation in % of installed capacity (no correlation for Sweden, partly different for other countries) and to an indicator for geographic dispersion (clear negative correlation between geographic dispersion and variability index). It is interesting that no correlation was found between variability and wind energy penetration level. For the case of Sweden where installed wind power capacity has significantly increased between 2007 and 2013, this might emphasize that installed capacity is well-dispersed.

3.5 Effects on net load

In Sweden, generation from wind power is increasing. During 2011, maximum hourly wind generation amounted to 2 287 MWh/h; at maximum, wind power contributed to cover 18 % of hourly peak load. For 2014, the corresponding values have increased: maximum hourly wind generation reached 4 663 MWh/h and at maximum, wind power contributed to cover 37 % of hourly peak load [57]. As outlined briefly in Section 1.1, this effects the market's merit order. Therefore, current and future effects of wind power generation on net-load have been studied in the licentiate thesis [48] and ☞[P7].

Figure 3.3 shows frequency distributions of wind generation, load and net-load. It illustrates that wind generation during 2011 decreased net-load (the mean of the net-load distribution is smaller than the mean of the load distribution) as well as that it increased the spread (the spread of the net-load distribution is larger than the spread of the load distribution). Statistical parameters of all three distributions



(a) Wind generation. (b) Load and net-load.

Figure 3.3: Frequency distribution of wind generation, load and net-load levels in Sweden. Figure also used in my licentiate thesis [48, Figures 3.1 (a) and 3.2 (a)].

Table 3.3: Statistical parameters of the presented frequency distributions. Compiled from [48, Tables 3.2–3.4].

Distribution	Spread	Mean	Standard dev.	1st quartile	3rd quartile
Wind generation	0.8419	0.2964	0.1886	0.1472	0.4231
Load	0.6690	0.6072	0.1322	0.5025	0.6990
Net-load	0.6816	0.5781	0.1299	0.4779	0.6658

are listed in Table 3.3. An interesting detail is that standard deviation of the net-load distribution is slightly below the one of the load distribution. This indicates that generation levels in the region close to the mean tend to occur more frequently. At the same time, also more extreme generation levels in the tails occur more often (spread increases).

In ☞[P7], observed generation levels are scaled up to simulate the effects on frequency distribution of net-load for increasing wind penetration levels. In the manuscript, focus is on hours where net-load becomes small. Figure 3.4 illustrates at what time of the day as well as during which period of the year hours with net-loads smaller than 25 % of the systems peak load would occur if wind penetration levels would increase to cover 30 % of annual consumption. For Sweden and Finland, the patterns are similar indicating that most hours of low net-load would be during night. In Sweden, electric heating (heat pumps and direct electric heating) plays an important role [58] and in 2012, the coldest months were February and December [59]. Together, this explains why there are hardly any hours with low net-loads during these two months.

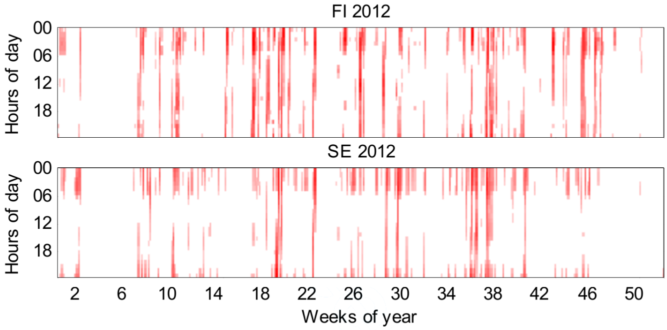


Figure 3.4: Simulation indicating hours in which net-load would be below 25 % of peak load if wind energy penetration levels would increase to 30 % of annual consumption. Figure shows selected parts of ☞ [P7, Figure 13].

3.6 Wind power forecasts errors

Perfectly accurate wind power forecasts would always exactly correspond to generation during the period for which the forecast was made. In reality, wind power forecasts can be accurate, but there is a probability $\gg 0$ that they either over- or underestimate generation. Absolute forecast errors are defined as the difference between forecast generation and observed generation. Positive forecast errors imply that generation was overestimated.

In order to facilitate comparison of forecast errors between different areas and countries, absolute forecast errors can be normalised by installed capacity of wind power plants in each area/country:

$$\epsilon_{\text{norm}}(t) = \frac{x_{\text{forecast}}(t) - x_{\text{observation}}(t)}{P_{\text{wind,inst}}(t)}, \tag{3.2}$$

where $P_{\text{wind,inst}}(t)$ is the installed capacity of wind power plants during hour t.

For Sweden, distributions of forecast errors are described in the licentiate thesis [48, Section 3.2.3] and plotted also here in Figure 3.5. The dashed curve represents a fitted normal distribution to each of the observed distributions. Calculating quantiles, one can observe that 80 % of all forecast errors range between −10.1 % and 7.5 % of installed wind power capacity. Comparing forecast errors of wind power generation per price zone with aggregated forecast errors for the whole of Sweden, significant smoothing effects due to geographic dispersion are visible. In combination with the statistical parameters, one can see that spread and standard deviation are reduced.

An interesting detail is that even though systematic errors (reflected by a mean $\mu \neq 0$) are negligible, all distributions are asymmetric; on the one hand small positive forecast errors occur more often than small negative forecast errors. This

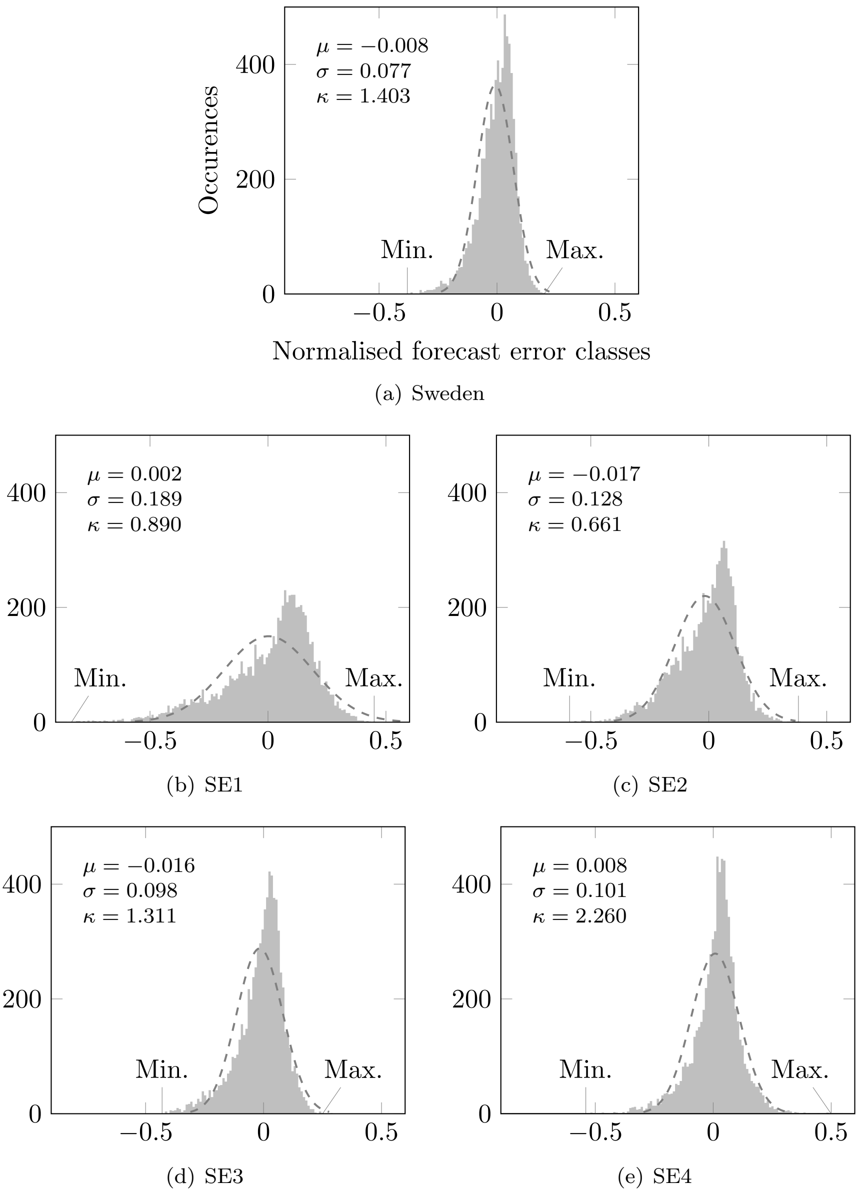


Figure 3.5: Distribution of wind power forecast errors in Sweden and selected statistical parameters: mean μ, standard deviation σ and excess kurtosis κ. The dashed line shows fitted normal distributions. Figure also used in my licentiate thesis [48, Figure 3.3].

means that forecasts often tend to slightly overestimate generation. On the other hand, large negative forecast errors are more frequent than large positive forecast errors, even though large forecast errors occur only rarely. These characteristics should be regarded when modelling forecast errors.

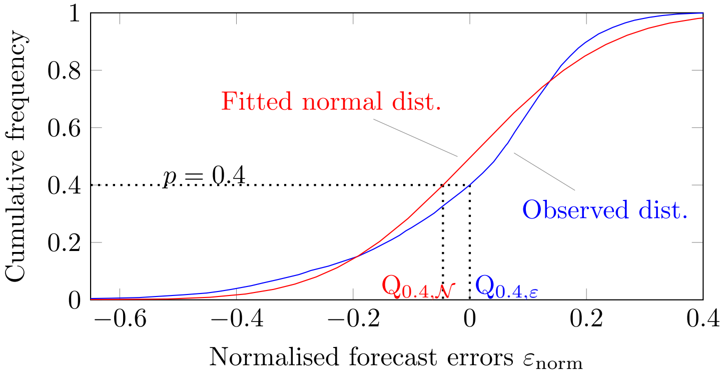
An interesting parameter is the excess kurtosis κ which describes to which extent the peak of a distribution is more or less pronounced than the one of a fitted normal distribution. If the excess kurtosis exceeds 1, the peak is more pronounced. For Sweden, the plotted distributions and the κ values show that a fitted normal distribution does not well describe the observed forecast errors. In article ☞[P2] it is shown that this also hold for other countries even though it is common practice to estimate wind power forecast errors to be normal distributed. In the article, also frequency distributions, cumulative density functions and quantile-quantile plots (Q-Q plots) are used to visualise the differences between observed and fitted distributions.

In Q-Q plots, quantiles of the observed forecast error distribution are plotted against quantiles of the fitted distribution, in our case a fitted normal distribution. Figure 3.6 illustrates the construction of a Q-Q plot for wind power forecast errors in SE1. Here, SE1 was chosen because in this price zone the distribution of forecast errors exhibits a comparatively long left tail. To construct the Q-Q plot in (b), many pairs of quantiles are calculated for both the observed distribution and the fitted distribution. For example, as illustrated in (a), the 40 % quantiles $Q_{0.4,\epsilon}$ for the observed distribution and $Q_{0.4,\mathcal{N}}$ for the fitted normal distribution. Then, this pair of quantiles is plotted in the Q-Q plot (b). Next, this is repeated for other quantiles. The closer the resulting curve in the Q-Q plot becomes towards a straight line, the better the fitted distribution describes the observed one. The main advantage of Q-Q plots is that they are very suitable to visualise differences in the tail regions of distributions because in these regions, quantiles vary significantly between different probability levels [60].

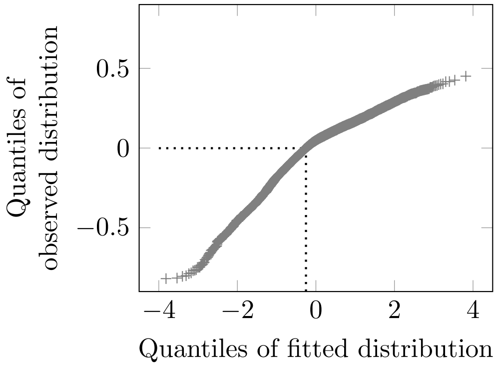
As a result of ☞[P2], it is suggested not to approximate wind power forecast errors by normal/Gaussian distributions. Instead hyperbolic distributions should be used because these fit the observed forecast error distributions better. This can, for example, be of advantage to improve accuracy of models used to calculate dynamic reserve levels or stochastic unit commitment. In general, hyperbolic distributions are better suited to fit distributions where large values occur (tails), see Figure 3.7 for Sweden. For details on how to calculate hyperbolic distributions, it is referred to literature on statistics, e.g. [61].

3.7 Open research questions

Apart from insights into wind generation in Sweden, this chapter briefly described some work that was done to compare wind power forecast errors and wind power variations of different countries and power systems. Here, the main obstacles are country-specific details that have to be regarded. Examples include different fore-



(a) Cumulative density function of the forecast error distribution in SE1



(b) Q-Q plot for SE1

Figure 3.6: Cumulative probability distribution and quantile-quantile plot for SE1. Figures also used in my licentiate thesis [48, Figure 3.10].

cast horizons of day-ahead forecasts and difficulties in estimating installed wind power capacity. In addition, issues on data quality have to be solved. For example, time series with lacking data, outliers and defective data have to be handled in a proper manner. Next, data has to be processed in the same way. Within the IEA Wind Task 25 working group, this was guaranteed by applying the same scripts when analysing the data. Last but not least, not all data is available in a similar time resolution or other level of detail.

Once, relevant data is accessible and collected as well as its quality checked, international comparisons offer many possibilities to improve understanding of the characteristics of the own power system. Usually, the value is not in finding, for example, which forecasts are more accurate and which power systems exhibit larger wind power ramps, but to provide a deeper understanding of the effects that influ-

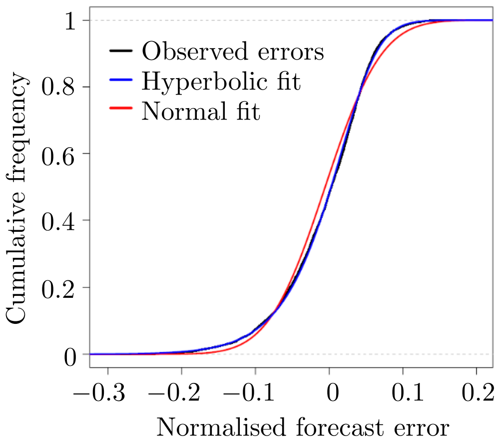


Figure 3.7: Fitting observed forecast errors with a normal distribution and a hyperbolic distribution. Cumulative density function for forecast error distribution in Sweden. Figure also used in ☞[P2, Figure 6].

ence forecast accuracy and variability of wind power generation.

One suggestion for further research on the areas of wind power variability and uncertainty, would be to build upon the presented studies and to assess forecast errors and wind power variations not for single countries, but combined for the Nordic power system. A research question could be to quantify wind power variations in the whole Nordic balancing area. Scaling observed wind generation data to simulate larger wind power penetration levels in future, one could identify transmission corridors that will become congested and assess to which extent wind power can be integrated into the joint Nordic balancing area based on technical characteristics of nowadays power system.

Chapter 4

Ex-ante self-balancing

Accuracy of wind power forecasts increases the shorter the forecast horizon. Therefore, forecasts with different forecast horizons, e.g. a day-ahead forecast and a two-hours-ahead forecast, differ. Several instruments exist to handle these differences already before the period of delivery. One is to expose market participants to imbalance costs if their observed generation level deviates from their planned generation level. This provides a financial incentive to update production plans based on the latest forecasts. In addition, one can implement incentives to stimulate market participants to have balanced positions in line with their updated generation forecast, i.e. to have no difference between their commitments (stemming from trades) and their scheduled generation. Both can lead to a lower need for activated balancing services during the period of delivery. Therefore, this chapter discusses to which degree balancing responsibilities can be distributed and which options market participants have to efficiently reduce their imbalances.

4.1 Why distribute balancing responsibilities?

Uncertainties related to production, consumption, transmission, import/export and distribution are the main reason for imbalances between generation and consumption in real-time. In competitive electricity markets, these uncertainties affect the market participants' trading decisions and, hence, their commitments.

Another reason for balancing needs stems from the design of day-ahead and intraday markets: on both markets, energy is traded for delivery during a certain period. Power systems, however, have to be in balance at every instant. This implies that even if all market participants would fully fulfil their day-ahead and intraday commitments, the TSOs would still face uncertainties regarding how generation and consumption varies within the period of delivery.

All balancing actions come at a cost: either some power plants have to increase or decrease their generation levels or market participants on the consumption side have to adjust their consumption. To do this, TSOs have to reimburse those market participants that provide (or offer) balancing services. For example, when the TSO needs to reduce generation within the period of delivery, it can offer balancing service providers to withdraw energy from the grid. In return, those market participants that accept this offer will reduce their generation accordingly (or increase their consumption). To remunerate this balancing service financially, the balancing service provider pays a price for the withdrawn balancing energy which is below the day-ahead price. Therefore, the balancing service provider can reduce its variable generation costs.

Besides reduced or increased variable generation costs, balancing service providers also face extra costs that stems from rescheduling; for example, due to deviations from the optimal generation/consumption plan that was computed day-ahead. This can imply running at lower efficiency or ramping up and down within the same hour to provide balancing power within shorter time periods which might increase wear-and-tear. But rescheduling generation/consumption for one hour can also affect generation/consumption schedules in preceding and following hours due to limited ramp rates, start/stop constraints or other constraints that again lead to deviations from the originally optimal generation/consumption plan for those hours. In addition, staff is needed if balancing services are manually activated by the TSO.

The later in time decisions are taken, the less freedom can be expected in the corresponding optimisation problems: if a market participant wants to adjust generation of a power plant in hour t without changing total daily generation of that power plant, there are fewer possibilities to do so the later the decision is taken. At the same time, uncertainties decrease closer to real-time. Therefore, it can be more cost-efficient to reduce the volume of activated balancing services by adjusting production plans shortly before the period of delivery using updated information.

In electricity markets where scheduling decisions are taken individually by market participants, TSOs have no direct influence on trading and scheduling decisions. However, market participants have several possibilities to plan and trade in such a way that their trades correspond to their planned generation/consumption and that these production/consumption plans are on average close to what they actually can generate/consume during the period of delivery. Such forms of trading and rescheduling can facilitate balancing actions in real-time and are therefore investigated in this thesis.

4.2 Reducing imbalances ex-ante

The overall idea of exposing market participants to imbalance costs is to provide an incentive to improve accuracy of production and consumption planning in such a way that differences between these plans and actual generation/consumption are reduced. Here, BRPs play a central role in distributing imbalance costs on those market participants with generation/consumption. In addition, BRPs also play another important role because they are expected to have so-called *balanced* *positions* where trading corresponds to planned generation/consumption [24]. The concept of BRPs is one way to link trading with system operation. It guarantees that trades on day-ahead and intraday markets are connected to physical injection and withdrawal of energy during the period of delivery. Another possible way would be to calculate imbalances not based on final production and consumption plans, but based on trades only.

BRPs have several opportunities to balance their positions: first, by well-done production planning at the day-ahead stage; here, production plans used for bidding decisions should be based on day-ahead forecasts of sufficiently good quality. Second, intraday trading allows to adjust positions according to updated forecasts. Third, rescheduling of own generation/consumption allows to keep the overall amount of energy constant while reacting, for example, on updated wind power forecast. Fourth, final adjustments can be made to the production/consumption plans before they become binding. Depending on the terms of the balancing agreement between TSO and BRP, these binding plans state generation and consumption in different levels of detail. After those plans become binding – which happens in the Nordic countries closely before the period of delivery, see Section 2.4.3 – BRPs are expected to follow their plans and cannot any longer adjust for new information.

Because in the Nordic countries consumption plans are not obligatory for all consumption in the Nordic countries, there arises one peculiarity with the calculation of production and consumption imbalances. As described in ☞[P8, Section 3.4], production and consumption imbalances are calculated as:

$$\text{Prod. imbalance} = \text{observed prod.} - \text{prod. plan} \tag{4.1}$$

$$\text{Cons. imbalance} = \text{prod. plan} - \text{sales} + \text{purchases} - \text{observed cons.} \tag{4.2}$$

Here, production plan refers to the binding production plan. Purchases and sales include both Elspot and Elbas trades as well as bilateral trades. In case BRPs provide balancing services, both imbalances are adjusted in such a way that the provided balancing services do not affect the BRPs' imbalances [27, 62–66].

The practical implications of the definitions in 4.1 and 4.2 are:

- All deviations between traded energy and the binding production plan will only affect the so-called consumption imbalance which then also accounts for volumes that stem from generation.
- Only deviations between the binding production plan and observed generation will be accounted for in the production imbalance.

Therefore, all efforts of BRPs to stick to their binding production plans affect the BRP's production imbalance while the consumption imbalance is affected by the degree to which BRPs succeed to achieve balanced positions before the hour of delivery.

As the two imbalances are prices differently (the production imbalance with a two-price system and the consumption imbalance with a one-price system) and as both pricing systems provide differently strong financial incentives to reduce the respective imbalance (see Section 2.4.1), a BRP in the Nordic electricity market has a financial incentive to submit production plans that are based on as accurate forecasts as possible, but no significant *financial* incentive to achieve a balanced position. However, the balancing agreement contains a legal obligation to do so [27].

In the end, this implies that costs and benefits of achieving balanced positions should – in case of the Nordic countries – be compared to the imbalance costs that would occur if only production plans would be updated but no actions would been taken to achieve balanced positions by rescheduling and intraday trading: the imbalance costs according to the Nordic *one*-price system.

4.3 Ex-ante self-balancing

4.3.1 Definition

Ex-ante self-balancing includes the following efforts of BRPs:

- All efforts to update production plans according to available information, e.g. latest wind power forecasts.
- All efforts to achieve balanced positions by the time the final production plan is submitted to the TSO; this includes adjustments in own production plans as well as intraday trading with other market participants.

Depending on *how* a balanced position is achieved, articles ☞[P3, P4] distinguish between *internal* and *external* ex-ante self-balancing: "Applying internal ex-ante self-balancing, a power generating company re-schedules its power plants in order to balance its commitments towards other market participants with the newest generation forecast. This is done shortly before the hour of delivery (ex-ante) and, in contrast to trading, only affecting the own power plants of a power generating company (internal self-balancing)" [P3]. As opposed to this, trading with other market participants to reach a balanced position, for example by intraday trading, is referred to as external ex-ante self-balancing.

4.3.2 Modelling

Planning and trading process

To simulate effects of internal ex-ante self-balancing, a model was build that compares balancing energy, the sum of all market participants' variable generation cost, and variable generation cost per power generating company. For the sake of simplicity, power generating companies are assumed to combine three roles: to be market participant on the day-ahead market, balancing service provider on the balancing market and BRP for their own generation. To represent these roles, the simulation model includes a sequence of decision making steps, see Figure 4.1. Day-ahead decisions steps as well as bidding to the balancing market are included in the same way in all three alternatives. Only the decision steps in the intraday time frame (after closure of day-ahead market and before submission of binding production

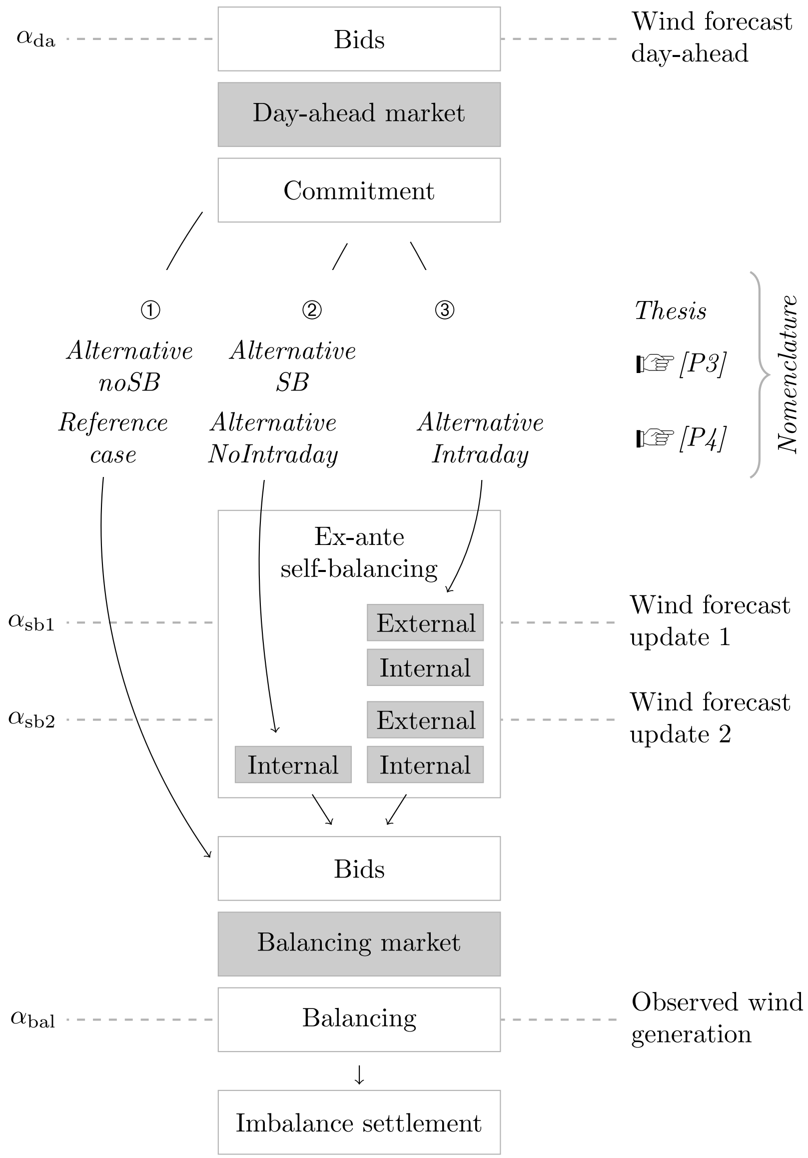


Figure 4.1: Modelling ex-ante self-balancing: an overview on the developed model. For each stage, α represents a cost factor that will be described later along with Table 4.1. Figure based on ☞[P3, Figure 1] and ☞[P4, Figure 1].

plans) differ depending on the investigated alternative. To keep the model simple, only wind power generation is assumed to be subjected to uncertainties.

In articles ☞[P3] and [P4], the some of investigated strategies are kept the same to allow for comparisons. Figure 4.1 also shows which names correspond to the same strategies. Within the thesis, I will then refer to alternatives ①, ② and ③.

At first, power generating companies bid according to their expected generation on the day-ahead market. For wind power generation, this is based on day-ahead wind power forecasts. Prices of all bids reflect variable generation costs. Based on the results of market clearing, power generating companies schedule their generation.

Closer to the hour of delivery, a first updated wind power forecast is available. This is, however, only used in alternative ③ which combines internal and external ex-ante self-balancing. Moving even closer to the hour of delivery, a second updated wind power forecast is available. This one is used in all three alternatives when deciding on bids to the balancing market. In addition, it is used for ex-ante self-balancing in those alternatives where power generating companies try to achieve balanced positions, i.e. in alternatives ② and ③.

Ex-ante self-balancing can be applied in the intraday time frame, especially at the end of this time frame closely before the final production plans are submitted. In alternative ①, power generating companies have no possibilities to trade with each other after closure of the day-ahead market. In addition, they show no efforts to achieve balanced positions: in this alternative, power generating companies are assumed to adjust their planned wind power generation according to the second updated wind power forecast, but they do not reschedule their other power plants to self-balance the deviations between the day-ahead wind power forecast and the second updated wind power forecast.

Following alternative ②, power generating companies react on the second updated wind power forecast by trying to minimise their expected imbalance volume by internal ex-ante self-balancing. This is done without considering costs and to the extent own flexibility is available. It is assumed that no trading is possible with other power generating companies which could be able to offer flexibility at cheaper costs. Hence, all deviations between the original day-ahead wind power forecast and the second updated wind power forecast can only be balanced against the commitments made earlier on the day-ahead market by rescheduling own power plants. This is, for example, a feasible option for BRPs that aggregate different types of power plants as well as for larger power generating companies that have diverse portfolios. After internal ex-ante self-balancing, updated generation plans are submitted to the TSO.

In alternative ③, trading between power generating companies is possible. However, trading possibilities are assumed to be limited. This choice is motivated by the fact that many intraday markets have limited liquidity [67]. In addition, it is chosen not to consider bilateral intraday trading which is assumed to play a minor role in the Nordic countries, mainly because transmission capacity between price zones is implicitly auctioned on Elbas; therefore only trades within the same price zone could be settled bilaterally.

To capture continuous intraday trading at least in a rudimentary manner in alternative ③, the process of combined intraday trading and internal ex-ante self-balancing is applied twice: first, based on a first updated wind power forecast and second, based on a more recently updated forecast which is is also used when deciding which bids to put on the balancing market. In alternative ③, each combination of intraday trading and internal ex-ante self-balancing consists of the following steps:

1. Own possibilities (available flexibility) for internal self-balancing are estimated along with an estimation on the necessary volume to achieve a balanced position according to an updated wind power forecast.
2. Own flexibility with lowest variable generation costs is reserved up to that volume that would be necessary to achieve a balanced position only through internal ex-ante self-balancing.
3. Remaining flexibility will be offered on the intraday market at its variable generation costs.
4. Each power generating company accepts those offers on the intraday market that are cheaper than the variable generation costs of the reserved own flexibility.
5. Each power generating company uses internal ex-ante self-balancing to achieve a fully balanced position.

This process represents a very risk-averse way of intraday trading which will result in low liquidity on that market. Still, it is an opportunity for power generating companies to achieve balanced positions according to their latest updated wind power forecasts. Trading with other market participants can be attractive not only if it is cheaper, but also if own flexibility is not sufficient. Also in alternative ③, power generating companies try to achieve balanced positions at independent of the costs.

The remaining decision steps are again equal for all alternatives. After submission of their final production plans (in these plans, wind power generation is equal to the second updated wind power forecast), power generating companies are assumed to offer all flexibility that is still available in their power plants to the balancing market. This includes positive and negative balancing energy in the following manner: positive balancing energy is offered according to the difference between maximum possible generation levels and generation levels in the updated production plans; negative balancing energy is offered according to the generation levels in the updated production plan. The only exception is wind power generation which is assumed not to be eligible to be used neither as positive nor as negative balancing reserve. This reflects common requirements that balancing reserves have to be dispatchable in the meaning that they can be fully activated with a maximum time delay and that they can be used during the whole period of delivery, as, for example, in Sweden [27].

During the hour of delivery, power generating companies supply as much wind power as available. Therefore, the TSO activates balancing market bids to keep generation and consumption stable in the test system. Apart from the cases in which the power generating companies are asked to provide these balancing energy, they stick to their production plans (for all power plants except wind power plants).

Finally, imbalances are settled. In the model, it is assumed that power generating companies minimise their expected imbalances irrespective of the costs of self-balancing. Therefore, the financial incentive of the imbalance settlement scheme to achieve balanced positions as discussed in Section 4.2 is – in the model – not of relevance in the decision making process.

In the model, production imbalances are priced according to the Nordic two-price imbalance system. Consumption imbalances, as defined in Section 4.2 are not represented in the model. However, the effects of neglecting them are limited due to two reasons: first, in the model, consumption imbalances occur only when a power generating company has no possibility to achieve a balanced position. Second, imbalance costs are are only considered to be able to compare the power generating company's costs for each of the investigated alternatives in order to check whether alternatives that lead to decreased total variable generation (system's perspective) also are more profitable from the perspective of the power generating companies.

In the following, several important details will be outlined. This includes handling of variable generation costs at each decision step, an overview on the formulated optimisation problems, and characteristics of the three wind power forecasts that were used (day-ahead forecast, update 1 and update 2).

Minimising variable generation costs

For day-ahead market clearing, unit commitment decisions, all ex-ante self-balancing decisions as well as for the activation of balancing bids, simple linear optimisation models have been formulated. In those models, generation is described by a set of units $b \in B(i)$ per power plant i. This allows to capture rescheduling costs, for example, when generation in a power plant is increased so that another unit is started which might reduce the power plant's total efficiency, for example in a hydro power plant. Alternatively, the units b can be interpreted as generation segments of a power plant; then, they allow to represent different levels of variable generation costs depending on total generation of the power plant.

The formulated optimisation models yield scheduling solutions $x(i, b)$ that satisfy a certain energy demand D at lowest minimum variable generation cost, which are reflected by $c(i, b)$ per power plant and unit/segment. These costs include a cost component for rescheduling. In order to be feasible, the solution has to respect maximum generation limits $xmax(i, b)$ per unit/segment. Summarised, the basic[1]

[1] More details, e.g. modelling of minimum and maximum generation limits per power plant and handling of situations where available generation is not sufficient, are described in articles ☞[P3, P4, Section 2.9].

Table 4.1: Overview of the models for each decision step depending on investigated alternative and direction of rescheduling/balancing. Except for day-ahead market clearing, $D < 0$ implied that actions are taken to increase generation (↑), and to decrease generation if $D > 0$ (↓).

Alt.	Step and direction	Perspective	Demand D	Costs
①②③	Day-ahead —	System	D_{da}	$c(i,b)$
③	1st self-balancing ↑	Company f	$\sum_{i\in J(f)}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{update1}}^{\text{wind}}(i))$	$c(i,b)\,\alpha_{\text{sb1}}$
③	1st self-balancing ↓	Company f	$\sum_{i\in J(f)}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{update1}}^{\text{wind}}(i))$	$c(i,b)\,(2-\alpha_{\text{sb1}})$
②	2nd self-balancing ↑	Company f	$\sum_{i\in J(f)}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{update2}}^{\text{wind}}(i))$	$c(i,b)\,\alpha_{\text{sb2}}$
②	2nd self-balancing ↓	Company f	$\sum_{i\in J(f)}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{update2}}^{\text{wind}}(i))$	$c(i,b)\,(2-\alpha_{\text{sb2}})$
③	2nd self-balancing ↑	Company f	$\sum_{i\in J(f)}(x_{\text{sb1}}^{\text{wind}}(i) - x_{\text{update2}}^{\text{wind}}(i))$	$c(i,b)\,\alpha_{\text{sb2}}$
③	2nd self-balancing ↓	Company f	$\sum_{i\in J(f)}(x_{\text{sb1}}^{\text{wind}}(i) - x_{\text{update2}}^{\text{wind}}(i))$	$c(i,b)\,(2-\alpha_{\text{sb2}})$
①	Balancing ↑	System	$\sum_{i\in I}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{real}}^{\text{wind}}(i))$	$c(i,b)\,\alpha_{\text{b}}$
①	Balancing ↓	System	$\sum_{i\in I}(x_{\text{da}}^{\text{wind}}(i) - x_{\text{real}}^{\text{wind}}(i))$	$c(i,b)\,(2-\alpha_{\text{b}})$
②③	Balancing ↑	System	$\sum_{i\in I}(x_{\text{sb2}}^{\text{wind}}(i) - x_{\text{real}}^{\text{wind}}(i))$	$c(i,b)\,\alpha_{\text{b}}$
②③	Balancing ↓	System	$\sum_{i\in I}(x_{\text{sb2}}^{\text{wind}}(i) - x_{\text{real}}^{\text{wind}}(i))$	$c(i,b)\,(2-\alpha_{\text{bal}})$

model for all decision steps can be expressed as

$$\min_{x(i,b)} \quad \sum_i \sum_b x(i,b)\, c_(i,b) \tag{4.3a}$$

$$\text{s.t.} \quad 0 \leq x(i,b) \leq xmax(i,b) \quad \forall\,(i,b) \tag{4.3b}$$

$$\sum_i \sum_b x(i,b) = D. \tag{4.3c}$$

Central differences between this basic description and the models for each decision step are listed in Table 4.1. Differences include system versus sub-system optimisation, demand that needs to be covered and generation costs as a (discrete) function of time. For all ex-ante self-balancing decisions as well as for activation of bids to the balancing market, two separate optimisation problems are formulated: one in case generation should be increased and one in case it should be decreased. This way, different prices/costs for increase/decrease in generation are fed into the optimisation problem. The last column shows how these prices/costs are adjusted to reflect rescheduling costs: all cost factors α depend only on the time distance towards the hour of delivery. As decisions on intraday trading and internal ex-ante self-balancing are taken around the same time (based on the same updated wind power forecast), the same cost factors are applied: α_{sb1} for the first sequence of intraday trading and internal self-balancing, and α_{sb2} for the second sequence, respectively. Bids to the balancing market are priced with the cost factor α_{bal}. For all cost factors, it holds that $\alpha \leq 1$.

Prices/costs are always adjusted in a symmetric way: increasing generation after day-ahead commitment comes at a higher cost than the day-ahead commitment; when decreasing generation, the "saved" costs equal $c(i,b)\,(2-\alpha)$ which implies that the avoided generation costs due to rescheduling will be smaller than the generation costs assumed in the day-ahead unit-commitment step. For example, if $\alpha_{\text{bal}} = 1.5$, the willingness to buy balancing energy from the system operator (and instead decrease generation in own power plants) equals the price reflected in the bids to the day-ahead market (which is always to the original variable generation cost because there are no rescheduling costs at that stage) times 0.5.

Depending on the decision step, generation is optimised from a system's perspective or from the perspective of an individual power generating company f which owns a set of power plants $J(f)$ that is a subset of all power plants $i \in I$. The demand for ex-ante self-balancing stems only from uncertainty in wind power forecasts; the need for real-time balancing of the TSO originates as well from wind power forecast errors (difference between update 2 and observed wind power generation) but also from rescheduling actions of power generating companies: for example, if update 2 would be less accurate than the day-ahead forecast or update 1, more balancing services would need to be activated.

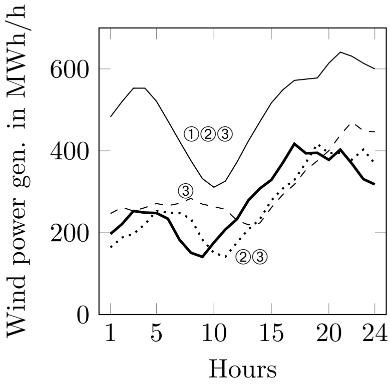
Input: wind power forecasts

Two case studies have been conducted to assess ex-ante self-balancing. Both need wind power forecasts as input; the chosen forecast accuracy will affect the performance of ex-ante self-balancing. For example, it an updated forecast for a specific hour has a larger forecast error than the day-ahead forecast for that hour, ex-ante self-balancing will lead to larger system imbalanced that have to be handled in real-time. Therefore, the employed forecasts and their corresponding forecast errors are plotted in Figure 4.2. The depicted day-ahead forecast and observed generation are taken from historic data. Here, a day was chosen that exhibited both significantly varying wind power generation levels and above-average forecast errors. The second updated forecast for hour t is a persistent forecast that equals the observed wind generation during hour $t-2$. The first updated forecast is a fictitious forecast that was fitted in such a way that it is always better than the day-ahead forecast, but – on average – less accurate than the second updated forecast.

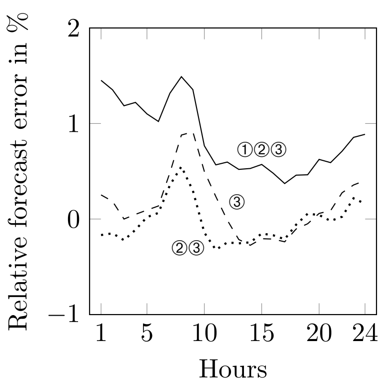
Modelling rescheduling possibilities along with two updated forecast, allows power generating companies to use ex-ante self-balancing first in one direction and then, in the opposite direction. This risk is inherent when using a sequence of updated wind power forecasts to continuously balance the own position [68, 69]. It exists, for example, also for intraday trading on continuous intraday markets.

4.3.3 Case study: Internal ex-ante self-balancing

The goal of the case study presented in ☞[P3] is to study effects when two power generating companies in a small test-system try to achieve balanced positions according to latest wind power forecasts by rescheduling their own power plants. Figure 4.3 shows that this behaviour can reduce the volume of balancing energy that is activated during the hour of delivery. Hence, if forecast errors of updated



(a) Forecasts.



(b) Forecast errors.

Figure 4.2: Wind power forecasts and their forecast errors used to test performance of alternatives ① – ③: day-ahead forecast (thin solid line), first updated forecast (dashed), and second updated forecast (dotted). Observed wind generation is indicated by the thick solid line. Figure also used in ☞[P4, Figures 3 and 4].

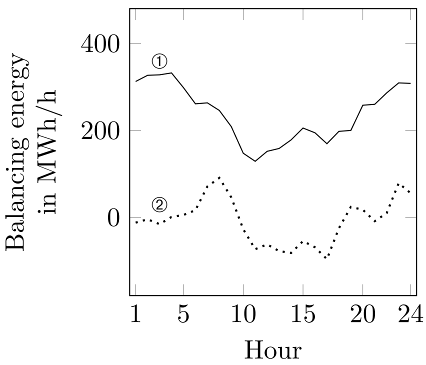
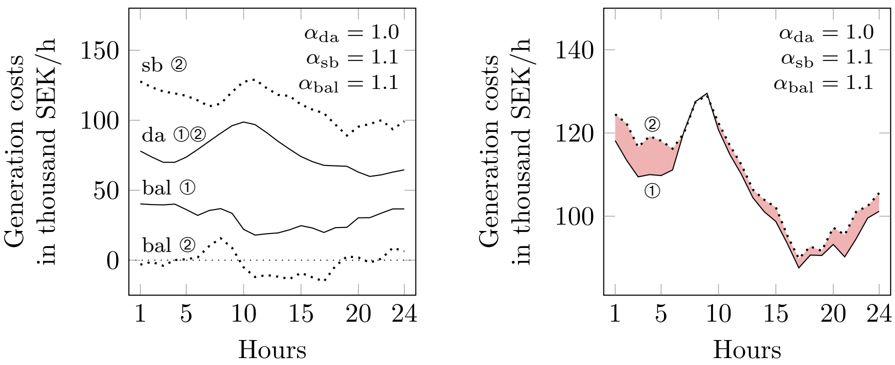


Figure 4.3: Hourly volume of activated balancing energy in alternatives ① (solid line) and ② (dotted). Up-regulation is indicated by positive balancing power, down-regulation by negative balancing power. Figure also used in ☞[P3, Figure 3].



(a) Distinction at which stages variable generation costs occur (system's perspective).

(b) Comparision of alternatives ① and ② highlighting negative gains of alternative ②.

Figure 4.4: Total variable generation costs of the system in alternatives ① (solid line) and ② (dotted). Regarding the cost factors α, *da* refers to day-ahead scheduling, *sb* to ex-ante self-balancing and *bal* to real-time balancing. Figure similar to ☞[P3, Figures 5 and 6].

forecasts are smaller than those of day-ahead forecasts, distributing some balancing responsibilities to market participants can facilitate system operation for the TSO. During hours 1 to 4, one power generating company was not able to fully reschedule generation in such a way that they could self-balance according to the updated wind forecast (update 2) because its own available flexibility was not sufficient; however, this is not visible in Figure 4.3.

Requiring BRPs to achieve balanced positions according to updated generation forecasts, implies that costs are moved to a certain extent from real-time towards the ex-ante self-balancing time frame; and hence, from the TSO to the BRPs. This is illustrated in Figure 4.4(a) which shows during which decision steps the costs arise for alternative ① and ②. In alternative ①, variable generation costs are only connected to day-ahead unit commitment and real-time balancing. Alternative ② includes a rescheduling step in the intraday time-frame, therefore generation costs are connected to day-ahead unit commitment, rescheduling and real-time balancing. From the system's perspective, parts of the additional rescheduling costs are compensated by decreased balancing costs during the period of delivery. Costs at the day-ahead stage are equal in both alternatives.

The advantage of internal ex-ante self-balancing in general is that the use of rescheduling closely before the period of delivery might be done at lower variable generation and rescheduling costs than the activation of balancing services during the period of delivery. The reason is that technical requirements for balancing bids are higher than for trading and scheduling decisions before the period of delivery; for example, balancing services often need to fulfil requirements on minimum ca-

Table 4.2: Modifications of the cost factors α: changes in total variable generation costs from the system's perspective. Table also used in ☞[P3, Table 4].

α_{sb}	α_{bal}	Average benefit of alt. ② compared to alt. ① in %	Hours where noticeable benefits occurs
1.1	1.1	−3.6	–
1	1	−3.3	–
1.1	1.2	−1.6	7–9, 19
1	1.1	−1.3	7–14, 16
1.1	1.3	+0.2	1, 6–10, 18–20, 23–24
1.1	1.4	+2.0	1–10, 15–16, 18–24
1.1	1.5	+3.6	1–10, 15–16, 18–24
1	1.5	+5.7	1–24

pacity and maximum activation times. Therefore, some available flexibility cannot be used as balancing services, wherever it might be perfectly suited to be used during the intraday time-frame to achieve balanced positions. However, in the example in Figure 4.4(a), cost factors for ex-ante self-balancing and balancing during the period of delivery are chosen to be equal. Therefore, the total variable generation costs as plotted in Figure 4.4(b) cannot be decreased by internal ex-ante self-balancing. Hours where alternative ② performs significantly worse than alternative ① are highlighted in red. Here, internal ex-ante self-balancing shows to be disadvantageous from the system's perspective as generation costs for alternative ② are above those of alternative ①. This is due to the fact that internal ex-ante self-balancing can only deploy flexibility within a market participant's own portfolio to achieve balanced positions according to latest generation forecasts. In contrast, a TSO can via balancing markets access flexibility of several market participants.

Therefore, the advantage of internal ex-ante self-balancing can only compensate this disadvantage if variable generation and rescheduling costs in real-time exceed variable generation and rescheduling costs in the day-ahead and intraday time-stage. Some selected cases are compiled in Table 4.2. For example, at $\alpha_{\text{sb}} = 1.1$ and $\alpha_{\text{bal}} = 1.4$, internal ex-ante self-balancing show to be more cost efficient than alternative ① from the system's perspective.

Also from the power generating companies' perspective, the value of internal ex-ante self-balancing is to a large degree depending on the assumed cost factors that are used to adjust variable generation cost at different time stages. Here, the flexibility within the own portfolio and the cost of it are of central importance. Therefore, there are hours where internal ex-ante self-balancing is only profitable for one power generating company on the other company's expense.

The obvious disadvantage of limiting available flexibility before the hour of delivery to each power generating companies' own flexibility will be addressed in the second case study.

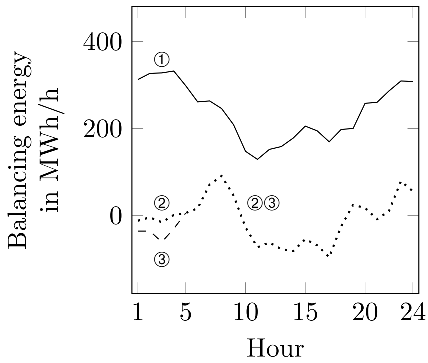


Figure 4.5: Total variable generation costs of the system in alternatives ① (solid line), ② (dotted) and ③ (dashed; costs mostly as alternative ②). Up-regulation is indicated by positive balancing power, down-regulation by negative balancing power. Figure also used in ☞[P4, Figure 5].

4.3.4 Case study: Internal & external ex-ante self-balancing

In the first case study, it was shown that the particular disadvantage of purely internal ex-ante self-balancing (alternative ②) is that market participants can only use flexibility in their own portfolio. Therefore, the case study in ☞[P4] investigates how results would change if power generating companies could also trade flexibility with each other shortly before the period of delivery (alternative ③).

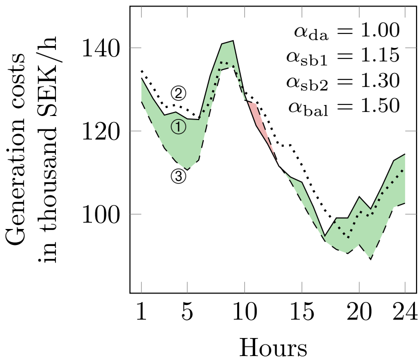
The chosen cost factors applied in this case study are:

- For the very first combination of intraday trading and internal ex-ante self-balancing (only applicable in alternative ③): $\alpha_{\text{sb1}} = 1.15$.
- For the second combination of intraday trading and internal ex-ante self-balancing (only applicable in alternatives ② and ③): $\alpha_{\text{sb2}} = 1.3$.
- For bids to the balancing market (applicable in all alternatives): $\alpha_{\text{bal}} = 1.5$.

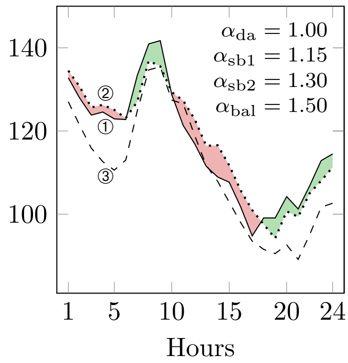
In comparison to the first case study, the cost factors are chosen to be higher. This explains why the total variable generation costs of the test system differ in both case studies for alternative ③.

As it can be seen in Figure 4.5, combined external and internal ex-ante self-balancing reduces the balancing volumes that in alternative ① otherwise would have been necessary to activate during the period of delivery. Except for hours 1 to 4, the reduction is the same as in the first case study. The reason is that both power generating companies still try to achieve balanced positions irrespective of the costs of internal and external self-balancing; being able to trade with each other, the company that does not have sufficient own flexibility can, now, buy flexibility from the other company.

For all hours except hours 11 and 12, alternative ③ was more beneficial from the system's perspective than alternative ②, see Figure 4.6. Because there are



(a) Comparision of alternatives ① and ③ highlighting gains of alternative ③.



(b) Comparision of alternatives ① and ② highlighting gains of alternative ②.

Figure 4.6: Variable generation costs in alternatives ① (solid line), ② (dotted) and ③ (dashed). Regarding the cost factors α, *da* refers to day-ahead scheduling, *sb* to ex-ante self-balancing and *bal* to real-time balancing. Figure similar to ☞[P4, Figure 6].

two (discrete) stages for intraday trading and internal ex-ante self-balancing, it is possible that power generating companies first use ex-ante self-balancing (both external and internal) in one direction and then, in the opposite direction. To a small extent, this happened in hours 14 to 20. However, as long as the difference between α_{sb1} and α_{sb2} is small, this does not translate to significant additional costs in the model.

4.4 Open research questions

There are at least three areas where further work could be done. The first one is a detailed analysis of costs that occur when rescheduling production plans. These costs are sensitive information to power generating companies because they are affected by various factors, for example, technical characteristics, risk attitudes, production planning processes, organisation etc. But even for power generating companies these costs seem to be hard to estimate. However, with liberalisation of the electricity sector, it is important for all power generating companies to be sufficiently paid for the balancing services and intraday flexibility that they provide. This might even become more important in future, if profits from day-ahead energy sales decrease due to price-reducing effects of a larger share of vRES. Therefore, such an investigation that aims at explaining and also quantifying rescheduling costs would both contribute to research (e.g. market modelling) and profit power generating companies (e.g. better base for decision making). For research, it would be sufficient to describe all data anonymously and on a more abstract level, because here, the driving factors and their links are of interest, not exact quantifications.

A second area of interest is a more precise modelling of continuous intraday trading that abstracts less from reality than the simulation model presented in this chapter. The following chapter which describes an analysis of trading behaviour on the intraday market Elbas can be seen as a very first step towards this goal.

Regarding the incentives to reach balanced positions, the effects of the Nordic one-price system for the so-called consumption imbalance should be investigated more in detail. Would the behaviour of BPRs change if a two-price system would be applied instead? Would this facilitate system operation to a considerable extent? In which magnitude would the additional costs that BRPs would face from a two-price imbalance system range?

Finally, estimations on the value of lower volumes of activated balancing services during the period of delivery are of interest. If this value would be substantial, distributed balancing would become more beneficial from the system's perspective.

Chapter 5

Continuous intraday trading

As the preceding chapter showed, internal self-balancing of expected imbalances before the period of delivery has the disadvantage that only flexibility in own power plants can be used. Including intraday trading, it was shown that ex-ante self-balancing can efficiently reduce total variable generation costs of power systems.

Also market participants can profit from intraday trading: those with large shares of vRES can reduce their expected imbalances; small BRPs with a less diverse mix of power plants are even dependent on intraday trading to reduce expected imbalances; and finally, also market participants with conventional generation units can profit from selling available flexibility.

However, acting upon sequentially updated wind power forecasts, there is a risk that individual imbalances are traded "forth and back". This risk exists if intraday markets allow for several trading possibilities for the same period of delivery, e.g. if intraday markets are designed as a set of discrete auctions or as platforms for continuous trading. The latter ones also allow for price variations to a larger extent because trades are not allocated. Moreover, it is challenging to model trading behaviour on continuous intraday markets in an appropriate manner. Therefore, the continuous intraday market ELBAS *has been studied in* ☞ *[P8]. An overview of the gained insights with regard to trading activity and price development is provided in this chapter.*

5.1 Adjustment markets

Intraday markets are meant to offer market participants a possibility to *adjust* their day-ahead commitments by trading closer to the period of delivery; they are not intended to be an alternative to day-ahead markets. This directly implies that traded volumes will be significantly lower than on day-ahead markets. Therefore, an absence of trades does not necessarily indicate shortcomings in the market design but can be due to that the demand to adjust own positions is low or that BRP already have quite well balanced positions in the intraday time-frame.

However, *liquidity* is a central prerequisite for intraday trading. On a liquid market, market participants can find other market participants to trade with as well as that successful trades do not significantly affect the price of other trades [67]. Basically, illiquidity can be regarded as a lack of bids and offers at "moderate" prices that are not too far off the market participant's willingness-to-trade. Liquidity can be assumed to increase with an increasing number of market participants and the number of settled trades. In [67], traded volumes of four European intraday markets are analysed and it is concluded that intraday markets are likely to often be hampered by illiquidity. To assess liquidity without fail, one would need to compare trading activity with the market participants' demand for intraday trading. However, this one is unknown.

Regarding the design of intraday markets as adjustment markets, one could, of course, also argue in favour of an alternative day-ahead market design: moving gate closure of day-ahead markets closer to the period of delivery. However, the combination of day-ahead and intraday markets bridges partly opposing interests of market participants: while those with a portfolio dominated by thermal power plants need a certain lead time to adjust generation levels in a cost-efficient manner, wind power generation forecasts become more accurate the shorter the forecast horizon [69, 70] which provides incentives to trade closely before the period of delivery. Combining these two perspectives, the combination of two markets with different gate closure times that complement each other seems to fit the technical characteristics of the power system.

5.2 Continuous trading

On a platform for continuous trading, trades are settled in a first-come-first-serve order as soon as one market participant accepts the price stated in the bid/offer of another market participant. This implies that prices vary from trade to trade which is a central characteristic that differs fundamentally from those of discrete auctions with uniform pricing. One relevant research question is whether – or to which extent – the choice to design an intraday market in either the one or the other way affects the market's liquidity.

While liquidity cannot be assessed directly, other indicators, e.g. trading activity, can be used to roughly estimate liquidity [67]. However, trading activity can be limited by several reasons, for example, between different price zones if the available transmission capacity for intraday trading is already fully utilised by day-ahead trades. Low trading activity can also be caused by a low demand for intraday adjustments. Hence, in both these cases, low trading activity cannot be attributed to the chosen market design.

However, the market design choice might affect trading activity with respect to time of trade. While there is no reason in a discrete auction to put a bid/offer sooner or later during the time bids/offers can be put, this is not the case with continuous trading platforms that can show significant price variations; an example

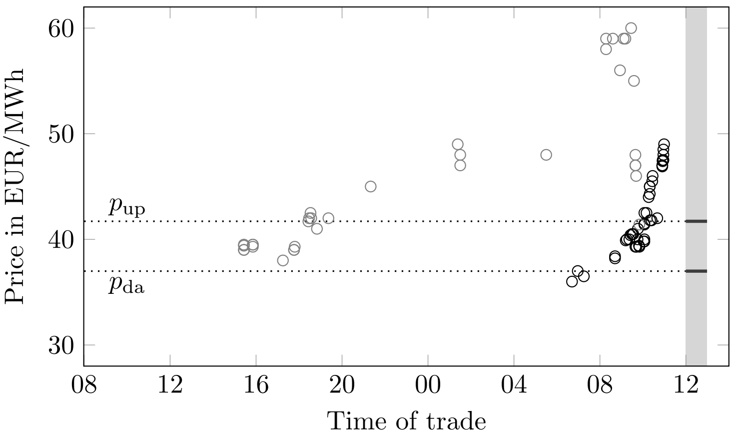


Figure 5.1: Price development on ELBAS for energy to be delivered/withdrawn during hour 12:00–12:59, on 30 January, 2013 which is highlighted by grey shade. The figure is a simplified version of ☞[P8, Figures 7(a) and 7(b)]. Trades marked in grey colour include at least one price zone outside the Nordic synchronous area; in trades marked in dark black, both buyer and seller are located in the Nordic synchronous area. The day-ahead price p_{da} of the hour as well as the price on the balancing market p_{up} are indicated by dotted lines. During this specific hour, both prices have been the same for all Nordic price zones.

is plotted in Figure 5.1. In this figure, each mark represents price and time of one successfully settled intraday trade on ELBAS for delivery/withdrawal during 12:00–12:59, on 30 January, 2013. Trades marked in light grey colour, include at least one price zone outside the Nordic synchronous area. All trades marked in dark black represent trades where both buyer and seller are located in the Nordic synchronous area. Here, focus should be on the latter ones because for the chosen period of delivery, both day-ahead and balancing prices have been the same for all Nordic price zones. This is of importance because those two prices impact the imbalance prices in the Nordic synchronous area and, therefore, most likely the market participants willingness-to-trade, cf. Section 2.4.1. In the plotted example, it can be seen that prices for the *same* good (here, one MWh of electricity for delivery/withdrawal between 12:00 and 12:59) change significantly depending on *when* an intraday bid/offer is put or accepted. Differently said, one can never be sure that it would not be (more) profitable to trade a bit later.

However, the preferred time of trade can depend on many factors. Besides technical characteristics of power plants, this can be driven by the demand for intraday adjustments or by the market participant's strategies for risk management. However, it can also be affected by the degree to which market monitor the market, for example, due to office hours.

Hence, we can summarise that trading activity is depending on many factors including demand for intraday trading, location of the market participant, time of trade and time of delivery. Therefore, also liquidity should be assessed not on a overall level, but, ideally, for each combination of price zones, periods of delivery, time intervals of trade etc. However, an assessment of liquidity is far beyond the scope of this thesis. The thesis does also not strive to estimate the real demand for intraday trading, which would be impossible with the data that was available for this study. The motivation for studying continuous intraday trading more in detail is to investigate trading behaviour in order to have a base to model continuous intraday trading which could significantly improve the simulation model presented in Chapter 4. However, this requires more detailed insights into market participants' trading on Elbas. Therefore, ☞[P8] addresses the following questions:

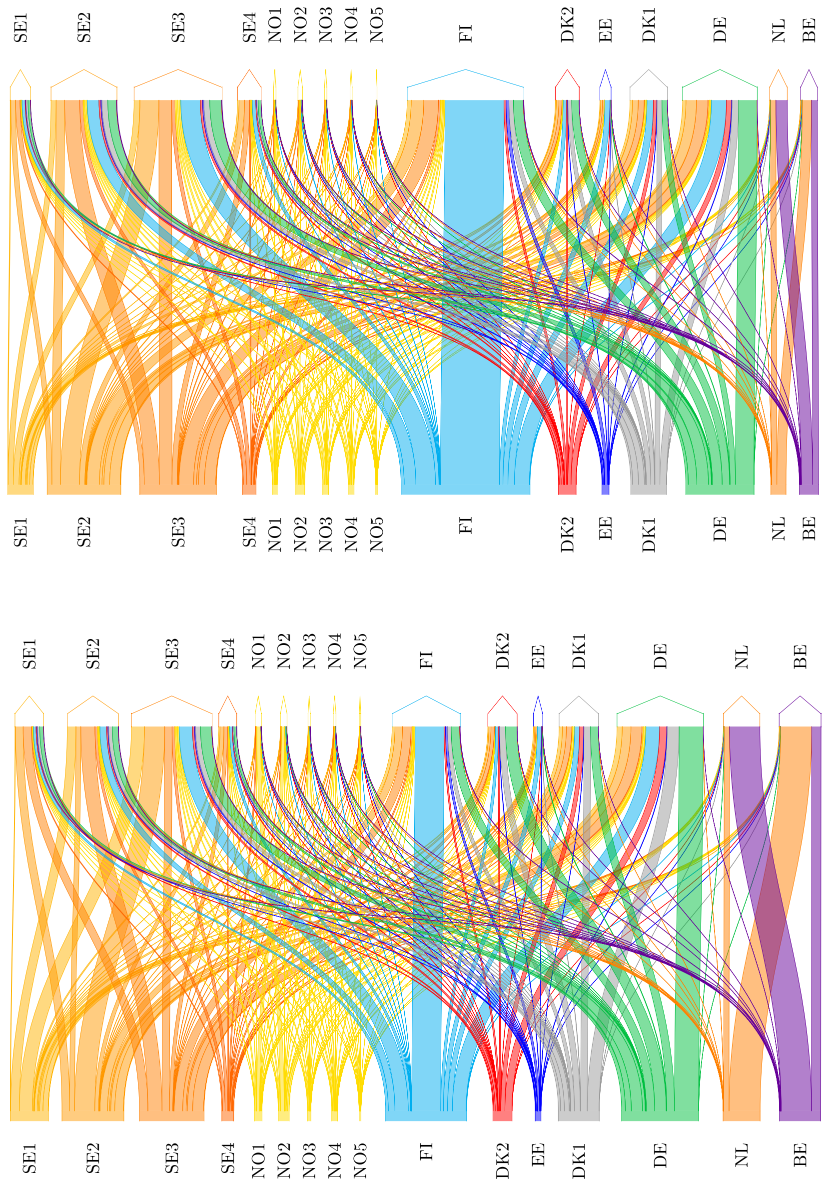
- Between which price zones is trading activity most intense? How large is the share of cross-border trades? Is trading activity related to vRES penetration levels, available transmission capacity between price zones, different levels of imbalance prices or other factors?
- How close to gate closure do market participants trade? Does trading activity follow office hours? Can more trades be observed for hours of delivery at the end of each day, i.e. is trading increasing the longer the day-ahead forecast horizon?
- How does intraday trading affect the market participants' imbalances? How are these imbalances calculated and priced?
- To which extent do intraday prices vary within the period of trading and how can these variations be explained?
- Can intraday trading be a profitable means for market participants to reduce their imbalance costs?

In the following sections, selected parts of ☞[P8] will be discussed. In addition it will be briefly commented on the question to which extent the development of grid frequency can be an useful signal to predict the development on the Nordic balancing market.

5.3 Trading behaviour on Elbas

5.3.1 Traded volumes and number of trades

During the course of the analysis, it became soon evident that trading activity varies significantly between from combination to combination of price zones. Traded volumes and number of trades, both with respect to location of sellers and buyers, are illustrated in Figure 5.2. The flowcharts show the successfully traded volumes, plot (a), and the number of successful Elbas trades, plot (b). All trades have been sold by market participants in the price zones listed on the left hand side of each diagram and bought by market participants in the price zones on the right hand side of each diagram. The width of each arrow is proportional to the traded volume or the number of trades, respectively. To give a reference point for the magnitudes,



(b) Width of arrows proportional to *number* of trades. Illustration of ☞[P8, Table 3].

(a) Width of arrows proportional to *volume* of trades. Figure as in ☞[P8, Figure 3].

Figure 5.2: Trading activity on Elbas including all trades between 2 March, 2012 – 28 February, 2013. All price zones shown above the Estonian price zone (EE) are within the Nordic synchronous area, EE is in the Baltic synchronous area, and all price zones shown below EE are within the Continental European synchronous area of the European electric power system.

here one example: in 28 695 trades, market participants in SE3 sold 460 061 MWh during the period of the analysis and in 32 961 trades, they bought 574 522 MWh. Out of these trades, 4 744 trades with a total volume of 52 548 MWh have been between settled between sellers and buyers located in the same price zone.

First, one can see that the patterns differ slightly when analysing volumes and number of trades. For example, market participants in Belgium and the Netherlands trade on average larger volumes per trade than market participants in Finland.

Second, the magnitude of trading varies significantly. Market participants in Sweden and Finland are, for example, much more active than market participants in Norway.

Third, different relations between intraday sales and purchases can be seen: with regard to Sweden, it was observed that market participants in the southern price zones (SE3 and SE4) buy more energy on Elbas than they sell on that market while the situation is vice versa in the northern price zones (SE1 and SE2). As outlined in ☞[P8, Section 3.1], this might be related to significant hydro storage capabilities in the two northern price zones. However, a different explanation can be added where we assume that wind power forecasts errors would be the dominating motivation for intraday adjustments: because installed wind power capacity was found to be quite well dispersed, cf. Chapter 3, one would expect market participants to use Elbas to balance both over- and underestimated expected generation levels to the same extent. However, studying wind power forecast errors, cf. Chapter 3, it was observed that even if forecast errors have a mean close to zero, they are asymmetrically distributed and often slightly overestimating wind power generation. This could contribute to an increased demand to buy energy on the intraday market and, hence, be another explanation for the observed trading imbalance between sales and purchases.

The underlying reasons for different trading activities can be various. Whether the observed trading activity corresponds to the potential intraday demand cannot be assessed based on the data that was available. This data includes only successfully settled trades, not those bids and offers that could not be matched. Therefore, one cannot study how many bids and offers remained unmatched as well as whether this was due to unfavourable prices for one market participant or due to limited market liquidity. However, two possible reasons for different trading activity should be briefly discussed in the following.

Influence of generation mix

Electricity generation is based on different types of power plants as illustrated in Figure 5.3. First, this is likely to influence the demand to reduce expected imbalance volumes. The penetration levels of vRES – here, wind and solar generation – vary significantly. Denmark and Germany have shares of 34 % and 12 %, respectively, while those of the other countries are moderate or even low. Higher shares of vRES tend to imply larger absolute forecast errors; however, as discussed in Chapter 3, geographical dispersion of wind power plants and a countries' expo-

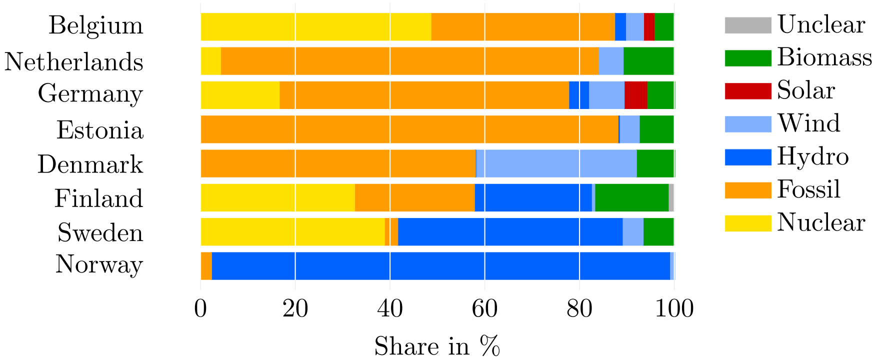


Figure 5.3: Power generation mix of ELBAS member countries: share of total national generation per technology. Data for the period 1 March, 2012 – 28 February, 2013 from [16].

sure to weather regimes strongly affect absolute forecast errors due to geographical smoothing. However, a clear positive correlation between trading activity and vRES penetration cannot be observed.

Second, the generation mix can also influence the incentives to reduce expected imbalance costs because power plants that can offer high flexibility at low costs, e.g. hydro power plants with storage capacities, might damp price variations on the balancing market. In turn this would imply low imbalance prices and a smaller incentive to use any form of ex-ante self-balancing including intraday trading. The large share of hydro power is likely to keep balancing prices low in Norway as well as in the northern price zones of Sweden, while this is not the case for Finland; cf. ☞[P8, Figure 6 and Table 2] for details.

Influence of available transmission capacity

Transmission capacity that is still available according to scheduled day-ahead trades is assigned to ELBAS. As day-ahead trades follow negative price gradients (selling energy from low-price towards high-price areas), several transmission corridors can be fully utilised with day-ahead trades. This holds, for example, comparatively often for exports from the Norwegian and the Swedish price zones towards the continent, as well as from the Swedish price zones towards Finland, cf. ☞[P8, Figure 5] for more details. Therefore, this might be a possible explanation why market participants in Norway only trade small volumes on ELBAS

5.3.2 Time of trade

Trading activity does not only vary from price zone to price zone (or rather from one combination of two price zones to another combination of two price zones).

It also varies within the time period of trading. Here, Figure 5.4 summarises the findings. For the sake of completeness, the figure includes the distribution with regard to the number of trades, plot (a), as well as with regard to traded volumes, plot (b). Both are, however, fairly similar. They differ only because the ratio of energy per trade is not constant; as the cumulative values show, trades settled long before the period of delivery tend to include larger volumes per trade than those shortly before the period of delivery. However, the main results are the general pattern of both distributions: about 20 % of all ELBAS trades are done between 1 h and 1.5 h before the start of each period of delivery. In most ELBAS member countries, this is the last half hour where trades can be settled (in most price zones, this is possible until 60 min before the period of delivery, see ☞ [P8, Section 3.3] for details). As the cumulated frequency on the right y-axis shows, 80 % of all trades are settled 4 h to 5 h before the period of delivery starts which means that there is a significant concentration of trading activity – and also market liquidity – during the last hours of the whole trading period. From the perspective of wind power producers, this behaviour could be explained by more accurate wind power forecasts and the intention to avoid trading forth and back as discussed in Section 4.3.2.

5.3.3 On the benefits of trading

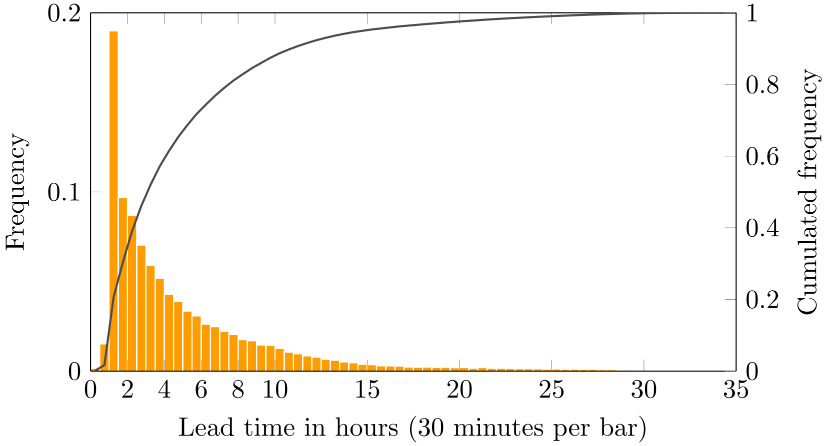
It is impossible to assess the benefit of all trades because each trade is made based on the individual estimations of seller and buyer on future costs and profits. The main uncertainties relate to generation forecasts, imbalance costs and behaviour of other market participants. Making some basic assumptions on decision rules, it is, however, possible to estimate the magnitude of how many trades have been profitable in an ex-post perspective when imbalance prices are calculated.

In the ex-post assessment, the following restrictions and assumptions apply:

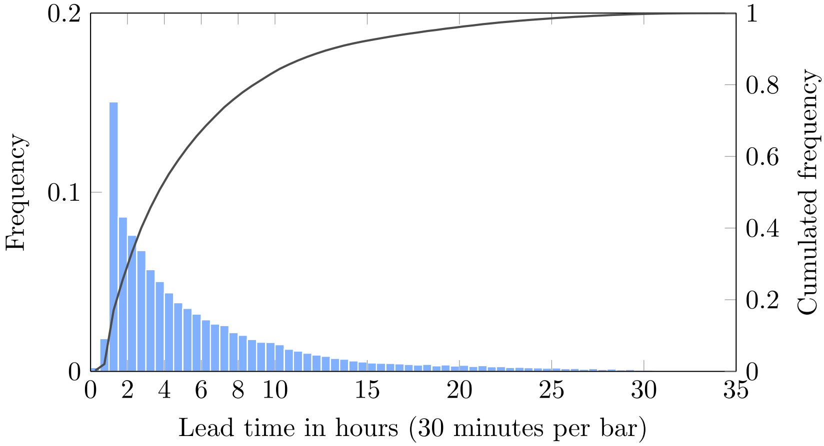
- Only ELBAS trades where both buyer and seller are within a price zone of the Nordic synchronous area are considered.
- Energy traded on ELBAS is assumed to be produced in generation units of power plants that are not sufficiently flexible and dispatchable in order to offer that energy as a balancing service to the TSO. Therefore, this energy cannot be traded on the balancing market.
- Market participants do only trade on ELBAS to reduce their expected imbalances. Furthermore, they are assumed to be risk-neutral. Together, this implies that profitability of each intraday trade can be estimated with respect to the avoided imbalance costs.

Restricting the scope of the assessment to cover only trades within the Nordic synchronous area is due to practical reasons, especially that the imbalance settlement rules outside the Nordic countries differ from those in the Nordic countries; therefore, data – if accessible – would be difficult to compare.

While the second assumption can be supported by the argument that the products traded on intraday and balancing markets differ (energy versus capacity) and that balancing services have to fulfil higher requirements (activation time etc.).



(a) Number of trades.



(b) Volume of trades.

Figure 5.4: Leadtime for all Elbas trades 2 March, 2012 – 28 February, 2013. Analysing number and volumes of trades, the bars show their frequency of occurrence on the left y-axis and the solid curve shows the corresponding cumulated frequency of occurrence on the right y-axis. Plot (a) also used in ☞[P8, Figure 4(a)].

The third assumption highly simplifies and reduces reasons of market participants for intraday trading. As outlined in ☞[P8, Section 1], market participants can use intraday trading to use flexibility of other market participants in order to decrease their own generation costs (rescheduling) or to offer available flexibility in their own power plants to other market participants at prices higher than the costs incurred when using this – otherwise unused – flexibility. Furthermore, market participants are very likely to be risk-averse in reality. They would, for example, be willing to pay a positive risk premium on top of their expected imbalance price when trying to minimise their expected imbalance costs by intraday trading. In the ex-post assessment, it this is fully ignored. Therefore, the results of the assessment will always underestimate profitability of intraday trading and this bias cannot be quantified.

In order to reduce the effect of these simplifications, it is assessed *how many* intraday trades have been profitable ex-post in the light of imbalance costs and not *how large* these profits have been. The assessment is then done twice, once considering all reduced imbalances according to a one-price system and once according to a two-price system as described in Section 2.4.1.

The two main results are the following: applying a one-price system, intraday trades are only rarely mutually beneficial to both seller and buyer; only for trades between price zones with different balancing prices or day-ahead prices trades could be mutual beneficial. Applying a two-price system, a significantly higher number of trades would be beneficial from the perspectives of both sellers and buyers under the mentioned assumptions. For more details, it is referred to ☞[P8, Section 3.6].

5.3.4 Grid frequency as a signal

Several BRPs stated in a survey among Swedish BRPs [71] to base their intraday trading decisions also on the development of grid frequency because grid frequency can indicate changes in balancing directions, balancing volumes and balancing prices. Therefore, it has been checked to which degree grid frequency might be a suitable signal in the intraday decision process. Here, an example was studied which includes the same powerhour that was used to illustrate price development on Elbas in Figure 5.1. Grid frequency and energy supplied or withdrawn by manually activated balancing services is plotted in Figure 5.5. In addition, the figure shows two more plots with accumulated information on frequency deviations. The first plot shows the development of grid frequency in the Nordic synchronous area as one-minute average values based on measurements every five seconds. It can be observed that significant frequency changes often occur at the end of an hour which is due to the day-ahead and intraday market's time resolution of one hour. But also during each hour, frequency varies. In the Nordic countries, frequency deviations in the bandwidth 49.9 to 50.1 Hz are regarded as acceptable [22], therefore additional measures (e.g. use of additional reserves, so-called *frequency controlled disturbance reserves*) might have been taken during times where frequency dropped below 49.9 Hz. In addition the Nordic TSOs have the possibility to require BRPs to

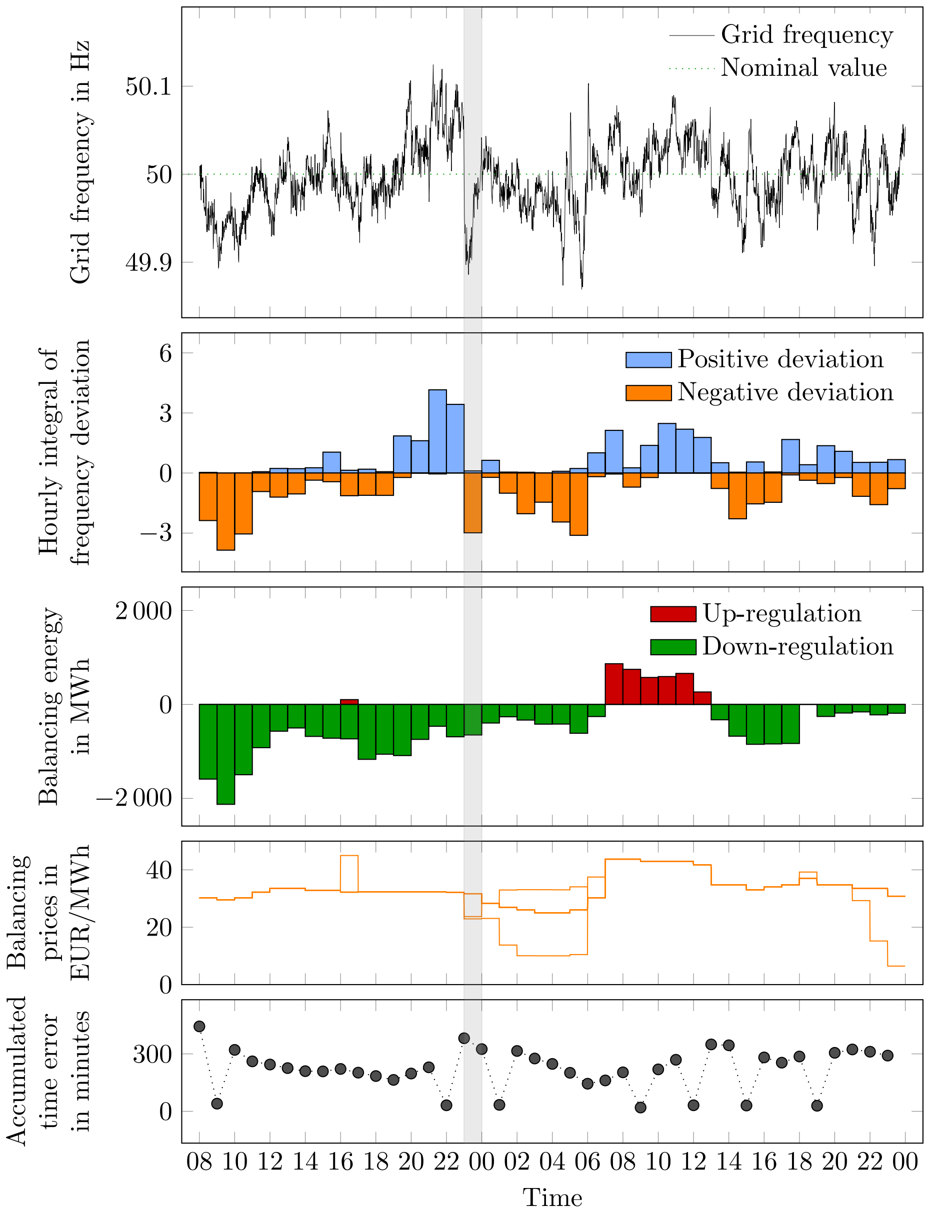


Figure 5.5: Relation between grid frequency and volume of manually activated balancing services procured through the balancing market in the Nordic synchronous area. Example for 08:00, 29 January, 2013 – 24:00, 30 January, 2013. Records of frequency and accumulated time errors from Svenska kraftnät, volumes of activated restoration reserves as well as balancing prices from [72].

move scheduled hourly changes in generation by ±15 minutes [27]. Whether these measures are taken or not cannot be seen in this figure.

The second plot shows the hourly integral of the observed frequency deviations. Here, deviations from the nominal grid frequency of 50 Hz are summed for each hour and deviations towards larger frequency levels as well as deviations towards lower levels are plotted separately. These values indicate the contribution of frequency controlled reserves to system balancing in terms of energy. These reserves are automatically controlled in proportion to how much frequency deviates from its nominal value.

In the third plot, the volume of activated restoration reserves, i.e. the energy of activated balancing bids, is plotted for each hour. Here, one cannot observe an obvious correlation between grid frequency and volume of activated balancing bids. There are several hours, for example the one highlighted by grey shade (23:00–23:59, 29 January, 2013), where down-regulation is predominating on the balancing market while frequency is below its nominal value. Another example is the time between 7:00 and 13:00 where balancing bids for up-regulation have been activated while frequency was predominantly above its nominal value[1].

In the fourth plot, price development on the Nordic balancing market is shown. Each line corresponds to one price zone in the Nordic synchronous area. One can see that prices are directly affected when the predominating direction of balancing changes.

Finally, the fifth plot shows the accumulated time error that is recorded by the TSO and which should be kept in the vicinity of zero.

When trading on the intraday market, market participants can observe frequency development in detail as well as calculate hourly integrals and the accumulated time errors. The information contained in the third and fourth plots is only accessible with a time lag of several hours seen from the point where intraday trading decisions are taken. Only market participants that are active on the balancing market can gain insights into development of prices and volumes because they see which of their offers become activated by the TSO. If we disregard from the latter possibility, e.g. taking the perspective of a BRP that does not a substantial amount of power plants that fulfil the requirements for balancing offers, no clear correlation between grid frequency and volume of activated balancing offers can be found. The same holds for accumulated time errors. Therefore, it is concluded that it is not evident how frequency could serve as a signal for prices on the balancing market and that there might be systematic inefficiencies if BRPs base their self-balancing decisions on the development of grid frequency. However, this conclusion is based on a single example and not on an analysis of a larger time period and should be taken with a pinch of salt.

[1] Please observe that this does not imply inefficient system balancing because restoration reserves are also used to release other reserves.

5.4 Open research questions

The analysis in ☞[P8] showed that number and volumes of successfully settled Elbas trades vary with regard to:

- Location of selling and buying market participant,
- Time of trade,
- Hour of the day during which trades are settled,
- Hour of the day during which energy should be delivered.

It was also illustrated that price variations for the same period of delivery can be be substantial during the time trading is possible. In total, these findings suggest that it is a relevant question whether the observed trading activity could be lower than the market participants' potential demand and whether a potential mismatch could be avoided by changes in the market design of Elbas.

However, it should not be a goal in itself to increase traded volumes on intraday markets [68]; it is the market design that has to guarantee sufficient liquidity to allow market participants to trade those volumes that they demand. Hence, the closer intraday markets can come towards perfect markets, the larger their potential as an element of a market design that facilitates efficient system operation.

One important area that should be investigated are advantages and disadvantages of discrete auctions with uniform pricing. Allocate all bids and offers in one auction would offer the advantage that market participants could not any longer gain from trading the same good a little bit later in time. On average, this might decrease transaction costs (reduced market monitoring) and avoid price changes for the same period of delivery.

In Europe, Spain, Portugal, and Italy have implemented intraday markets that are completely designed as discrete auctions [36, 38]. Other countries have added intraday auctions on top of their continuous trading platforms, e.g. EpexIntraday has recently introduced an intraday auction for delivery within Germany[2] [73]. A starting point would be to study these market designs in detail including specific adjustments. Next, it should be investigated how discrete auctions would effect market participants on Elbas. Here, special focus should be on how suitable discrete auctions would be for market participants with thermal and hydro power plants and which economic and technical influences later rescheduling decisions (they would not any longer be able to trade as soon as, for example, an outage occurs, but need to wait for the auction clearing before rescheduling their generation). From the perspective of wind power producers, it is expected that discrete auctions cleared closely before the period of delivery would be favourable due to reduced forecast errors the shorter the forecast horizon. While short rescheduling times might be unproblematic for wind and hydro power producers, thermal power plants might face higher rescheduling costs the closer rescheduling is done to the period of delivery because they are constrained by ramp rates etc. to a larger extent.

[2] This auction is cleared at 15:00 and allows for trading for each 15 min interval of the following day [73]. Therefore, it cannot be compared to intraday auctions that would be cleared close to gate closure times of continuous intraday markets.

As all power plants can contribute with available flexibility, it is of importance to form the market in a way that allows all flexibility to be efficiently used.

Another open research area is modelling of trading behaviour on continuous intraday markets. As discussed in ☞Section 3.9 of [P5], many models for production planning and bidding neglect intraday markets. The challenge of modelling includes two issues: one has to model under which circumstances market participants would like to trade as well as the possibility that market participants might not find a counterpart to trade with.

Regarding liquidity and the potential of intraday trading on Elbas, access to Elbas ticker data for all bids/offers that have *not* been successfully paired would open for important insights into both trading behaviour and trading possibilities. Analysing these data in combination with those on successfully settled Elbas trades could contribute to modelling of continuous trading platforms. An appropriate modelling would be a prerequisite for more detailed simulations, e.g. how changes in single market rules would affect market participants as such as system operations. Those simulations would be helpful to analyse market design and to improve it even further.

Chapter 6

Conclusions

This chapter summarises the main findings and discusses their policy implications. To conclude the thesis, a selection of important questions for further research is presented.

6.1 Summary of findings

In this thesis, three areas that are directly connected to system balancing have been studied: wind power variations and forecast errors as sources of balancing needs, internal rescheduling of power plants and intraday trading as possibilities to achieve balanced positions according to latest wind power forecasts and trading behaviour on Elbas to gain insights into trading activity and price development on a *real* market.

Wind power variations and forecast errors in Sweden

The studies presented in Chapter 3 describe wind power generation in Sweden. On the one hand, they intent to identify basic characteristics of wind generation in Sweden; on the other hand the same studies have been done in other countries in order to compare these characteristics. The value of such a comparison is to highlight similarities and differences between countries.

The main findings of the study on wind power variations relate to correlations between a proposed variability index and different parameters. Here, it was shown that geographic dispersion has a clear influence, that energy penetration levels do not have an influence and that the influence of capacity factors is not clear. As a side product, it was that hourly wind power variations in Sweden do not exceed 10 % of the installed wind power capacity which is a small share as compared to other Nordic countries. Moreover, most variations are small (half of all observed variations do not exceed 1.2 % of installed wind power capacity). This is explained by high geographic dispersion as well as the large total size of the country.

Regarding hourly day-ahead wind power forecast errors, the main result of the study was that hyperbolic distributions are more appropriate to approximate wind power forecast error distributions than normal/Gaussian distributions are. This holds for Sweden as well as for all other countries included in the study. As a side result, it was shown that hourly day-ahead forecast errors for wind power generation on Sweden do not to exceed values between $-40\,\%$ and $20\,\%$ of installed wind power capacity and that $80\,\%$ of all forecast errors are between $-10.1\,\%$ and $7.5\,\%$ of installed wind power capacity.

Modelling internal and external ex-ante self-balancing

In order to tackle balancing needs, TSOs use balancing services during real time. Electricity markets can facilitate this task by giving market participants the possibility to adjust their positions before the period of delivery. This way, intraday trading and rescheduling can be based on new information with increased forecast accuracy. Hence, parts of the uncertainties can been handled already before real-time which on average reduces the need of activated balancing services.

Possibilities for individual market participants to adjust their positions based on latest generation/consumption forecasts might be very limited if they would have no possibility to trade with other market participants. However, BRPs can aggregate power plants of different market participants and power plants of different generation types and, hence, have more available flexibility. Still, depending on the size of the BRP, this flexibility can be small compared to the potential that could be accessed through well designed intraday markets.

In general, BRPs have two possibilities to balance their positions based on latest generation/consumption forecasts as investigated in Chapter 4: they can reschedule their own power plants (internal ex-ante self-balancing), they can trade energy with other BRPs (external ex-ante self-balancing) and they can combine both possibilities. Basically, ex-ante self-balancing is a way to move parts of the balancing task from the TSO's level to the BRPs' level. This can be efficient because flexibility provided in the intraday time-frame has different characteristics than balancing services provided by power plants in real-time. The latter ones have to fulfil higher requirements because they need to be available *at specific times* during the period of delivery. Therefore, parts of available intraday flexibility might otherwise remain unused.

If BRPs cannot trade energy in the intraday time-frame to adjust their positions, they are left with the possibility to rescheduling their own generation/consumption or to simply leave all expected imbalances to the TSO for balancing. Being limited to the flexibility that is available in those power plants for which a BRP is balance responsible for, significantly reduces efficiency because other BRPs might have spare flexibility that would be cheaper to use. The simulation results in Section 4.3.3 showed, that pure internal ex-ante self-balancing is not efficient. The main reason is that the TSO, in contrast to BRPs, can access flexibility from all market participants that put offers on the balancing market. In addition, the TSO would not need to balance each BRP's imbalance, but only the aggregated imbalance of all BRPs. However, with increasing wind penetration levels, net imbalances might become significantly larger compared to today's net imbalances which can increase the cost of balancing. Especially as "high quality" balancing services will be used instead of using flexibility that is available in the intraday time-frame to profit fromt increased forecast accuracy of wind power forecasts with short forecast horizons.

Including trading, ex-ante self-balancing can facilitate system balancing in a cost-efficient way under one of the following conditions: either all available flexibility is offered on the intraday market or generation and rescheduling costs for balancing services exceed those of intraday flexibility. In the simulation done in Section 4.3.4, not all flexibility was offered on the intraday market. But even in such a case, the cost difference between self-balancing flexibility and balancing services was moderate. Because the case studies were based on a simple test system, the exact value of the applied cost factors is not meaningful. However, modifying those cost factors shows that there is a point where advantages (access flexibility with low generation and rescheduling costs) dominate disadvantages (balance each BRP's expected imbalance instead of the total observed net-imbalance).

To conclude, it should be emphasised that the findings of this chapter support the common opinion that intraday trading can be a key element to facilitate integration of vRES. Therefore, it is important that intraday markets are designed in a way that allows BRPs to efficiently use the available intraday flexibility.

Analysis of intraday trading in northern Europe

In Chapter 5, a detailed study of trading activity and price development on Elbas was presented. Especially the possibility to decide whether to trade now or in a few minutes, increases complexity significantly; both with respect to the market participants' trading decisions as with respect to ambitions of modelling their trading behaviour. The study showed that market participants are exposed to significant price variations for the same good (energy for delivery/withdrawal during a specified hour) during the time trading is possible for that specified hour. These price variations complicate the decision making process of power generating companies because it might always be (more) profitable to wait and to trade at a slightly later point in time. It should be recalled here, that this is no peculiarity of Elbas, but a characteristic that is inherent to all platforms for continuous trading (the most prominent examples are stock exchanges). To a smaller extent, this will also be the case if intraday markets are designed as a sequence of several discrete auctions.

Analysing volumes and numbers of trade, differences in trading activity between price zones, hours of delivery and time of trade have been observed. Here some examples: there are very few trades between the Netherlands/Belgium/Estonia and the Norwegian price zones; there are fewer trades for early hours of delivery than for later hours, trading activity is low the early morning as well as long before gate closure. These examples should give an impression how unevenly trading activity is distributed.

It should also be observed that the underlying demand for intraday trading cannot be quantified because only data on successfully settled bids/offers could be accessed. Therefore, it is impossible to estimate whether low trading activity is due to not existing demand for intraday trading or to liquidity issues. However, the results of the analysis supports the assumption that available transmission transmission capacity and differences in the distribution of balancing prices are likely to influence trading activity.

6.2 Policy implications

This thesis includes policy recommendations in two areas that are also suggested as important areas for further research: design of intraday markets and imbalance settlement rules.

Regarding intraday trading, it needs to be investigated to which extent continuous trading platforms can provide efficient possibilities for intraday trading. It is questionable whether continuous trading is an adequate market design for electricity markets where an increasing share of balancing needs stems from wind power generation and other vRES. Power plants that use weather-dependent resources, exhibit significantly higher forecast accuracy the closer the forecast horizon. If forecasts are continuously updated from day-ahead to hour-ahead time, forecast generation levels are likely to oscillate, i.e. even though forecast errors are on average reduced, consequent continuous trading according to each update will lead to trading forth-and-back. This should absolutely be avoided [68, 69]. Therefore, design of intraday markets might need to be adjusted to fit tomorrow's power systems.

Ex-ante self-balancing described the possibilities of BRP to achieve balanced positions and was found to be an important element that can facilitate an efficient handling of wind power forecast deviations. Therefore, the incentives that BRP have to achieve balanced positions according to their latest generation/consumption forecasts are of importance, too. In the Nordic countries, the incentives for BRPs include both financial and legal incentives. Financial incentives are set by exposure to imbalance costs; legal incentives comprise obligations in the balancing agreement that both BRPs and TSOs agreed upon. An example for the latter one is the obligation in the Swedish balancing agreement not to have systematic imbalances. This implies that BRPs have to achieve balanced positions based on latest generation/consumption forecasts. Violating this obligation can result in termination of the agreement which implies that the BRP looses its role [27]. It is, however, difficult to assess the BRP's effort to achieve balanced positions because generation/consumption forecasts are private information of each BRP. In addition, the definition of imbalances in the Nordic countries opens for possibilities to move expected imbalances between expected and planned generation to the consumption imbalance. This can have two effects: first, it might be harder to track a BRP's effort to reach a balanced position, and second, it might affect incentives for all forms of ex-ante self-balancing. Therefore, this topic should be investigated. A possible solution could be to introduce binding consumption plans and to calculate one imbalance with regard to deviations between trading and these plans and one with regard to deviations from these plans during the period of delivery. Furthermore, this solution should include that all imbalances are priced according to the Nordic two-price system. Such an investigation should also be part of future research.

6.3 Suggested future research questions

At the end of Chapters 3, 4 and 5, suggested research questions for the areas discussed in the respective chapter are outlined. Four topics which I consider most interesting and relevant, are briefly outlined in the following. Please check the corresponding sections at the end of each chapter for more details.

There are many interesting research questions in the area of continuous intraday trading. For example, to study and to simulate effect of price variations on market participants' trading activity. This requires a detailed model of trading on continuous intraday markets. Such a model should, for example, consider that trading activity is higher shortly before the period of delivery. It should also include elements of risk management in the market participants' strategies. This would be of high importance. Finally, it would be interesting to include external limitations, e.g. imposed by limited transmission capacity.

However, also alternatives to continuous intraday trading, should be part of further research. One straight-forward suggestion is to investigated whether discrete auctions with uniform pricing would be a more suitable intraday market design for power systems that are to a significant share based on vRES.

Another important topic for further research is a detailed estimation or rescheduling costs for different types of power plants. Such estimations would also allow to investigate the effects of the Nordic imbalance settlement rules more in detail. This should include simulations in which situations market participants would change their planning and trading behaviour if alternative rules would be applied and which flexibility this would make accessible. Finally, such a study could focus on the question to which extent current imbalance settlement rules should be adjusted in order to facilitate balancing of vRES.

Of course, there are many more challenges within the areas of power generation and competitive electricity markets that need to be tackled in order to efficiently and effectively mitigate climate change, destruction of our environment as well as an unsustainable and inefficient use of natural resources.

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To facilitate literature search in the electronic version of this thesis, a doi/url is provided wherever a fulltext is available online; all links have been checked in June 2015.

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