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Optimal Production Balance with Wind Power

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Preface

This thesis is submitted in partial fulfillment of the requirements for the degree of master of science (M.Sc.) at the Norwegian University of Science and Technology (NTNU) in Trondheim. It is weighted with 30 credits on the final diploma. The work done in this report is supported by TrønderEnergi AS. My supervisor has been Professor Gerard Doorman and my contact at TrønderEnergi has been Gunnar Aronsen and Magne Røen.

Acknowledgements

I would like to express my gratitude to my supervisor, Professor Gerard Doorman, for his guidance and encouragement throughout the work of this report. Also a great thanks goes to Hossein Farahmand and Gro Klæboe, for their constructive feedback and valuable discussions. Furthermore a thanks is owed to Gunnar Aaronsen at TrønderEnergi for his guidance and help. A great thanks is also owed to Morten Hegna of Montel AS, for letting me participate in the conference "Nordic Price Drivers" in Oslo in April and for setting up a student account at Montel.no.

My colleagues at the office have throughout the year provided an enjoyable work environment and kept the spirit high. A great thanks is therefore owed to Robert, Sigurd, Runa, Henrik, Raghav, Kristin and Ingri.

Abstract

Maintaining a continuous balance between generation and load is crucial for the safeguarding of the power system. To efficiently deal with uncertainties and unexpected events the TSOs procure balancing services through the so-called balancing markets.

The variability and low predictability of the wind speed makes handling of balances a difficult task for wind power producers. Literature regarding the development of the balancing market and Elbas is presented. This research has found that the volatility in the balancing market are expected to increase as a result of cross-border integration of such markets. The low liquidity in the Norwegian Elbas market are expected to rise, as the need of an intraday market becomes more imminent. With increased investments in renewable energy and cross-border capacity the balancing markets are expected to change. With higher volatility in the markets the balancing of production will come at a higher cost. In this report the current wind power balancing done by TrønderEnergi is presented and some possible improvements to better handle the balance, are drafted.

The wind power production error and the price in the balancing market are modeled. A Monte Carlo analysis is carried out for three different alternatives:

1. Settling the imbalances in the balancing market.

2. Settling the imbalances in Elbas.

3. Settling the imbalances by using the re-bidding procedure.

The parameters are modeled stochastically, so the simulations are carried out a large number of times to get conclusive results.

It is the findings of this thesis that the implemented two-price system in the production balance leads to a large deficit when balancing the wind power production. The procedure currently used at TrønderEnergi saves the company a significant amount per annum, but as Elbas matures, this market should be exploited for reducing the costs of balancing and possibly profit seeking operations.

Samandrag

Å opretthalda ein kontinuerleg balanse mellom forbruk og produksjon av straum er essensielt for tryggleiken til det elektriske kraftsystemet. For å effektivt kunne takla usikkerheit i forbruk og produksjon, samt uforutsette hendingar sikrar systemansvarleg balansetenester gjennom regulerkraftmarknaden.

Usikkerheit knytt til vindstyrken gjer balansehandteringa til ei vanskeleg oppgåve for produsentar av vindkraft. Litteratur som omhandlar utviklinga til regulerkraftmarknaden og intradag markedet, Elbas, er presentert i denne rapporten. Dette litteratursøket konkluderer med at volatiliteten i regulerkraftmarknaden er spådd og auke. Dette grunna internasjonal integrering av denne marknaden. Det er vidare forventa at den låge likviditeten i Elbas skal ta seg opp, då ettersprselen etter ein slik marknad vil auke. Dette grunna investering i uregulerbare energikjelder og overføringskapasitet til utlandet. Auka volatilitet vil medføre høgare kostnadar i handteringa av vindkraft. I denne rapporten er ubalansehandteringa til TrønderEnergi presentert og nokre forbetringar er føresltt.

Usikkerheita i vindkraftproduksjonen og prisane i regulerkraftmarknaden er modellert og Monte Carlo simuleringar er utført for tre forskjellige alternativ.

1. Handtere ubalansen i regulerkraftmarknaden.

2. Handtere ubalansen i Elbas.

3. Handtere ubalansen etter hengetimeprinsippet.

Sidan dei forskjellege parameterane er stokastisk modellerte er simuleringane gjentekne eit stort antall gonger, for å gi konkluderande resultat.

Denne rapporten konkluderer med at den implementerte prosedyren hjå TrønderEnergi sparar dei for store kostnader årleg, men dersom Elbas utviklar seg som spådd, bør denne marknaden utnyttast for å redusere balansekostnadene.

Abbrevations

Abbrevation	
ACER	Agency for Cooperation of Energy Regulators
BRP	Balance Responsible Party
BSP	Balance Service Provider
DK	Denmark
ELBAS	Electrical Balancing Adjustment System
EMPS	European Multi Power market Simulation
ENTSO-E	European Network of Transmission System Operators for Electricity
ERGEG	European Regulators' Group for Electricity and Gas
EU	European Unioin
GE	Germany
NL	The Netherlands
NO	Norway
NORWEA	Norwegian Wind Energy Association
NPS	Nord Pool Spot
NVE	Norwegian Water Resources and Energy Directorate
NWP	Numerical Weather Prediction
OMEL	Iberian Market Operator Energy - (Operador del Mercado Iberico de Energia)
PDF	Probability Density Function
PSST	Power System Simulation Tool
SARIMA	Seasonal Auto Regressive Integration Moving Average
TSO	Transmission System Operator
WPP	Wind Power Production
WPPT	Wind Power Production Tool

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Chapter 1

Introduction

1.1 Introduction

This report deals with the increasing investments in wind power in the Nordic and European system. With increased integration of wind power the generation optimization and balance handling of a power producer will become more difficult. The object of this thesis is to examine how the integration of wind power will make the operations of a power producer more difficult and attempt to suggest some measures to handle this challenge. Different procedures used to handle the imbalances have been modeled. The results give a clear indication of how to most cost efficienttly balance the wind power production. The work in this report is supported by TrønderEnergi and focuses on how they should handle their balances in the future.

1.2 Problem Definition

The current expertise and knowledge of the handling of the production portfolio at TrønderEnergi is mostly directed towards the handling of the hydro power production. Integration of the intermittent wind resource has proven to be a challenge. The output of the wind farms can not be controlled, and the production can not be stored for production at a later time. The hydro power optimization is supported by great infrastructure and experience at the company and supported by computational optimization tools. As the firm is penalized if the traded volume in the day-ahead market do not match the actual production, the balance handling becomes a challange that TrønderEnergi would like to investigate more. The problem for TrønderEnergi is that with the penalizes the company often receive less then the spot price for their wind power production. It should be specified that when the terms losses are used this do not refer to an expenditure. The current spot price in the dayahead market is the value of the production and the intraday balancing prices often vary from this.

Therfore the losses found are the difference between the value of production (spot price) and what they actually get paid (the balancing price). In other words, if there are no imbalances TrønderEnergi would get spot price on all production and there would be no losses.

With increasing amounts of wind power, both in TrønderEnergi's production portfolio and in the power system, the losses associated with handling of the balances are predicted to increase. With this in mind TrønderEnergi want to increase their expertise around this issue. The purpose of the thesis is to evaluate opportunities to optimize production balance, taken specifically into account the uncertainty in wind power production. The following sub tasks are included:

1. Investigate various methods to improve production balance, e.g.

   - Use of intraday market, Elbas.

   - Updated forecasts for the prices in the balancing market.

   If time permits, and if found relevant, also:

   - Use of own hydro power resources.

   - Better wind forecasts and/or better use of existing forecasting.

2. After discussion with supervisors, implement a procedure of own choise into a (simple) simulation tool. This can be a tool that e.g. provides decision support regarding the use of Elbas or the balancing market and the possible use of own hydro power. The model should take into account the specific conditions at TrønderEnergi, but some simplifying adjustments can be made

3. Evaluate/discuss the result and suggest further work.

1.3   Report Outline

In Chapter 2, the current Norwegian and Nordic system is described and the functioning of the power markets are explained. This includes the day-ahead market, the intraday market and the balancing market. The financial markets are not subject to this report. The cross-border trading of power at the current time is examined and the future development of wind power in Norway is sketched and the corresponding problems discussed.

In Chapter 3 a case study of the current operation of Bessaker wind farm is presented. Then the future development of the balancing market and the intraday is presented. The future development of the day-ahead market is mentioned, but is outside the scope of this report. Furthermore, the benefits and drawbacks of internal balancing handling is described. Then the future development of more accurate weather forecasts is examined.

The relevant parameters when evalutating the costs of balancing is modeled in Chapter 4. Simulations of the different balancing aproaches are done, and the results are presented. These results are discussed in Chapter 5 and conclusions are made in Chapter 6. Some cues for further work are presented in Chapter 7.

1.4   Work Structure

The object of this thesis is as mentioned to increase the knowledge of how increased penetration of wind power production will affect the imbalances of a producer, and to suggest some measures to handle this challenge. This is done by first conducting a litterature serach on the respective areas. Then modeling of the different parameters is done and the different options of handling the balancing volumes are simulated. The results are discussed and a conclusion is made.

Chapter 2

The Nordic Power System

2.1 The Nordic Power System

In this section the nordic power system is described. The Nordic power system includes the Nordic countries Norway, Sweden, Finland and Denmark-East. Denmark-West is synchronized with continental Europe.

In general this system can be categorized as a hydro/thermal power system. The Norwegian power system is dominated by hydro power production facilities representing around 97% of the installed capacity and annual production. In Sweden hydro and nuclear power make up approximately 45% each. In Finland hydro power covers around 20% of the annual electricity consumption while the remaining 80% are covered by thermal power plants. The environmental policy, in combination with feed in tariffs and investment incentives establish the legislative framework for renewables in Denmark. This has provided good conditions for investments in wind technology. Wind make up about 20% of the Danish power production, while the remainder of production is covered by coal, gas and biofuels. The production portfolio of the Nordic countries is shown in Table 2.1.

	Denmark	Finland	Norway	Sweden	Total
Hydropower	0,0	12,8	117,3	66,2	196,3
Nuclear	0,0	21,9	0,0	55,6	77,5
Other thermal power	29,0	42,0	5,3	19,7	96,0
Wind	7,8	0,3	0,9	3,5	12,5
Total production [TWh]	36,8	77,0	123,5	145,0	382,3
Total consumption [TWh]	35,6	87,4	128,4	141,5	392,9

Table 2.1: Power production in the Nordic countries 2010 [TWh] [35].
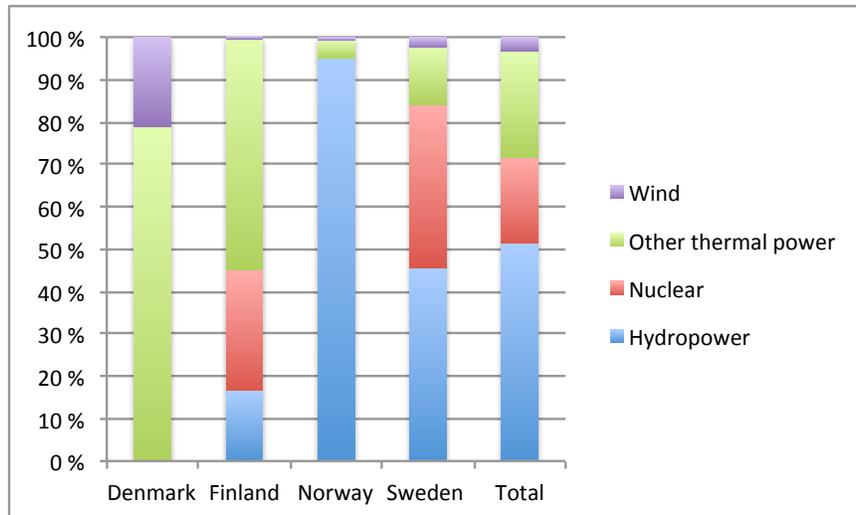
Figure 2.1: Power production in the Nordic countries 2010 [35].

As seen in Table 2.1 and Fig. 2.1 the Norwegian power system have a large proportion of hydro power production. Hydro power plants provide a high production flexibility in combination with relative low marginal production costs. The reservoirs can store water over days and seasons and this gives the opportunity to produce when the prices are high. In reality the production is based on the demand. With the flexibility the hydro power possesses the producers may adjust their price bidding in the market based on the current- and expected reservoir levels. For a hydro electric power plant the marginal cost of production is very low[1], so the value of the water is set according to the opportunity cost of using the water. The opportunity cost reflects the expected value of future production. The producers now have to take into account the possibility of higher or lower prices in the future. The most important factors affecting the value of the water is the filling of the reservoirs, time of the year, the expected inflow and the price of alternative energy sources.

2.2 The Nordic Power Market

In this section the basic functions of the physical Nordic Power Market are described. In this project only the physical market solutions offered at Nord Pool Spot are described[2]. Nord Pool Spot runs the leading power market in Europe and offers both day-ahead and intraday market to its customers [4]. The exchange is owed by the nordic TSOs; Statnett SF, Svenska Kraftnat, Fingrid Oyj, Energinet.dk and the Baltic TSOs; Elering and Litgrid.

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[1]High investment cost and low operational cost over a long lifetime.
[2]The financial Nordic power market is operated by Nasdaq OMX

Time	Business procedures
10:00	Transmission capacities published on NPS web
12:00	Gate closure
12:02	Market coupling Nordic-Germany
12:20	NPS price and flow calculation Nordic market
13:00	Publication of prices in the Nordic area
14:00	Settlement

Table 2.2: Business procedures for Nord Pool Spot [39].

2.2.1 The Day-ahead Market - Elspot

The day-ahed market, Elspot, is the main area for trading power in the Nordic area. Elspot is the physical market of power trading with delivery the next day. In this market all participants must submit their bids for the forthcoming day within 12:00 CET. The supply, demand and transmission capacities determine the price in each area for each hour. The business procedures for each day in the Elspot-market are shown in Table 2.2.

The producers in the system can submit either single hourly bids or block bids in the market, and the market price is found where the supply and demand curves intercept. The system price is the price found with the assumption that there are no physical transmission constraints in the system. This is an important benchmark that is used as a reference in the financial market.

With the general conditions mentioned in Section 2.1 the hydro power production have a relative low price and are located to the left in the merit order of the system, as seen in Fig. 2.2.

In Fig. 2.2 the supply and demand curves for the whole system are shown, and the system price is found. The figure also illustrate how the average price over one year will change, depending on if it is a dry, wet or normal year. In a normal situation there are different price setters in the countries.

In Norway the hydro power production normally sets the price. In Sweden the nuclear or hydro power is the price setter, while in Finland there often is a mix of nuclear and other thermal power. In the Danish system gas or coal based power production sets the price. In countries where hydro is the price setter, the hydrological balance is essential. In situations with high reservoir levels the prices are often very low compared to other countries and with low reservoir filling the prices tend to be high.
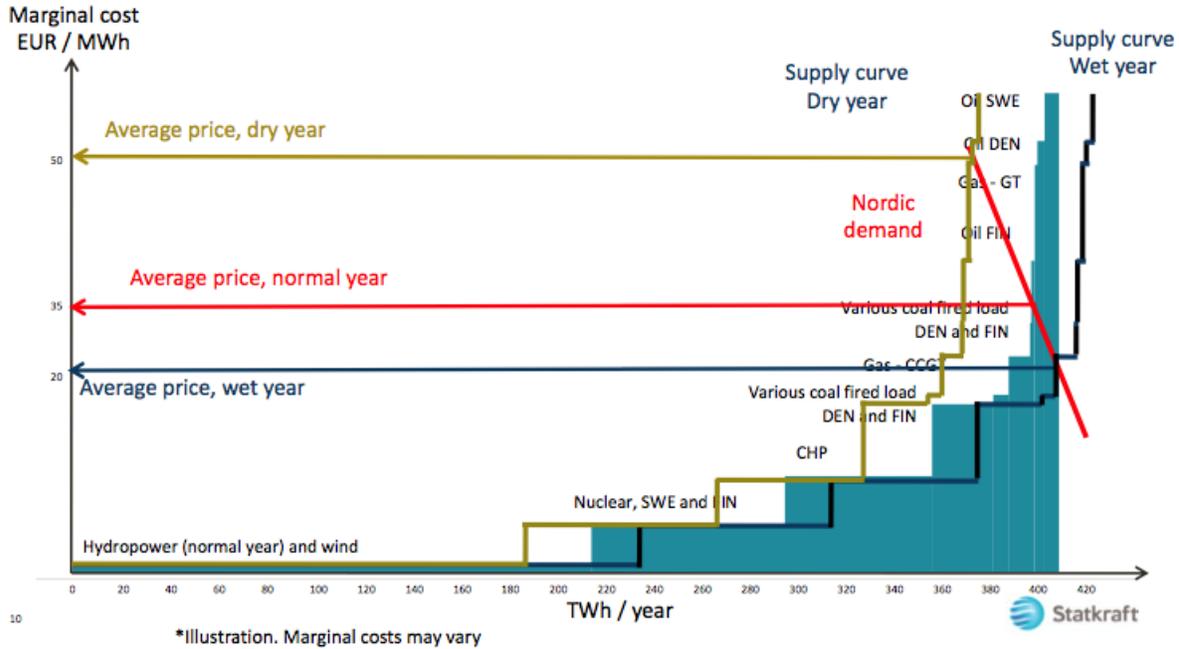
Figure 2.2: Schematic illustration of the merit order in the Nordic electricity market for a normal year [41].

2.2.2 Balancing Markets

In the Norwegian system two different trading setups are used and two different imbalances are calculated. The TSO is responsible for the balancing of consumption and production. An imbalance results from production or demand deviations differing from the prescheduled day-ahead results. One imbalance is calculated for production and one for consumption and trade. The imbalances are different with respect to calculation and penalties. The definition of the production imbalance is given below:

$$Production \quad imbalance = Actual \quad production - planned \quad production$$
$$+ active \quad regulations_{production} \quad (2.1)$$

Where planned production is the last production scheme. This can be changed, in accordance with Statnett, no later than 45 minutes before the hour of operation.

If the actual production deviates from the schedule the producers will adjust their output in a manner that is most profitable. To prevent the producer from taking speculative positions the production imbalance is priced after the two-price model. The two-price model sets the imbalance price based on the required balancing support. If the balance responsible party (BRP) supports the needs of the system, the imbalance will be priced after the current spot

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price. If the BRP do not support the need of the system, the imbalance will be priced after the price in the balancing market. The TSO is at all times responsible for the balancing of the production and consumption of electricity. As these factors may randomly change the TSO take measures to ensure the compliance between the consumption and production. When they do not match the system is either over supplied or under supplied.

In the two-price system the TSO will se an economic surplus equal to the difference between the current spot price and balancing price, while in the one-price system the TSO will break even. This, however, is not the driver for implementation of the two-price system. In the one-price system the players can take speculative positions, which makes the frequency control more difficult as the actual production is more uncertain. Taking speculative positions refers to situations when the producers on purpose produce some volume of imbalance according to expected state of regulation. For example if a producer expects upward regulation in the hour at hand, he increases the production as the additional production will be better priced then the spot production.

The two-price system can be explained using an example. Suppose that a producer e.g. TrønderEnergi in one hour is producing less then what they are obliged to. We then say that TrønderEnergi is under balanced. They have already sold the planned production, so now they have to enter the market and buy back their balance deficit. If the system is over supplied TrønderEnergi supports the needs of the system and can buy back their deficit at spot price, at the same amount they initially sold it for. If in the given situation the system is under supplied the price of balancing power will be higher then the spot price and TrønderEnergi will have to pay more for the electricity then what they sold it for. In the best case scenario the producers will break even in handling their imbalance. This gives the producers an economic incentive to comply with their schedule.

The pricing of the imbalance is shown in Table 2.3.

Production imbalance	Under supplied	Over supplied
Producers deficit	RK price	Spot price
Producers surplus	Spot price	RK price

Table 2.3: Price structure of producers imbalance [21].

An example of how the price in the two-price system varies throughout the day is shown in Fig. 2.3.

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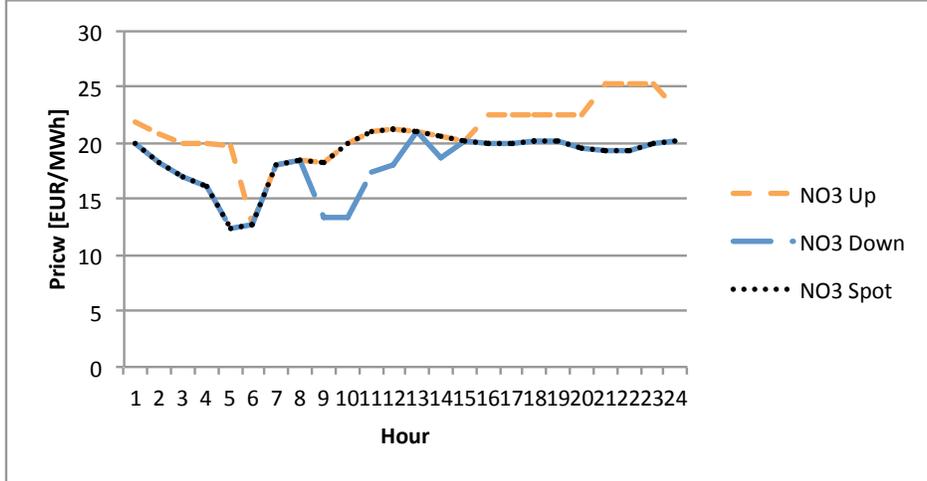
Figure 2.3: An example of the price in the balancing market. [28]

If the market is under supplied the spot price will equal the price of upward regulation, and the price of down regulation will equal the highest accepted bid. From the example in Fig. 2.3 we see that in hour 1-5 and 16-24 the market was under supplied and hour 9-12 and hour 14 was over supplied. In hour 15 the market was in balance, as the three prices are the same.

All of the BRPs also have to relate to the consumption and trade balance, hereafter denoted as the consumer balance. In this balance the consumption is weighted with all trade and planned production. The balance definition is:

$$Consumer \quad balance = Planned \quad production + Actual \quad consumption$$
$$+ Trade_{prior \quad to \quad the \quad operating \quad hour} + regulations_{consumption} \quad (2.2)$$

In the definition sales and consumption are counted as negative. Unlike the production balance, the consumption and trade balance is priced after the one-price model, i.e. the balance is priced after the current balancing price. As a part of Statnetts exception scheme, power stations with total capacity of under 3[MW] are calculated as consumption. This is an exception meant to ease the production planning for small scale power plants and hence boost investment in this sector. For simplicity the consumption and trade balance is hereafter referred to as the consumer balance.

2.2.3 Balance Sheet Example

To get a deeper understanding of how the different imbalances changes with measures done by the BRP a simple example is presented.

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Initially we assume that the reported spot production is 100 [MWh] and that the reported consumption is 100 [MWh] and that there is no active regulation in the operating hour at hand. If the actual production is 90 [MWh] and the consumption is 105 [MWh], the production and consumer balance becomes:

Production balance =	90 [MWh]	- 100 [MWh]	= -10 [MWh]
Consumer balance =	100 [MWh]	- 105 [MWh]	= -5 [MWh]

Table 2.4: Balance sheet example No. 1. Ref Eq. 4.14, and Eq. 4.15

If the BSP before the hour of operation suspects that the production will be lower then reported and the consumption will be higher, he or she can update its schedule. Assuming that the planned production was lowered to 98 [MWh] the production- and consumer balance becomes:

Production balance =	90 [MWh]	- 98 [MWh]	= -8 [MWh]
Consumer balance =	98 [MWh]	- 105 [MWh]	= -7 [MWh]

Table 2.5: Balance sheet example No. 2. 4.14, 4.15

By changing the production schedule we see that the production imbalance decreases and that the consumer balance increases. As mentioned in Section 2.2.2 the production balance is priced after the two-price system and the consumer balance is priced after the one-price system. By moving volumes from the two-price to the one price system the producer has the possibility to gain a profit on their imbalance opposed to the two-price system. Updating their production schedule will therefore in this case be beneficial, as the consumer balance increases and the production balance decreases. This procedure is hereafter referred to as the "re-bidding procedure." Further reading on this topic is found in Section 2.4.2 and a model of the re-bidding procedure is implemented in Section 4.4.6.2.

2.2.4 The Intraday Market - ELBAS

ELBAS is short for electrical balancing adjustment system and is a continuous intraday trading market operated by Nord Pool Spot. Elbas offers two products; hourly contracts and block contracts. The market is open every hour of every day and the gate closure differs from each country. In Norway the gate closure is 1 hour before the operating hour.[3] Any trades done in Elbas will be counted as trade before the operating hour in the consumer

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[3]As discussed later on the gate closure was changed from 2 hours to 1 hour on the 26th of February 2013

balance. The trade model used in Elbas is called continuous auction. In this model the lowest selling price and highest buying price are presented to the market first. If there are equal bids the "first-come first-served" principle applies. An example of the Elbas market is shown in Fig. 2.4.

Product	High	Low	Last	Avg	Volume
PH01121031	38.20	34.00	35.80	37.48	198
PH02121031	36.00	32.70	35.20	35.27	242.5
PH03121031	37.20	33.00	36.70	35.88	335.2
PH04121031	37.50	34.00	37.50	36.17	472.3
PH05121031	37.70	32.20	34.90	35.92	630.1
PH06121031	40.00	36.00	39.00	38.07	496
PH07121031	50.60	37.70	50.00	43.80	83
PH08121031	47.00	39.90	45.80	43.30	50.7
PH09121031	51.00	40.10	51.00	46.60	110

Figure 2.4: The first 9 hours of the ELBAS market on October 31st 2012. [33]

The column to the left in Fig. 2.4 is the identification of the hour of operation[4]. The first digits are the hour of operation and then the year, month and day follows. High represents the bid from the seller and low the bid from the buyer. If a market participant wants to buy it would have to pay the high bid, and if the participant wants to sell he or she would get paid the low bid. Alternatively the participants can submit bids themselves. This will generally encourage the players to bid close to the expected equilibrium point. This model is contrary to the market clearing model that is used in the Elspot- and balancing market. A downside with this model is that the market bids do not reflect the marginal cost of production. For this reason there is a possibility that the resources are not allocated in the optimal way. On the other hand, Elbas improves the competitiveness between the flexibility of thermal power plants and the flexibility of hydro power plants. The thermal power plants need longer time to adjust their output so if they are chosen as a provider of flexibility, the bids must be submitted within a certain period of time. For the hydro power plant the time of regulation is significantly shorter then for the thermal power plants. In the Elbas market both hydro and thermal power plants can submit their bids beforehand and the buyer of flexibility can choose between the sources of flexibility. With this in mind it is reasonable to assume that the benefit of the pay-as-bid model is greater than the drawback of not using the clearing model [21].

The Elbas market is a market where the BRPs can reduce their imbalance ahead of the hour of operation. Elbas has the advantage of knowing the price of regulation ahead of time. The

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[4]PH = Power hour

equivalent to Elbas is the balancing market, where the price of regulation is not known until the hour of operation.

By using the Elbas market the example in Section 2.2.3 can be updated. The producer suspects that he or she will produce less then reported to the spot market. By purchasing 2 [MWh] on Elbas the production balance can be reduced without increasing the consumer balance. After buying 2 [MWh] the production plan must be changed. This changes the production balance, but is offset in the consumer balance. The balance sheet becomes:

Production balance =	90 [MWh]	- 98 [MWh]		= -8 [MWh]
Consumer balance =	98 [MWh]	- 105 [MWh]	+2 [MWh]	= -5 [MWh]

Table 2.6: Balance sheet example No. 3. 4.14, 4.15

Buying in Elbas is accounted as positive while selling is accounted as negative. In reality the traded volumes are larger then 2 [MWh], but for consistency in the examples it is used here.

2.2.5   The Balancing Market

The balancing market is the tertiary tool used by the TSO to ensure the control of the frequency. In Norway all producers are obliged to submit bids on the available capacity for the forthcoming day. The TSO now arranges a merit order of the bids, where the cheapest bids are accepted first, and the last accepted bid is price setting in the market. Large consumers can also offer bids to reduce their consumption in any given hour[5]. In this way the TSO balances the system in a cost efficient way.

The price in the balancing market is essential for all BSPs as it is the acting price in the one and two-price system. As mentioned in Section 2.2.4, this price is not known prior to the operating hour and there is a risk that the imbalance for a producer can be very costly.

One should be aware of the differences between an active and passive imbalance. An active imbalance is when the TSO has accepted a producers bid in the balancing market. Now the producer have an active imbalance, and the compensation is priced after the latest accepted bid. A passive imbalance is a result of an unexpected event like change of consumption, tripping of a machine ect. The volume of imbalance is found by using equations 4.14 and 4.15. Lauritzen et.al. [21] states that this price system does not increase the financial risk for consumers and affects the financial risks for a producer to a small extent. The exception is producers with limited regulatory capacity. It is mentioned that such producers can eliminate the risk by changing their schedule continuously and by trade.

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[5]Minimum bid volume is 25 [MWh]

2.3 Trade between Bid Areas

Different prices in different areas is a result of insufficient transmission capacity in the Nordic transmission grid. With increased market coupling, the cost efficient production and consumption is allocated geographically apart. If the market efficient power flow exceeds the capacity of the transmission system, congestion occurs. Congestion can be defined as the inability of the transmission system to accommodate the energy flows arising from an unconstrained market settlement [7]. There are many ways to handle the congestion that occurs in the system. The Nordic TSO have chosen to use market splitting to manage the bottlenecks. This method consists of splitting the power exchange into geographical bid areas with limited exchange capacity. First the market price is found by the supply and demand in the whole area. Then the TSO calculates the necessary power flow and identifies the bottlenecks. Geographical bid areas are now defined according to the identified bottlenecks and a new pool price is found. Areas downstream of a congestion will have a higher price and areas upstream will have a lower price [2]. In this way the market will give incentives to balance the production and consumption. In a surplus area the price will be low, so the consumer in the area will have an incentive to consume more electricity. In the deficit areas the prices will be high, which will give incentives to power producers in the area to increase their production. An example of two areas with insufficient transmission capacity is shown in Fig. 2.5.
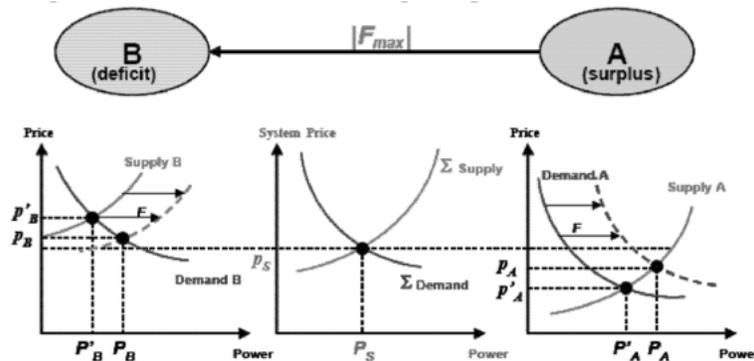
Figure 2.5: Market splitting [20]

In area B, with a deficit of power, the trade will be beneficial for the consumers as the increased supply decreases the price. The producers in the area will now receive a lower price for their production. In the surplus area the demand curve are shifted to the right and the price increases. This is beneficial for the producers in the area whilst the consumers have to pay a higher price for their consumed elektricity. We see from Fig. 2.5 that the social welfare will be maximized if there is sufficient transfer capacity. In this case both the consumer- and producers surplus is maximized.

With a market splitting approach the TSO will see profit equivalent to buying power in the

surplus area (area A) and selling it in the deficit area (area B). The revenue is equal to the price difference in the two areas times the actual flow of the interconnector. In a congested situation the actual flow is equal to F_{Max}:

$$Profit = (P_A - P_B) * F_{Max} \tag{2.3}$$

The TSO in Norway, Statnett, has stated that such profit will benefit the people through a corresponding reduction of transmission tariffs. There are currently a total of 15 price areas in the Nord Pool area[6]. This includes 5 in Norway, 4 in Sweden, 2 in Denmark and 1 in Finland, Estonia and Lithuania. There is also one price area that is difficult to geographical determine. The ELE area is a result of co-operation between the Estonian TSO, Elering and Nord Pool Spot to make power trades across the Estonian - Latvian border more efficient [37]. The price areas in the Nordic power system and the capacity of the interconnectors are shown in Fig. 2.6.

Figure 2.6: Nordic pricing areas after November 1st, 2011 [34].

In the nordic region cross country trading of electricity will be beneficial for all regions. The countries with a large share of hydro power production can ensure the supply of power in years with low rainfall and ensure higher prices in years with high rainfall. Hydro based power

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plants can regulate their output very quick compared to the thermal production units, and by such, comply with changes in the consumption at a lower cost. If the regulatory commitment is left to the hydro power producers, the thermal units can run their power plats with a higher efficiency throughout the year, and the hydro power producers can produce when the prices are favorable. For the Norwegian system this means that electricity will be imported when the prices are low, typically during the night, and exported when the prices are high. The net imports of the Norwegian system is shown in Fig. 2.7.
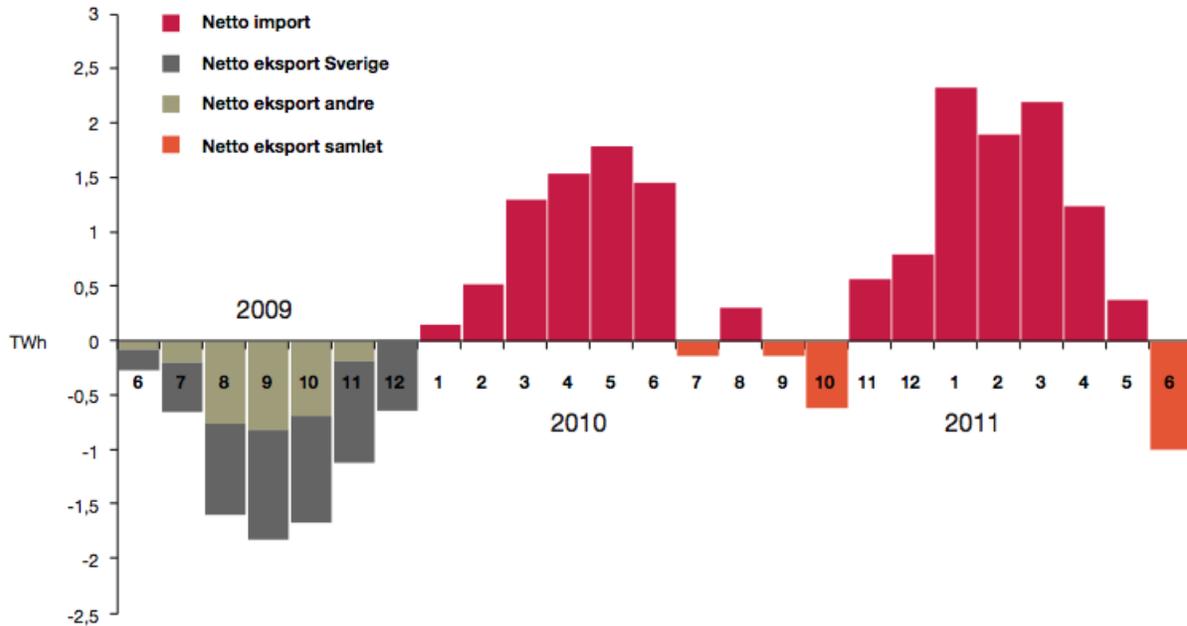
Figure 2.7: Net exchange in Norway, June 2009 - June 2011 [35].

Months with net import are shown as red positive columns and exports shown as negative columns. About two thirds of the exchange capacity is connected to Sweden. In 2009 the Swedish nuclear power was reduced due to troubles, and Norwegian hydro power contributed to ensure the power of supply in Sweden. In other situations, the Swedes have covered a deficit, for example in the middle of Norway. From Fig. 3.2 we see that net imports vary from year to year. There have now been two years in a row with challenging energy situations. There have also been many periods of weather that can be characterized as extreme compared to the statistics used for forecasting. The Norwegian TSO states that the electricity market worked well in this period by high utilization of import capacity to Norway. However, more extreme weather situations can lead to additional challenges in handling the balances.

Furthermore continental Europe and Great Britain are currently focusing on renewable energy sources. With higher penetration of intermittent resources the need for balancing power will be increased. This is elaborated in Chapter 3. Increased capacity between the hydro

power based Nordic system and the European system will facilitate an exchange of power, where excessive power can be stored in Norwegian reservoirs, so that it can be used when needed, either in Norway or Europe. This solution will promote more renewable power generation, while it facilitates the creation of wealth in both ends of the cables and increased the security of supply [35]. It is at a later stage pointed out that cross-border integration of balancing markets are on the horizon and that the intraday market is given all available transmission capacity after the day-ahead market is closed. Therefore, the transmission capacity to foreign countries will have a large say. For this reason, current operation of cross-border capacity and the development of the Norwegian interconnectors are included.

2.4 Wind Power Production

2.4.1 Installation Scenarios

In this section the possible outcomes of increased integration of wind power are discussed. For an investor considering investment in wind power the future spot and balancing prices are important factors. Increased penetration of wind power in the system will probably increase the volatility of the prices in the market, and one will possibly see bigger differences in the balancing prices and the spot price. To increase the knowledge on the subject, a case study of the market impact of integration of wind power in Denmark is suggested. In this case the differences of the power system also should be studied, and it should be concluded if a comparison is valid.

At the moment, fluctuations in the intermittent resources in Norway are compensated by increased production from hydro power facilities. As the share of unregulated resources are small, this is not a problem. With increased investment in wind and run-of-river power plants this may change.

As mentioned above, the environmental policy of the Danish Government has given incentives to invest in wind power. As a result, Denmark started its investments in wind power in the early nineties. The installed capacity and yearly production in the Danish system is shown in Fig. 2.8

As seen in Fig. 2.8 the installed capacity in Denmark increased from under 500 [MW] to over 4000 [MW] in a period of 15 years, and the production from approximately 1000 [GWh] to 10 000 [GWh], depending on the wind speeds in the relevant year.

If we consider the balancing market in itself, the fluctuations in price will be reduced if a stable production from the intermittent resources is expected. It has been pointed out that this is possible by diversification of the power plants, both in geographical location and in technology. The geographical diversification is desirable as the weather conditions will differ in different areas. With a sufficient transmission system and market, a stabilized expected production can be achieved.
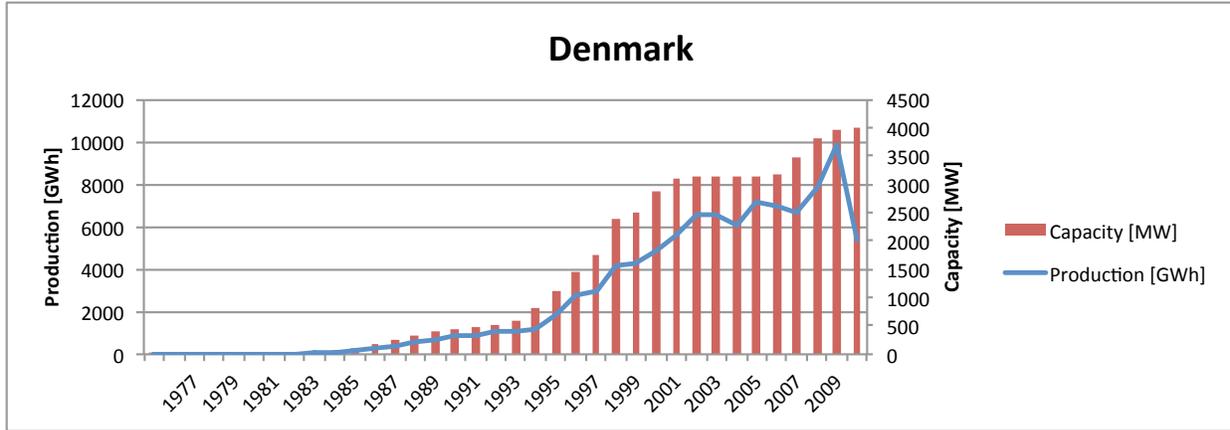
Figure 2.8: Yearly installed capacity and production in the danish power system. [29]
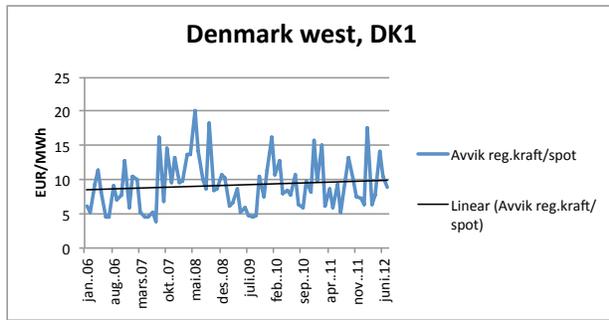
Figure 2.9: Deviation between spot and balancing prices in DK1 [29].
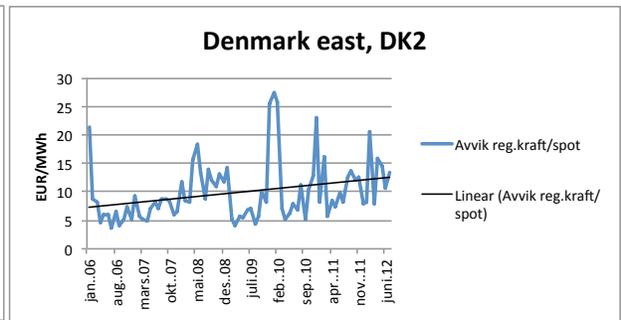
Figure 2.10: Deviation between spot and balancing prices in DK2 [29].

Fig. 2.9, Fig. 2.10 and Fig. 2.11 shows how the difference between the spot and balancing prices have developed since January 2006. The price difference has been calculated for each hour, and a monthly average of these have been plotted in the figures. Whether the regulation has been up- or down regulated is not illustrated, so it is the absolute value of the difference that is plotted. We observe an increasing trend as the installation of wind power has increased. Data from 2006 is used, as the danish TSO, energinet.dk do not have data from earlier times.

Compared to Fig. 2.8, the percentage increase of installed wind capacity in Norway is relatively small. Despite this, one can see that the balancing prices become more uncertain.

Furthermore, the variance and standard deviation for the curves are calculated. This is done for the monthly average and for each hour. The results are shown in Table 2.7.

The results of these calculations are somewhat unexpected. One would expect a larger difference in the two systems. As Denmark has 20% wind power and 80% thermal power plants one would expect a bigger difference between the spot- and balancing price, than in
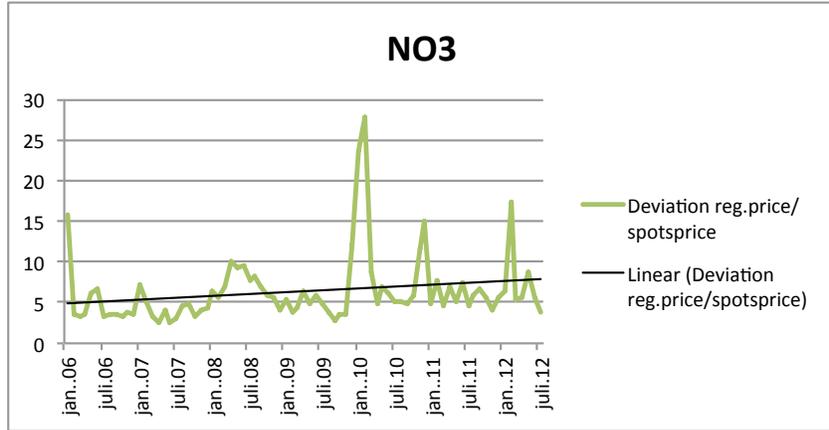
Figure 2.11: Deviation between spot and balancing prices in NO3 [29].

Area	Standard deviation monthly averages	Standard deviation hourly values
DK-West, DK2	3.66	23.80
DK-East, DK1	5.36	30.13
NO3	4.25	25.10

Table 2.7: Variance and standard deviation for DK1, DK2 and NO3 [29].

Norway with 98% hydroelectricity.

A possible reason for the unexpected results may be experience and adaption. As shown in Fig. 2.8 the large-scale development of wind power started in the early nineties. Over a twenty year period it is possible that the participants in the Danish power market have a great knowledge and experience in wind power expectations and are able to predict the production for the forthcoming period. Furthermore, a penetration of 20% is significant so the diversification effect, discussed in Section 2.4.1, may have an effect in Denmark.

As mentioned above, these results are relevant for the development in wind power in Norway. For this reason a short summary of the future investment in wind power in Norway is described. The development in Norway since 2001 is shown in Fig. 2.12.

The Norwegian regulator, Norwegian Water Resources and Energy Directorate (NVE), stresses that the collected data is somewhat simple, regarding both years of operation and the number of power plants. With limited data, individual events and special circumstances will have a large impact on the statistics. Furthermore, the regulator mentions that the production estimates for each wind power plant is too high.

When it comes to planned investments of wind turbines in Norway, there is a large technical potential supported by political goodwill. Fig. 2.13 shows the placement of wind farms where concession is given, concession is applied for and where concession is denied.
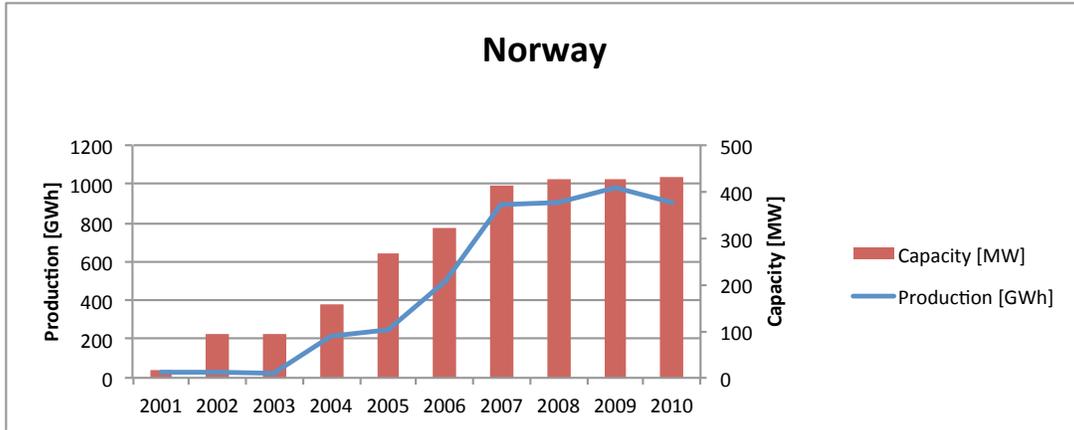
Figure 2.12: Yearly installed capacity and production in the Norwegian power system [29].

Figure 2.13: Geographical placement for planned wind farms in Norway [29].

From Fig. 2.13, we see that the areas with the most wind power development is along the coastline from Kristiansand to Stavanger, around the Bergen area, Florø and the Trøndelag-coast. Table 2.8 shows the extent of the planned production in Norway. The numbers are taken from NORWEA and NVE.

	Installed capacity [MW]	Production [GWh/year]
In production	527	1742
Under construction	228	753
Under consideration	23149	76492
Issued licenses	4575	12576
Planning completed	2713	7242
Licenses denied	3051	8740
Planned license application	380	1066

Table 2.8: Wind power licenses in Norway [29].

On the basis of these numbers it is reasonable to assume that Norway will see an increasing development in wind power similar to the trend in Denmark in the late nineties and two thousands. It should however be pointed out that a realization of all of the described projects is highly unlikely. It is pointed out that the Nordic and Central-European power systems will change significantly over the coming decades. Especially climate policies and market integration will lead to radical changes, from being a power system with relative predictable production to a system with more intermittent and unpredictable production and closer integration between the countries. The Swedish-Norwegian certificate marked has a goal to reach 26.4 [TWh] of renewable production in the two countries before 2020. About half of this is expected to be built in Norway [37].

2.4.2   Challenges with WPP

In this chapter some of the challenges and disadvantages of wind power production are described. Especially the handling of the production- and consumer balance is discussed.

Passive producers, such as run-of-river hydro and wind power have a disadvantage in the two-price system. As these are intermittent resources the production is only controlled by the wind speed and inflow of water in the hour of operation. Uncertain forecast gives significant imbalances. The deadline for changing the schedule is 45 minutes before the hour of operation. For the run-of-river hydro this may be acceptable, as the inflow does not change significantly over 45 minutes. Furthermore the prognosis for inflow is well developed as it makes a great difference in optimization of traditional hydro power plants. Therefore the production of run-of-river hydro is more predictable than the production of wind power plants. The run-of-river power plants normally has a high output when there is a lower demand, typically in the spring and autumn. In this period the prices are normally low

and the price of balancing correlates with this. The wind speed, however, may change significantly in only five minutes. In a larger area the short term variations will be smoothed out. In Denmark the maximum hourly production change is approximately 15-20% [1]. This represents a risk as an imbalance of 20% at an unfavorable time can represent a great challenge when handling the balances.

Furthermore, there are speculations that a major investment in intermittent renewable energy sources will lead to higher fluctuations in both the spot and balancing prices. Increased volatility in the power markets increases the risk for economic losses in the production imbalance. For this reason it may be unfavorable for a producer to have large penetration of wind in the production portfolio, compared to flexible hydropower.

Today the production schedule for wind power is established on the basis of future projections of the wind speed, provided by the weather services Storm.no and the Norwegian Metrological Institute. These have proven to differ from actual wind speed. As mentioned above, the production schedule can be changed 45 minutes before the hour of operation. An alternative method for the wind forecasting has been developed and proven to be better than the current projections. In this alternative method the production of the next hour is scheduled as the measured production this hour. The production scheme is changed and sent to the TSO 45 minutes before the hour of operation. This method is hereafter referred to as the re-bidding procedure. An example of the two procedures is shown in Fig. 2.14.
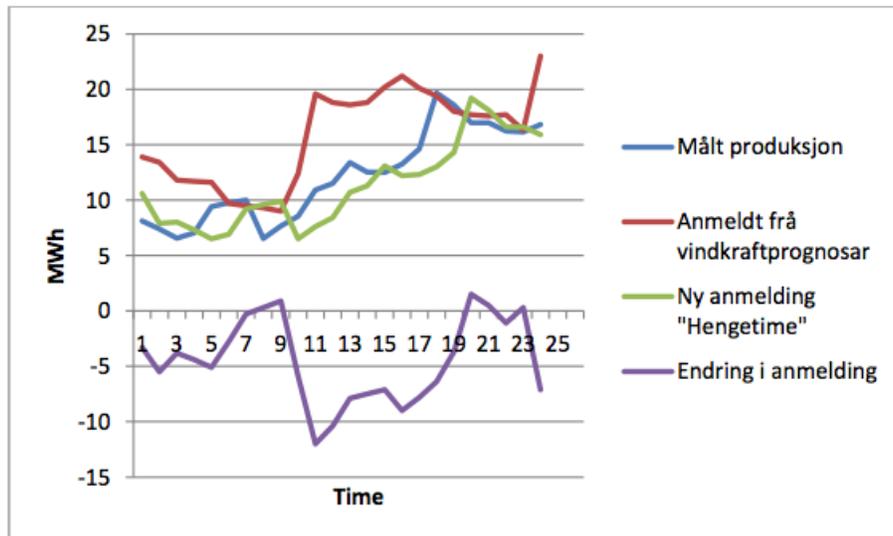
Figure 2.14: Actual production, projection and the re-bidding procedure. Bessaker wind farm - July 8th, 2012 [29].

The red line represents the production reported to Nord Pool Spot according to weather forecasts and the blue line is the actual production. The green line is the production reported one hour ahead and set equal to the production in the current hour. We see that the

green line is more accurate then the red line. The purple line represents the change of schedule in each hour. We see that the modified method matches the production profile better than the prognosis. The total change of schedule in this example is 73.65 [MWh] [29]. The forecast error over 24 hours is hardly conclusive. This example is included to get a better understanding of how TrønderEnergi handle the imbalances caused by Bessaker wind farm.

For a wind power producer it is desirable to have the imbalance priced after the one-price model. In this model the producer has the possibility to gain a profit on their uncontrollable imbalance. Therefore it is beneficial to have most of the imbalance in the consumer balance shown in Eq. 4.15. In this equation the term trade prior to the operation hour is the trade done in the Elspot and Elbas market witch Nord Pool Spot operates. In the spot market the trade is done 12:00 CET the day before. This scheme is set up according to weather forecasts provided by Storm.no and the Norwegian Metrological Institute. The term trade before operating hour can be changed intraday by using Elbas, but this is not considered in this section. By changing the planned production for the next hour, the production imbalance is hopefully reduced, as the modifications done normally are more accurate than the weather forecasts.

When changing the production schedule 45 minutes before the hour of operation the producers change the planned production for the forthcoming hour, reducing the difference between actual and planned production. This will reduce the imbalance in the production balance in equation 4.14. The original schedule is delivered for each hour before 12:00 CET the day ahead, and is according to different weather forecasts. Furthermore, the difference between planned production and trade prior to the operation hour will increase when changing the planned production, so the consumer imbalance in Eq. 4.15 is increased. In this manner some imbalance is moved from the production balance to the consumer balance. This is as mentioned desirable as the consumer balance is priced after the one-price model, while the production imbalance is priced after the two-price model. An example of how the balance sheet would be changed using the re-bidding procedure is found in section 2.2.3, and illustrated in Table 2.4 and Table 2.5.

Arne Kjell Nystad [24] in Statnett points out that increased integration of wind power will affect the time horizon in the balancing market. Nowadays it is the consumer gradient, not the production, that varies during the hour of operation. This will probably change with increased integration of wind power. With a more unstable production it will be harder to manage the frequency control, the balancing of the production and consumption. This will increase the need for regulations with a short time horizon, which will give unfavorable results for producers. In the active balancing market, the producers assume that if they are put into operation the start and stop costs will be covered when they get their demanded price in the hour of balancing. The TSO, however, have the right to activate the bids at any time. With a more uncertain production portfolio in the system, some producers may be activated for only 10-15 minutes. In such situations they will see a loss. For the next bid of balancing power, a reasonable producer will increase their bid. This, combined with

increasing demand for balancing power, may contribute to a increasing difference between the spot price and balancing price.

Chapter 3

Analysis of the Planning Situation

In this section different variables in handling the uncontrollable wind power production are analyzed. In Section 3.1 a case study of the current handling of Bessaker wind farm is done and in Section 3.2 the future development of the balancing market is described. The opportunities for a integrated balancing market using cross-border transmission capacities is evaluated in Section 3.2.1. In Section 3.3, the development of the intraday market in Norway is discussed, followed by Section 3.4 which describes the benefits and drawbacks of using internal hydro power to compensate the balance position. There is not much literature on the two latter subjects, so conversations with actors in the market have been a good source of information. Finally, in Section 3.5, the development of improved weather prediction using numerical weather predictions are elaborated.

3.1 Case Study of Bessaker Wind Farm

To get a better insight of how the development in the mentioned markets and better forecasts will affect TrønderEnergi, the current balance handling of Bessaker wind farm is studied. In this case the balance is handled by using the the principle described in Section 2.4.2 and shown in Fig. 2.14.

With 57.5 [MW] Bessaker wind farm is the largest wind farm in TrønerEnergi's production portfolio. Bessaker wind farm is a wind farm located in Roan municipality in Sør Trøndelag, Norway. It consists of 13 wind turbines of 2.3 [MW]. With 57.5 [MW] it is the second biggest wind farm in Norway. The case study examines the economic results of balancing WPP between September 2010 until August 2012. The respective day-ahead market prices are used as a reference. The difference between the spot price and balancing prices is calculated for each hour and multiplied with the imbalance at the time. The summed result, in NOK, is shown in Table 3.1.

	2010	2011	2012
Production imbalance	-552 121	- 1 176 874	-778 444
Consumer imbalance	1 078 426	-782 095	-361 415
Sum	526 305	-1 958 969	- 1 139 859

Table 3.1: Balance results in NOK for Bessaker wind farm, September 2010 - August 2012 [29].

The calculations are shown in Appendix A.5.1. One can see from the table that the average wind farm losses sum up to about NOK 100 000,- per month in the production imbalance compared to spot price on all production. The losses in the consumer imbalance is somewhat different as it is priced after the one-price system. Furthermore there was a great surplus in the consumer balance in 2010, as a result of a beneficial position and high prices over 4 days. These dates and some selected facts of 2010 are presented in Table 3.2.

Selected facts		Unit
Surplus on the 29th and 30th November	504 735	[NOK]
Surplus of hour 18 the 29th November	72 204	[NOK]
Surplus on the 21st and 22nd December	457 024	[NOK]
Number of hours with Spot price over NOK 1000	67	-
Number of hours with Balancing price over NOK 1000	95	-
Higest Spot price	2003	[NOK/MWh]

Table 3.2: Selected facts from 2010

This example emphasizes the risk of not having control over the own imbalances. In this case the balances of TrønderEnergi were in line with the requirements of the system. For this reason the company had a great surplus in some hours and days. If the balancing volume of TrønderEnergi had been in contrast to the needs of the esytem, the company had faced losses simular to their presented gains. For example if this had happened on the 29th and 30th November, TrønderEnergi had seen a loss of a half million NOK instead of a gain. It is fair to assume that if this situation had occured the company would have taken preventive action, but this certainly illustrate the risk in the balancing markets.

3.2   The Development of the Balancing Market

In this section an analysis of the planning situation is given. For being able to properly analyze the alternatives for a producer, the expected development in the balancing market and intraday market is described. The development of these markets is thoroughly analyzed in [12], so a brief summary is included in this thesis

The Ph.D. studies of Stefan Jaehnert [18] and Hossein Farahmand [10] are focusing on an integrated balancing market in Northern Europe. In both thesises a large integration of WPP is included and two scenarios are set up. The first scenario assumes no cross-border procurement of balancing power, and the second scenario assumes full integration of national balancing markets. To adress the importance of their thesises, some regulatory developments are scetched.

In March 2011 the EU Agency for the Co-operation of Energy Regulators (ACER) published its "Revised Guidelines of Good Practice for Electricity Balancing Market Integration (GGP-EBMI)." The guidelines explicitly state that: *"balancing market integration has been highlighted as a necessary step to reach the ERGEG and EU aim of the development of an effective, competitive single market for electricity across the whole of the EU. Balancing market integration will allow TSOs to more efficiently procure balancing services and avoid inefficient comitant up and down regulation in adjacent areas. This integration will promote efficient and competitive price formation and market liquidity."* [8]. The integration of balancing market will provide more diversified balancing resources, increase security of supply and increase the competition in the markets, thus reducing the possibilities for the exercise of market power [10].

In the two Ph.D. thesises two cases have been introduced. Case I is the case with no integration and Case II assumes full integration of the national balancing markets. It should be mentioned that the ENTSO-E suggest that 50% of the required reserves must be procured within the country, so the probable state can be seen as a blend of the two scenarios. In [18] the time frame is until 2020 and in [10] the time frame is until 2030.

The need of balancing in the system is correlated to the uncertainty in the WPP forecast. At the time of the day-ahead spot market clearing (12:00), the WPP forecast horizon is between 12 and 36 hours. In both thesises it is assumed that wind power producers balance their production portfolio either by redispatch of their own production portfolio or in the intraday market up to 3 hours before the hour of operation. So the results presented are with 3 hour uncertainty of production forecasts. It is expected that a rescheduling is much cheaper then settling the imbalances due to the forecast error in the balancing power market. The costs due to rescheduling, which occur in the intraday market are not taken into account in the analysis.

An important result from the simulations done, are the day-ahead market prices. In a well-functioning balancing power market the balancing power prices lie in the vinicity of the day-ahead prices, so the day-ahead prices give a rough indication of the available regulating reserves. The results are shown in Fig. 3.1.

It can be seen that the average day-ahead market price is lower in 2020 then in 2010 for both Norway and Germany. Furthermore, the volatility increases in Germany but decreases in Norway. The lower day-ahed price indicates cheaper regulating reserves in 2020 compared to 2010. The increased volatility in the system, however, indicates bigger changes in production, which indicates higher balancing requirements.
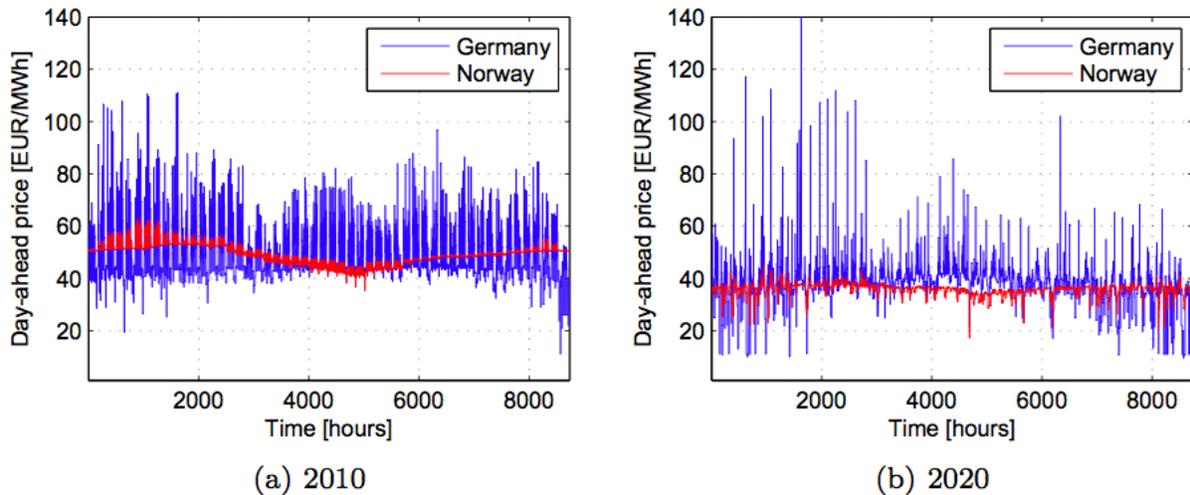
Figure 3.1: Day-ahead market prices Norway, Germany [18]

The effect such market integration will have on the respective countries is examined. The key results from Jaehnerts thesis is shown in Fig. 3.2. The numbers shown in the figure show that in the case with no integration the activated reserves increase in all countries towards 2020. This is to be excepted due to the increased share of WPP. The largest percentage change is observed in Belgium and the Netherlands with 235% and 196%, respectively. However, the greatest change of volume is in Germany with 3197 [GWh]. The Nordic countries have a modest change in regulating reserve activation. As seen in Fig. 3.2(b), full integration of the balancing markets will change the geographical location of the activated reserves. Especially Norway and Sweden will procure the activated reserves. The total annual exchange from Norway and Sweden is 6340 [GWh]. Furthermore, the activated reserves in Denmark, Germany, Belgium and the Netherlands are significantly reduced compared to the no market integration case.

The results presented in [10] coincide with Jaehnerts results. Farahmands results are presented in Table 3.3. Case I represents no balancing integration where regulating reserves have to be procured in the particular country. There is no possibility to exchange balancing services between the Nordic system and the central continental European system. Balancing services can, however, be exchanged within the Nordic area. In Case II balancing services can be exchanged system wide, thus representing full integration of balancing markets in the northern European system.

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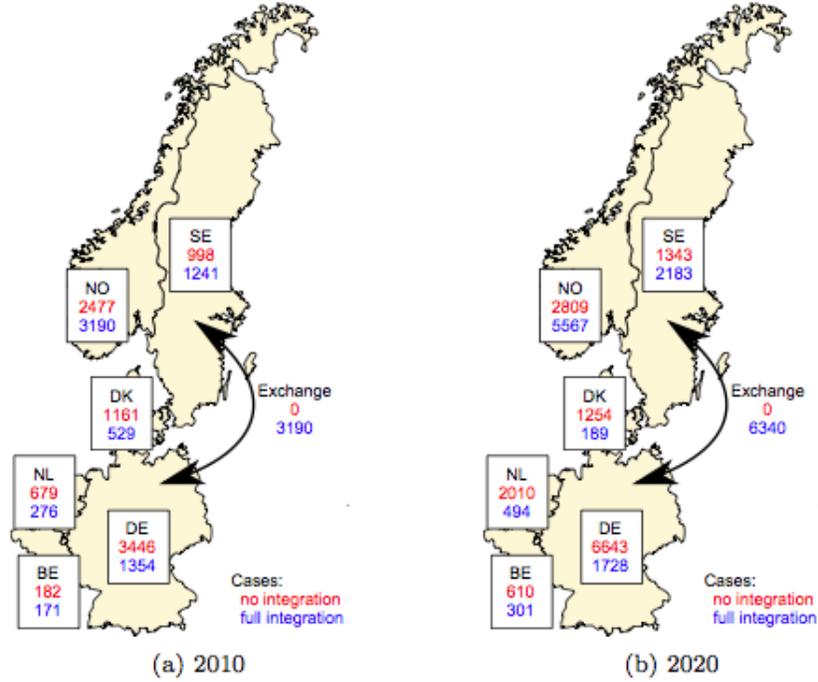
Figure 3.2: Country wise annual regulating reserve activation [GWh] [18]

Area	Reserve req.		Case I		Case II	
	Up	Down	Up	Down	Up	Down
Sweden	1733	-1733	2289	-2218	2923	-2387
Norway	1470	-1470	2863	-2602	4996	-2539
Finland	949	-949	698	-789	734	-790
Denmark	2029	-2029	331	-571	204	-644
Nordic	6181	-6181	6181	-6181	8857	-6361
Germany	7393	-6430	7393	-6430	5142	-6477
Netherlands	1607	-1742	1607	-1743	1182	-1516
GE+NL	9000	-8173	9000	-8173	6324	-7993

Table 3.3: Averaged annual per country procured reserve [MW] [10]

Within the Nordic area the results in Table 3.3 show that Norway and Sweden supply Finland and especially Denmark with regulating reserves. Denmark imports more then 70% of required balancing reserves, in both cases. When balancing markets are integrated for the whole area (CaseII), the biggest changes are the increased upward regulating provided by the Nordic area, and hence the reduction of upward regulation especially in Germany (-2251[MW]). The upward reserves are mostly procured in Norway (+2133 [MW]) and some from Sweden (+643[MW]).

Due to the increased reserve requirements, the reserve procurement costs in the no market integration case are more than doubled in 2020. The additional WPP in 2020 increase the system imbalances by 90% and the reserve activation rises by 80%. The reserve activation are less then the system imbalances due to netting of imbalances within the Nordic and German systems. The balancing costs are estimated to only increase by 25%, far less then the increase in reserve activation. The reason for this is the mentioned price decrease in the day-ahead market and the expected availability of more reserve capacity in 2020 than in 2010. With full market integration only 40% - 50% of the total imbalances are activated. The reduction is achieved by cross-border netting of imbalances between the countries. As mentioned, the reserve activation in the Nordic system increases dramatically with full market integration. The share of the overall activated reserves increases from 40% to 70% in 2010 and from 30% to 80% in 2020.

It should be elaborated that the assumption of a 3 hour error of WPP forecasts reduces the turnover in the balancing market by 40%. The thesises indisputable states that the need for balancing power will increase with increased capacity of WPP. As most of the cheap regulating reserves are situated in the Nordic area, their exchange will grow and become more important in future scenarios, whereas the activation of reserves in continental Europe will decrease by about 30%.

Furthermore, the need of a well functioning intraday market is of increasing importance as the reserve requirements increase. The development of the intraday market in the Norwegian area is discussed in Section 3.3. The analyzed WPP forecast horizons show that a short horizon lead to a significant reduction of system imbalance and hence less regulating reserves are required. This will result in a lower balancing power market cost for the TSOs and possibly higher costs in the intraday market. The latter is not regarded in Jeahnert's thesis, but may be of great importance to the power producers. The shorter forecast horizon can be interpreted as more accurate WPP forecast, which can be expected in the future. This is discussed in section 3.5. The potential cost savings of better forecast become tremendous in 2020. This clearly points out the value of high quality WPP forecasts.

In his conclusions Jaehnert states that WPP does not have a big impact on the balancing power market in 2010, but the impact in 2020 is significant. Without an integration of national balancing power markets in 2020, the power system is operated at its limits. This will lead to unacceptable rationing of demand, significant shut down of production and high costs in the power market. With national integration, the prices are reduced and the above can be avoided, leading to a more secure operation of the system.

On the new Skagerrak 4 cable, connecting Norway and Denmark, a capacity of 10 [MW] is reserved for secondary balancing reserves and 100 [MW] is planned to be reserved for the exchange of regulating resources. According to ENTSO-E [43] this should only be done if it enhances the social welfare. In his thesis, Jeahnert [18] concludes that the reservation of capacity for balancing purposes between the Nordic and continental European systems increases the exchange of balancing power significantly. This leads to a reduction in reserve

procurement and system balancing costs. According to Jaehnert [18], the socio-economic benefit in the day-ahead market is far higher than the reduced balancing costs, so the transmission capacity is better used in the day-ahead market. With this conclusion Jaehnert contradicts the decision made by the regulators in Denmark and Norway.

3.2.1 Development of the Norwegian Interconnectors

The 2011 Grid Development Plan [35] developed by the Norwegian TSO, Statnett, describes the planned development of new interconnectors. The current interconnectors are:

Interconnector	Capacity [MW]
South-Norway - Sweden	2050
South-Norway - Denmark	950
South-Norway - Holland	700
North-Norway - Sweden	1400-1700
North-Norway - Finland	120
North-Norway - Russia	50
Sum	5270 - 5570

Table 3.4: Current interconnector capacities [35]

The Nordic regulators have long traditions for cooperation in the electricity-sector and meet annually to discuss future development. They have agreed that they will have a Nordic perspective when planning future grid investments. This is important to achieve socio-economic benefits for the whole area, especially considering the integration of renewable energy sources. Statnett also points out that by linking the Norwegian power system to the central European system, Norway can exploit the value of the flexible hydro power [35]. The future interconnectors are shown in Table 3.5.

Interconnector	Countries	Capacity [MW]	Expected commissioning
Skagerrak 4	Norway - Denmark	700	2014
NSN	Norway - Great Brittain	1000	2018 or 2021
NordGer / NORD.LINK	Norway - Germany	1000	2018 or 2021
Sum		2700	

Table 3.5: Planned interconnectors [35]

Based on these numbers, the previously discussed fully integrated balancing market may seem optimistic. This is enhanced considering the findings of Jeahnert [18] that states that it is not socio-economic beneficial to reserve capacity for balancing purposes. With a new

interconnector to Denmark, having high demand for balancing power, the volatility and volume may increase in 2014. How this will effect TrønderEnergi is however uncertain. In some cases the bottlenecks in the Norwegian grid may limit the export opportunities from NO3, leaving the balancing in this area unaffected.

However, an increase of export capacity of 2700 [MW] from the south of Norway is a large increase of the current capacity. With a stronger internal grid these interconnectors can to a large extent affect the activation of regulating reserves of producers in Norway. With a long time horizon the interconnectors with central Europe and the UK may give the high volatility and increased balancing requirements, as described above.

It should also be mentioned that a fourth interconnector from Norway to Sweden called "Sydvest-linken" was planned, with a capacity of 1400 [MW]. This project was abandoned as recent cost-benefit studies have shown the investment could no longer be justified [38]. With this decision the capacity of planned interconnectors dropped from 4100 [MW] to 2700 [MW], a reduction of 34%. The decision made by the TSO's in Norway and Sweden in many ways illustrate the political risk in the power market. By a stroke of the pen, projects with large consequences are made or shelved.

3.2.2 Conclusion

The work done by Jaenhert [18] and Farahmand [10] suggest that the procured reserves in Nordic area, and especially Norway, will increase with a fully integrated balancing market and increased penetration of WPP. Based on this work and the political deceptions of ACER described in Section 3.2, it is reasonable to assume that Europe will procure balancing power from Norway. This suggests that the trend in Fig. 2.11 will continue.

3.3 Development of the Intraday Market

In this section the future development of the intraday market in Norway is described. The intraday market is operated by Nord Pool Spot ASA. It is named ELBAS, which is short for electrical balancing adjustment system.

In [39], Ellen Stavseth points out the benefits of trading on the Elbas market. It is argued that in the balancing market there are only national counterparts, and thus higher price changes. By using Elbas, one gets access to counterparts from Nordic and German areas, which increases the liquidity and gives higher competition and a more efficient market. The different production mix with different marginal cost is brought together to a mutual benefit. Furthermore, trades done closer to the hour of delivery are based on more accurate market information. The use of the Elbas market will efficiently use the remaining cross-border capacity, given to the market after the day-ahead market is cleared. These are

the competitive advantages of a well functioning intraday market. The liquidity and the performance of the Elbas market in Norway has, however, been subject for discussion.

The liquidity of a market is generally understood to describe the easiness of trading a particular asset and the fact that any transaction in the asset will not affect its value significantly [42]. Various definitions of liquidity and measurement of the liquidity concept have been suggested. The easiness of trade is certainly a function of the number of market participants and the number of trades. Therefore the trading volume is a frequently used indicator for the liquidity of a market. This is easily observable and will be used in the following as a measure of liquidity.

The balanced position for a power producer or consumer can be adjusted in both the intraday market and in the balancing market. Weber [42] stresses that in an efficient marked design as many of these adjustments as possible are done in the intraday market. Both Weber [42], Stavseth [39] and Randen [26] point out that the observed volumes in the Norwegian Elbas market is too low. A major reason for this, is according to Weber [42], the market concentration in the market. The large producers and consumers in the market can find it advantageous to do a netting of open intraday positions within their own portfolio instead of going through the power exchange. Furthermore, it is pointed out that the low liquidity is related to the fact that producers submit bids in large quantities in the balancing power market. These bids are included in the short-term merit order of the TSO and activated if economically attractive. This makes it easy to put the excess production capacity in the balancing market, and not in the intraday market. This, however, has one advantage. Since flexible hydro power is not scarce in the Nordic system, this leads to relatively low differences between the intraday market and the balancing power prices.

The key concern with dividing the balancing between the intraday and balancing markets is whether both market can remain sufficiently liquid. Weber [42] points out that introducing intraday markets does not necessarily have to be an improvement, due to lack of liquidity. If the traded volume is low, then the actors do not exploit the benefits of the market, and the balancing market is not relieved, which is the case in Norway. As previously mentioned the liquidity of the Norwegian Elbas market has shown low liquidity in the past.

Another explanation for the historic low liquidity in the Norwegian Elbas market is pointed out by Stavseth [39]. She points out that the 2 hour gate closure on the Norwegian Elbas market has had a significant effect on the liquidity. Borggrefe and Neuhoff [6] confirms this by acknowledging that the flexibility provided by the transmission system increases closer to the hour of operation. Furthermore, Randen [26] points out that due to the 2 hour gate closure, Norwegian market players missed out on nearly half of the liquidity of cross border balancing, as other countries have shorter gate closure with high volume close to real time. Øbert et.al. [9] estimates this number to be 40% . It seems that the regulatory body in Norway has realized this issue and on the 9th of November Nord Pool spot received the following message from the Norwegian TSO, Statnett: *"Statnett has decided to change gate closure for the Elbas market in Norway from 2 hours before operation hour to 1 hour before operating*

hour from 26th of February 2013. This follows a legal decision by the Norwegian regulator, NVE. Gate closure for ELBAS trade between Norway and the Netherlands on the NorNed cable will be 2 hours until further notice." [32]. With the assumptions from Stavseth [39], Borggrefe and Neuhoff [6] and Randen [26] it is reasonable to assume that this measure from the Norwegian regulator will facilitate an increased trade in the Norwegian Elbas market. This statement is confirmed by both Strøm [40] and Gimmestad [13]. Additionally it has been pointed out that an increase of the liquidity is excepted with a larger share off WPP. With higher penetration of wind power the need of the Elbas market increases and more participants will enter the market.

Øberg et.al. [9] has through the KUBE project under the auspices of Statnett commented on the low liquidity in the Norwegian Elbas market. Like Gimmestad [13], Borggrefe and Neuhoff [6] and Weber [42] point out that the gate closure is a major factor of the low liquidity. Furthermore, they mention that due to the flexibility of the Norwegian hydro power the need for intraday balance is not yet imminent. They also state that the economic incentives for intraday trading is not very large, as the costs in the balancing market are relatively low and the bids in the intraday market are high. The KUBE project also points out that in the future, with higher transmission capacity and integration of intermittent energy resources, the balancing costs will be higher and the intraday trade will be more efficient. Therefore, the potential of the intraday market in the future is large.

To be able to submit and accept bids in other price areas then the area the producer is stationed, sufficient transmission capacities between the areas are required. As seen in Fig. 2.6 in Section 2.3, the Norwegian grid has many bottlenecks. With a stronger national grid and increased cross-border capacity trade in the Norwegian Elbas would be subject to less congestion, and hence have increased trade volumes in all bid-areas. This raises the issue of reserving capacity on cross-border cables. In the current market, all available capacity after the day-ahead market clearing is given to the Elbas market [39]. As mentioned in Section 3.2 the reservation of capacity of the cross-country transmission capacity will not lead to a socio-economic benefit, compared to the savings in the balancing market. For this reason Grønstedt [14] rejects the possibility of reserving capacity for the Elbas market.

Another measure that can increase the liquidity of the Elbas market is the implementation of a common North-Western European intraday market. Today Elbas is operative in 8 countries covering 16 bidding areas. The goal of Nord Pool is to integrate Great Britain and France and such expand the trading area. If this is achieved, orders from all exchanges will be visible for all trading parties. If a area has two exchanges, a trading party will have access to the overall liquidity independent of their exchange membership [26]. This will increase the number of trading parties and thus the volume. The Norwegian market will, however, be constrained by the transmission capacities.

Borggrefe and Neuhoff [6] emphasizes the opportunities of monitoring the power market. The closer to real time the balancing services are traded, the fewer participants with the necessary technical flexibility and organizational capacity are able to participate in the market. This

can lead to great market power for these participants. With growing penetration of wind power, the necessity of the intra-day market will increase close to the hour of operation. This can amplify the excess of market power due to limited competition. The exercise of market power will distort the price signals and create inefficiencies that increase the cost of system operation and might provide misleading signal for investment decisions. The key issue with the current EU system is related to monitoring market power. In the pay-as-bid system it is difficult to differentiate between competitive and strategic bidding behavior. This kind of behavior is a challenge with the Elbas market, which both actors and regulator should be aware of.

It has also been pointed out by an anonymous source that the business concept of pooling many small power producers into one balancing responsible party will increase the liquidity of the Elbas market. In practice a third party offers to handle the imbalance of many small producers such as run-of-river hydro or small local power producers. The third party specializes in handling imbalances by acquiring expertise in power and consumption forecasts and experience in the balancing markets. The use of Elbas will in this case be crucial for such a firm.

Haakon Reinersen Leknes from Nord Pool Spot [22] has provided some data regarding the current development in Elbas. He points out that they in 2013 have observed a considerable increase in the traded volumes in Elbas. In the Nord Pool area as a whole the, traded volumes have increased by 9,7%, and this trend is consistent in all of the different price areas, with the exception of NO4. Leknes [22] believes that this is due to few counterparts in this particular area, as a result of the low transmission capacity. This trend according to Nord Pool Spot, that the intermittent renewable energy sources leads to greater imbalances for the market actors. When it comes to the Norwegian volumes a similar trend is observed. The weekly traded volumes in Norway are presented in Fig. 3.3 and Fig. 3.4.
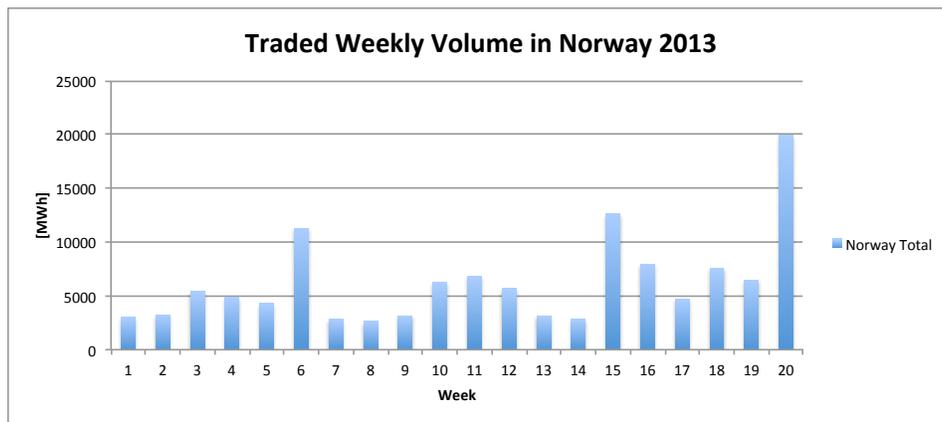
Figure 3.3: Weekly Traded Volumes in Norway 2013 [MWh].
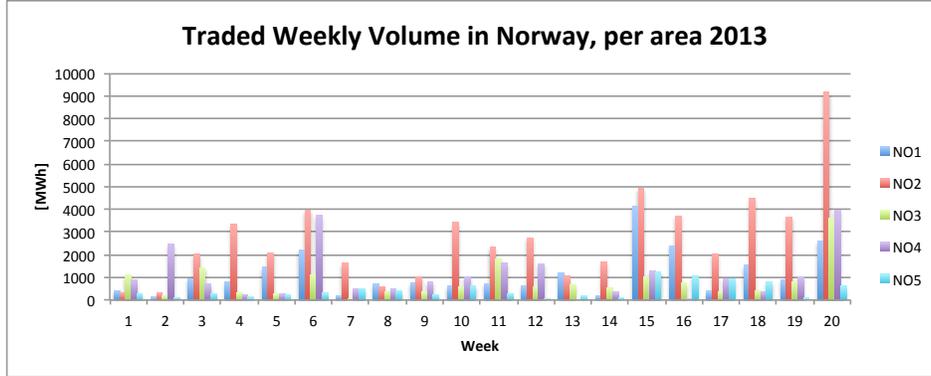
Figure 3.4: Weekly Traded Volumes in Norway 2013, per area [MWh].

From Fig. 3.3 and Fig. 3.4 it can be seen that there has been an increase in the traded volumes after the gate closure was reduced in week 9. According to [22], the shorter gate closure and increasing integration of WPP has been an eye-opener for some inactive members. In total there are 114 actors with license to trade on Elbas. 25% of the actors are Norwegian but these players only account for 5% of the traded volumes. A reason for the low activity might be the backround of the production planners sitting in the respective operating centrals. It is pointed out that many of these have a technical background, and hence, have higher regards to the wear and tear of the equipment. With the easyness of trade in the balancing market and the implemented routines within the company, the threshold of trading in Elbas might be high. With a rising liquidity more of these inactive members have become active and it is expected that the volumes in Norway will continiue to rise. [22] points out that this would provide opportunities for increased profit for many of the actors by exploiting the high volatility in foregin power prices. In the past there have been actors from Germany with a desire to balance the system downwards at a low price during the night, and buy it back during the peak hours during the day. This represents a clear arbitrage for the Norwegian hydro power producers, but as they are not active in Elbas the opportunity has passed by unexploited. To illustrate these opportunities the highest and lowest prices in 2012 and sofar in 2013 are presented i Table 3.6.

Year	High	Low
2012	555 [€/MWh]	-175 [€/MWh]
2013	185 [€/MWh]	-185 [€/MWh]

Table 3.6: High and Low prices of 2012 and 2013 in [€/MWh] [22].

The numbers in Table 3.6 show that there is a great difference between the price spikes in 2012 and 2013. This is in extreme situations, but it certainly illustrates the opportunities Elbas provides.

3.3.1 Conclusion

At its current state, the Norwegian Elbas market has low liquidity and is not used in a large scale for balancing the positions of power producers. It has been pointed out that there are some factors that will increase the liquidity in the market on a short, medium and long term:

1. Investments in WPP will increase the need for intraday balancing.

2. Development of a service industry that handles imbalances for many small power producers.

With a liquid Elbas market there is a opportunity for TrønderEnergi to better handle their wind power production.With good expertise and experience the Elbas market will provide an opportunity of handling the risk of low prices in the imbalances. Thus, a higher income can be expected.

3.4 Balancing Own Generation by use of Hydro Power.

Power producers with a large portfolio in some cases find it beneficial to do an internal netting of imbalances. There is limited literature on this subject, so the arguments presented in this section are based on discussions with actors in the industry that have solid expertise in this field [40], [13]. The netting of own balance is, however, briefly mentioned in the Ph.D. thesis of Hannele Holtinen [15]. In her thesis, Holtinen states that self regulation should be discouraged, as it is more cost effective for both the system and the individual players to bid all regulation power to a joint pool for the TSO to use the cheapest options first.

In practice, the TSO has a merit order list of bids in the balancing market. In the Nord Pool area the last bid accepted sets the price of balancing. This will be the most cost efficient way to balance the system. If TrønderEnergi in a situation has higher water values then the last accepted bid, it would be beneficial to trade its imbalance in the market. This is obviously valid regardless of whether TrønderEnergi has a positive or negative balance. If TrønderEnergi is the price setting actor, it would not matter, as it would pay the same price in the market as it has reported to the TSO. No matter what the balancing price is, the market mechanisms ensure the most cost efficient way to balance the system. The last possible scenario is if TrønderEnergi have lower water values than the balancing price. If this is the case, it would be beneficial to increase own balancing if it has a net negative balance. This, however, is an unusual situation, as the price in the day-ahead market, balancing market and intraday market would differ significantly. With such low water values the power plant is expected to produce at its maximum as it would see a large surplus in the day-ahead market. When this is the case, the power plant can not be used for internal upward regulation.

The arguments presented in the two previous paragraphs are valid when there is an opportunity to trade the imbalances on the Elbas market or if the imbalances are priced in a one-price system. The implementation of the two-price system was, as mentioned in Section 3.1, an incentive to avoid that producers take speculative positions in the balancing market. When the imbalance is priced after the two-price system, the assumptions of Holtinen are not applicable. The imbalances of the producers will not be fairly priced. This is a good incentive to stay in balance if the producer has full control of own balance. With increased penetration of WPP, most of the economic losses occur in the production balance. This is shown in Section 3.1. With higher volatility in the balancing market, the opportunity of internal balancing may prove to be beneficial. In this study no literature is found on the subject and conversations with market actors reflect that there are not many studies on the subject. TrønderEnergi should therefore be aware of this opportunity and encourage further work on the subject.

When considering netting the balance by regulating own hydro power production, the different water values should be taken into account. These are highly dependent on the physical state of the power plant. The size and filling of the reservoir, the installed production capacity and participation have a large impact of the individual water values.

According to Strøm [40], the balance handling of Statkraft is similar to the strategy used by TrønderEnergi. New production schedules are updated 45 minutes before the hour of operation, using newer, more accurate forecasts. The deviation from the previously committed sales are settled in the balancing market. Internal balancing using own hydro power production is not encouraged. The maximum socio-economic benefit is reached by using the intraday market for balancing. Furthermore, Strøm [40] mentions an important point about the future state of the Norwegian power system. As mentioned both TrønderEnergi and Statkraft[1] let their wind power production get settled in the balacing market. When the penetration of wind increases in the Norwegian system, the balancing volumes gets larger, which may lead to unacceptable safety margins in the system operation. In this situation, the Norwegian TSO may introduce economic incentives to stay in balance[2]. Furthermore, the practice of these power producers is actually illegal. Paragraph 4 part 6 of the regulations on system responsibility[3] [36] states that: *"the concessionaire is obliged to follow the reported production plan."* If further incentives or penalties are realized, the function of the Elbas market becomes more important for the wind power producers.

In [3] an analysis is carried out regaring the use of own hydro power or using the balancing market to balance the wind power forecast error. This analysis uses data from Valsneset and Bessakerfjællet wind farm and Søa hydro power plant. The analysis is based on hourly data and the time period is limited to 2011 and 2012. The findings of this analysis states that the minor volumes can probably be regulated cheaper by the use of own hydro power then settling

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[1]Statkraft and TrønderEnergi are the largest wind power producers in Norway

[2]This was last done by introducing the two-price system on the 1st of January 2009 as mentioned in section 2.2.2 on page 9

[3]Forskrift om systemansvaret i kraftsystemet FoS.

the volumes in the market. This can also be regulated automatically. Some drawbacks of using own hydro power for balancing is elaborated. It is mentioned that the small sampe shows that using the market will be preferred in many hours and that concurrent effect significant reduce the number of hours available for regulation with the use of own hydropower. Furthermore the start stor costs for the firm will increase and several medium sized hydro power plants are required to balance even a small wind farm. The conclusion of this analysis is that using own hydro power should not be implemented at this stage. If this kind of operation is desired, in-depth studies on the relevant hydro power plants must be done.

3.5   Possible Improvements by Better Wind Forecasts

In this section some developments in wind power forecasting are presented.

In lectures at the Norwegian University of Science and Technology (NTNU), Tobias Aigner [1] presents the workings and benefits with numerical weather predictions (NWPs). These are mathematical models to predict and evaluate different weather phenomena and are based on the physical laws of preservation of mass, momentum and energy. The temporal evolution of the model is computed in a three-dimensional grid, stretching from ground level to the upper limits of the atmosphere. The NWPs are a valuable tool in simulating the wind power production with high accuracy. The simulation structure of the NWPs is shown in Fig. 3.5. We see from the figure that the model requires measured data from the atmosphere as the initial values. Values for humidity, air pressure, temperature, wind etc. The topographical data needed are related to the surface of the earth and the geographical roughness. The simplicity of the topography and surface roughness offshore should make the prediction of offshore wind parks very accurate. This is, however, not the case. A smooth surface will cause large wind gusts, so forecasting the wind speeds offshore is actually very hard. If the investments in offshore wind technology become as large as anticipated, this may lead to large production forecast errors.
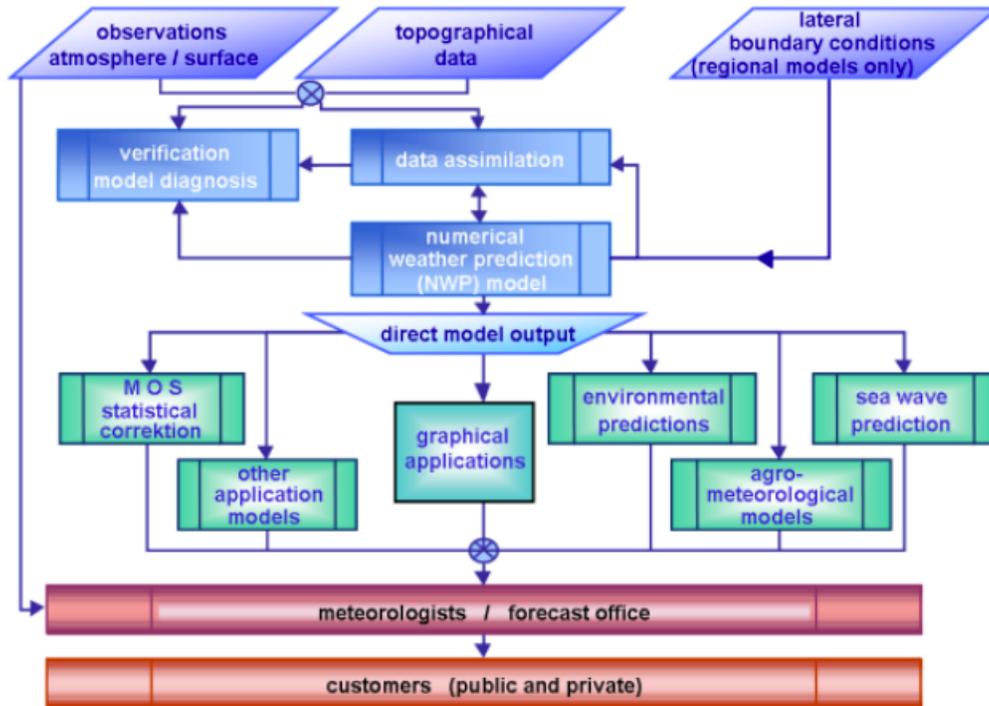
Figure 3.5: The simulation structure of the NWPs [1].

As with any tool, the NWPs also have a couple of drawbacks. It is an initial value problem, which uses the current weather information to predict the weather in the future. The complexity of the meteorological phenomena requires data for a large area, not only the area at hand. Approximately 10 million data points are required for all layers of the atmosphere. Since it is not possible to measure all these data points, the value of many points are found using linearization to interpolate between the points that are not accurately measured. This represents a great uncertainty in predicting the future wind speeds.

The results of the NWPs are presented as probabilities of the expected participation or temperature. An example of a weather prediction is shown in Fig. 3.6. From the figure it can be seen that the uncertainty of the forecasts increases with time, hence it is more accurate close to the actual hour. Observed data from Germany show that the wind forecast uncertainty decreases from 15% to 4% in the last 24 hours before actual generation.

The accuracy of the NWPs are shown in Fig. 3.7. The figure shows simulated data and actual data measured by the TSOs in Denmark and Germany, over a time period of one year. The red line represents the simulated data using NWPs and the blue line shows the actual data, recorded by the respective TSOs. The figure shows that the NWPs are able to predict the variations in wind speed pretty accurateley, but the timing of the wind speeds are harder to predict. The figure also shows some large deviations that should be improved.
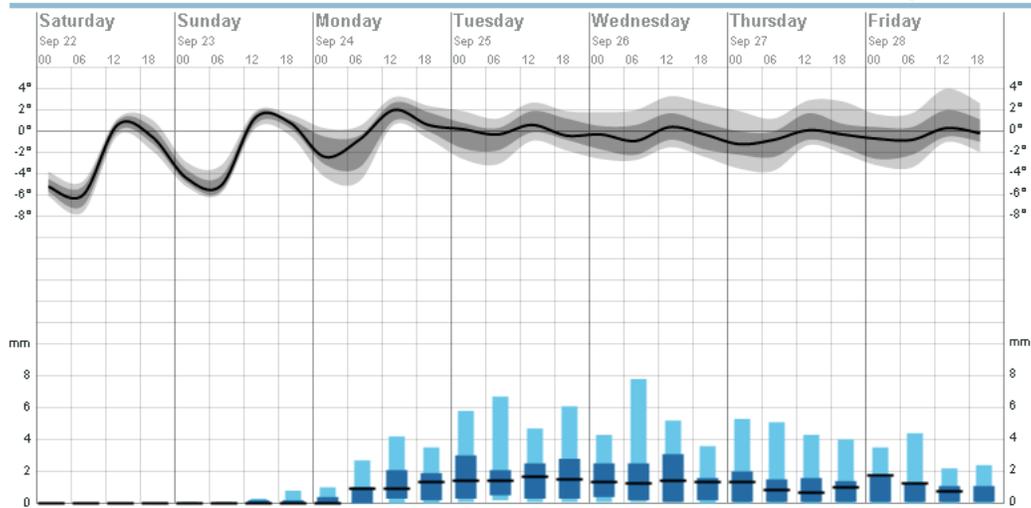
Figure 3.6: Probabilistic presentation of NWPs. [1]
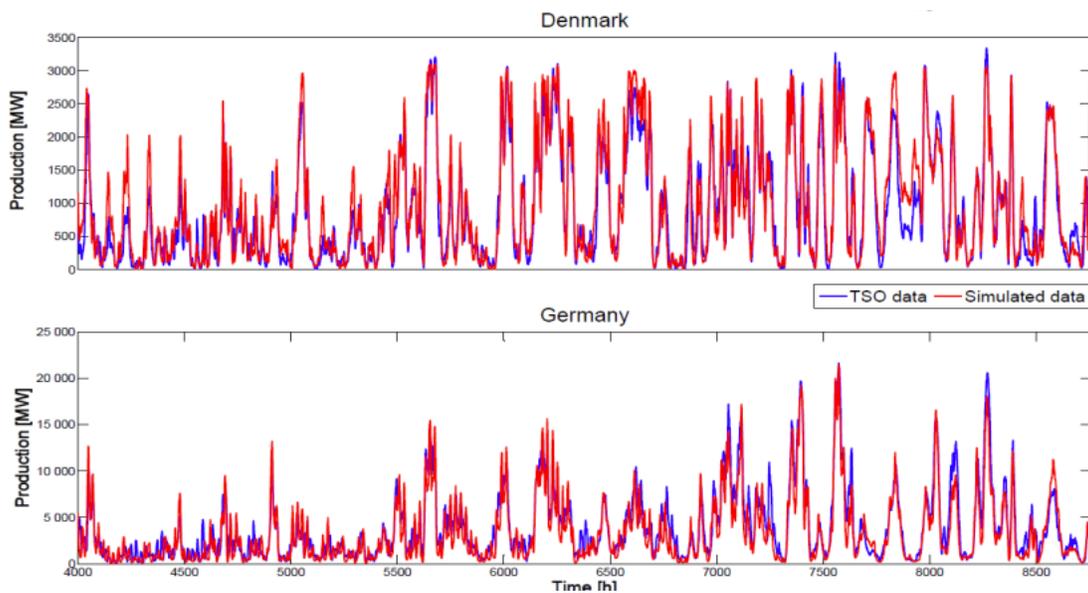
Figure 3.7: Simulated data and actual TSO data. [1]

One of the limitations with the NWPs is the time frame of the resolution. Only hourly resolutions are available, while inter-hourly variations cannot be simulated[4]. With increased penetration of WPP throughout Europe, quarterly market resolution has been proposed as a mean to ease the system operation. Also the simulations uses a 3D-grid of the atmosphere as

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[4]Lower then hourly resolution will require far more computational power. With hourly values approximately 40 gigabyte is produced each hour

a model. Considering the point-to-point distance between the nodes, single wind turbines or small wind farms cannot be modeled with sufficient accuracy. The third limitation of NWPs are the large data sets used in the modeling. This requires large amounts of computational power and the data conversion is slow.

As mentioned, observed data from Germany show that the wind forecast uncertainty decreases from 15% to 4% in the last 24 hours before actual generation. Further improvements and coupling of different wind models might lead to an increase in forecasting accuracy in the coming years. Borggrefe and Neuhoff [6] state that the forecast errors onshore might be reduced by as much as 41% by 2020. With increased transmission capacity and installed wind power the correlation between wind farms will reduce the wind uncertainty. This effect can be observed even for significantly large areas. In a case study done in 2009, Germany the day-ahead root mean square error for each of the four TSO was between 6.6% and 7.8%. Bundling the whole area, the forecast error was reduced to 5.9% [6].

3.6 Summary of Presented Material

In the presented litterature some sound asumptions about the future balancing markets can be made. Regulatory bodies have expressed an intention for cross-border integration of balancing markets. This will allow the TSOs to more efficiently procure balancing services and bundle the imbalances in adjacent areas, and hence less balancing power will be required. Furthermore, the integration of balancing markets will increase the security of supply and increase the competition in the markets. The presented reasearch on the area point out that in such a situation the flexibility of the Nordic hydro power will have a large benefit and a lot of balancing power will be aquired in Norway and Sweden. The installed capacity of WPP is predicted to increase substantially. When this is combined, a potential challange arises for the hydro power producers. With increased balancing power procurement and installed intermittent power production the volatility in the balancing market will increase. With the implemented two-price system in the producer balance, this can lead to losses for both the WPP producers and the hydro power producers.

A so far unexploited opportunity to the balancing market is Elbas. It has been pointed out that the liquidity in the Norwegian market historically has been to low, but this is expected to change in the comming years. A mature Elbas market will provide opportunities to a more cost efficient handling of the imbalances associated with WPP and provide opportunities for higher gain when allocating the hydro power. For this reason the different markets are modeled in the next chapter. Initially this is done regarding cost efficient handling of the balances asociated with the WPP. However the results can be interpreted in both cases.

Chapter 4

Modeling the Respective Markets

4.1 Objective

Chapter 2 and Chapter 3 describe the challenges with increased integration of WPP and how the balance handling for the responsible BRP's is challenging. Furthermore, increased capacity of cross-country transmission capacity will integrate the Nordic balancing market with the continental European markets. With an installed capacity of approximately 70 MW and an annual production just over 200 GWh, the deviations between predicted and actual wind power production can lead to substantial imbalance cost for TrønderEnergi. For this reason, a simulation tool is developed that aims to provide decision support regarding the use of Elbas as an alternative to the balancing market.

4.2 Previous Work

The model that is used in this thesis is inspired by the work done by Hossein Farahmand [10] and Stefan Jaehnert [18]. This is a model that is developed to properly analyze the effects of integrated North-European balancing markets. In his master thesis "Optimal bids for a wind farm" Kristian W. Ravnaas [27] has done some improvements to the model.

A description of the model used in the respective thesis's is found in [30]. The developed model includes a linear model based on statistical behavior of the regulating volumes for the impending five years and a short time model based on the SARIMA[1] model. The objective of the model is to forecast the upcoming balancing prices, and use the predicted prices to make a sound decision of how to handle the current imbalances. In [27] an optimal spot-bidding strategy is found by using the forthcoming balancing prices. The prices found therefore have

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[1]SARIMA: Seasonal Auto Regressive Integrated Moving Average

to be in the next operating day, a time horizon of 48 hours, according to the bidding in the spot market.

As the spot price varies from hour to hour, week to week and from season to season, the model uses the difference in the spot brice and the balancing prices for the hour at hand. If this difference is to small, there will be low costs when handling the balances. Therefore it is natural to focus on the difference between the balancing prices and the spot price. The difference between the two prices is defined in Eq. 4.1.

$$\Delta pr = Balancing_{Price} - Elspot_{Price} \tag{4.1}$$

The model is based on modeling Δpr as a function of the volume in the balancing market. A alternative would be to model Δpr as a function of the spot price. Statistical analysis however, show that the correlation between Δpr and the balancing volumes is 0.7811 and the correlation between Δpr and the spot price is -0.0164 [27]. This makes it clear that the volumes in the balancing market are a more suitable parameter then the spot price.

4.2.1 The Long Term Model

The long term model is stated in 4.2 and consists of a deterministic and a stochastic part. Furthermore, it is split up into three different states: upward regulation, no regulation and downward regulation.

$$\Delta pr = \begin{cases} \eta_{up} + \kappa_{up} * vol_{reg} + \epsilon_{up} & \text{,if upward regulation} \\ 0 + \epsilon_{no} & \text{,if no regulation} \\ \eta_{down} + \kappa_{down} * vol_{reg} + \epsilon_{down} & \text{,if downward regulation} \end{cases} \tag{4.2}$$

The deterministic part describes the linear dependence of Δpr and the balancing volumes. The dependency and trend lines are shown in Fig. 4.1. The recorded market data is plotted as dots. This indicates the percentiles for the excepted balancing price, describing the probability for a balancing price given a regulating volume [30]. The figure shows data from 2007 and in [30] similar parameters are found for the years 2003-2007. From the statistical analysis values for $\varkappa$, and η, in Eq. 4.2, are found.

If the results of the deterministic model are compared to the actual market prices there will be a considerable deviation. To model this deviation the model is extended by a stochastic part. To extend the model the error terms denoted ε, are introduced. As the different balancing states, upward regulating, downward regulating and no regulating is determined separately, the statistical parameter for their error function also should be calculated separately. This is done based on recorded data for each state. It is found in [30] that the error functions follow a Generalized Extreme Value (GEV) distribution, as shown in Fig. 4.2.
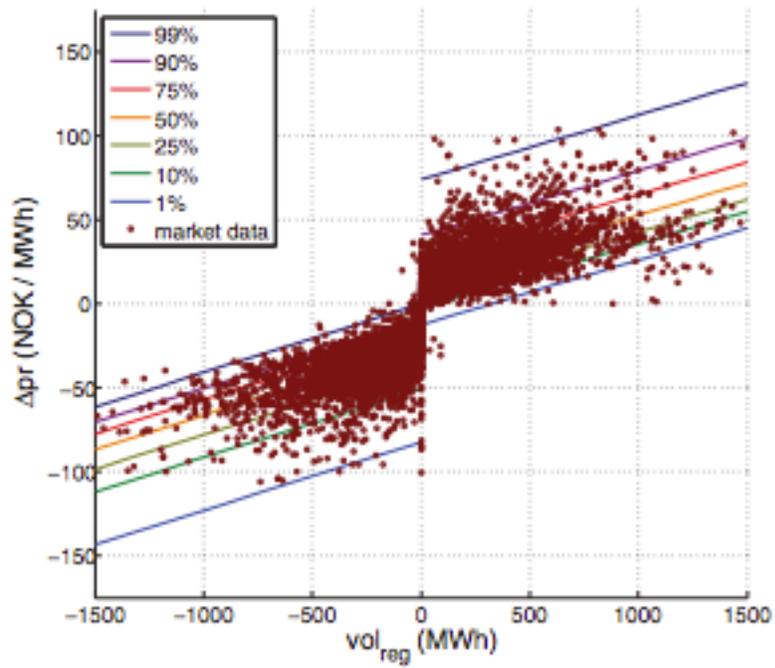
Figure 4.1: Correlation between Δpr and balancing volume [30].
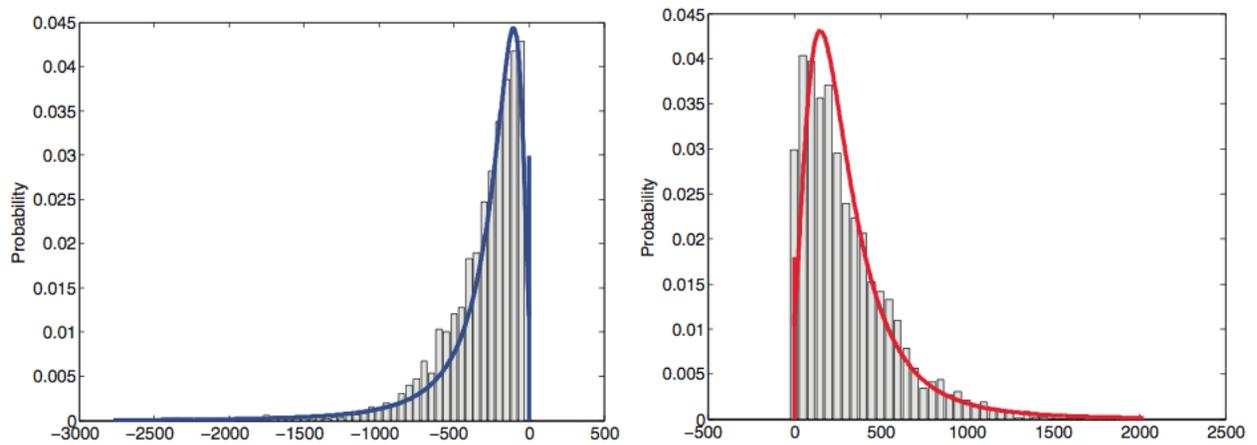
Figure 4.2: GEV distribution for downwards and upward regulation

From the material presented in Fig. 4.1 and Fig. 4.2 the following can be noted:

1. The histogram in Fig. 4.2 indicates that the volumes for upward and downward regularion have asymmetrical distributions.

2. The scatter plot in Fig. 4.1 suggest that there exist a dependence between the balancing volume and Δpr.

4.2.2 The Short Term Model

To find Δpr, as described in Section 4.2.1, the regulating state of the system in the forthcoming hours have to be found. To do this [30] uses a SARIMA model. By investigating the autocorrelation of Δpr for a year, a significant time dependency is found on a weekly scale. The autocorrelation for Δpr is shown in Fig. 4.3.
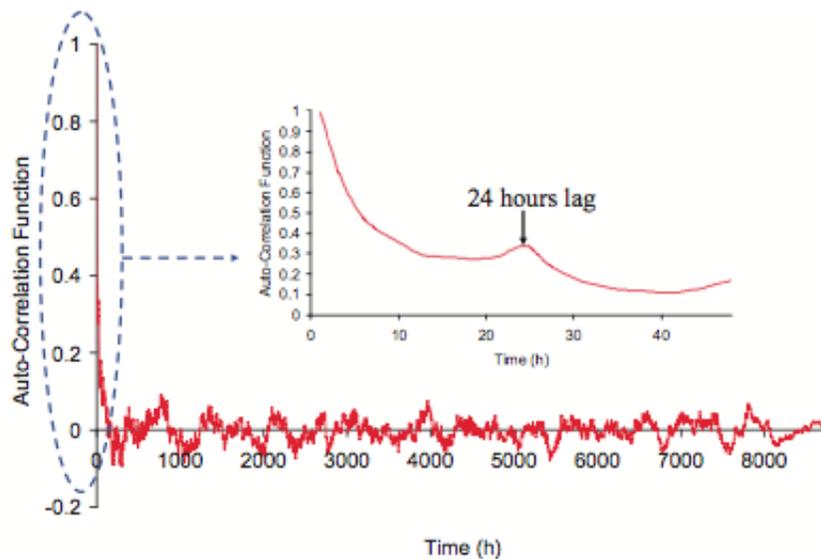
Figure 4.3: Autocorrelation for Δpr for 2007 [30].

Fig. 4.3 shows that the autocorrelation of the subsequent hours are substantial. The peaks shown in the figure also show that there is a correlation between the hours of the previous day, there is a seasonal correlation. The previous used model uses the SARIMA process to estimate the upcoming balancing volumes. These volumes are then used as input parameters in the long term model. Now the model is run multiple time, creating many scenarios. The output of the model is a probability distribution function of the upcoming balancing states. This distribution is then used to construct the optimal bids to the spot market for the next day.

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4.3 Intended Model

As discussed in the previous chapters, the Elbas market is an important tool for controlling the imbalances of a BRP. To be able to improve the described models, some statistical analysis is done to see if the trades in the Elbas market can be used to forecast the upcoming balancing prices. The analysis includes the correlation between the volumes and the prices in the two markets. In Elbas the last accepted trade sets the price, so in the analysis the price of the last trade sets the price for all of the volume that hour. This is done after consulting with TrønderEnergi and is the common way to account the price in other pay-as-bid markets.

4.3.1 Correlation Between the Volumes in Elbas and the Balancing Price

The initial thought was to try to use the volumes in the Elbas market in the same way as the balancing volumes was used in the model presented in [30]. In other words, the initial idea was to check if large volumes in Elbas could give price signals in the balancing market. This could, at an early stage, seem reasonable as it is expected that the traders in Elbas have some idea of what the upcomming balancing price would be, and trade accordingly. Then it would be reasonable to assume that with high volumes intraday, many analysts and traders with good knowlegde of the market would adjust their positions for a benefit. The found correlation between the volumes in Elbas and Δpr are 0,1087, which is not very large, to say the least, and certainly not sufficient to base a model on.

The autocorrelation for the volumes in Elbas was found, and is presented in Fig. 4.4.
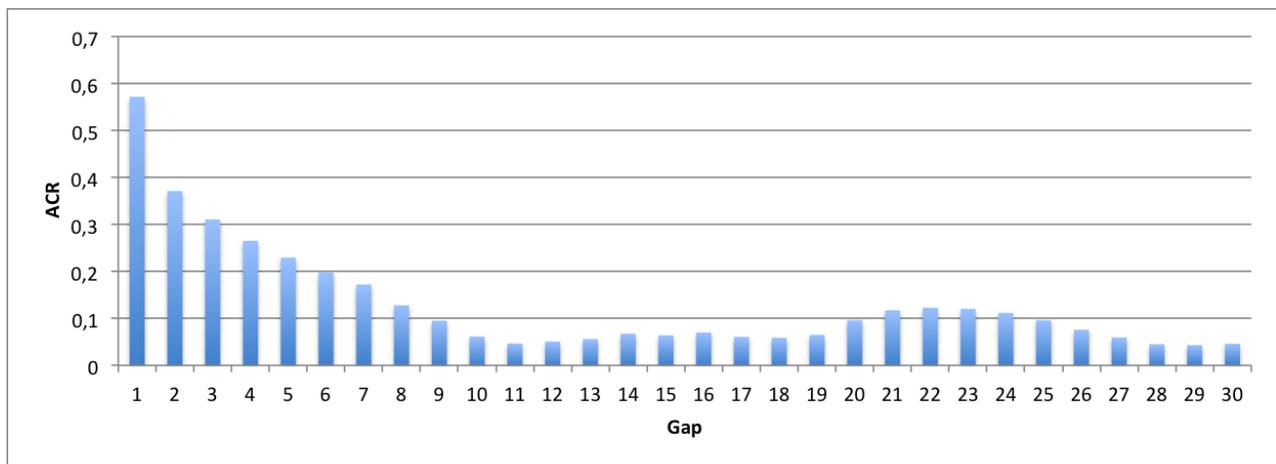
Figure 4.4: Autocorrelation of the volumes in Elbas.

As seen in the figure there is a autocorrelation in the traded volumes in Elbas. The seasonal

trend that is exploited by using a SARIMA model is present, although the autocorrelation is not very high. To some extent the autocorrelation can be explained by the office hour at the BRPs. After office hours it is reasonable to assume that the trading in Elbas will decline. This might explain the low autocorrelation, especialy the dip around 12h.

With the low correlation between the traded volumes in Elbas and Δpr, it is clear that the volumes in Elbas can not in a significant way give any price signals in the balancing market. Therefore, the correlation between other parameters was investigated.

4.3.2 Correlation Between the Volumes in Elbas and Volumes in the Balancing Market

The correlation between the volumes in Elbas and the balancing volumes was studied. Trades in Elbas are counted as down regulating when the sale is done in the area at hand and the buyer is stationed in another area. For example, if a producer sells power in SE3 and the buyer is stationed in SE2 or any other area the trade is counted as "downward regulation" as it is exported out of the area. This is, however, not very relevant as no big dependency was found between the two volumes. A scatterplot showing data from every hour of 2012 is shown in Fig. 4.5.
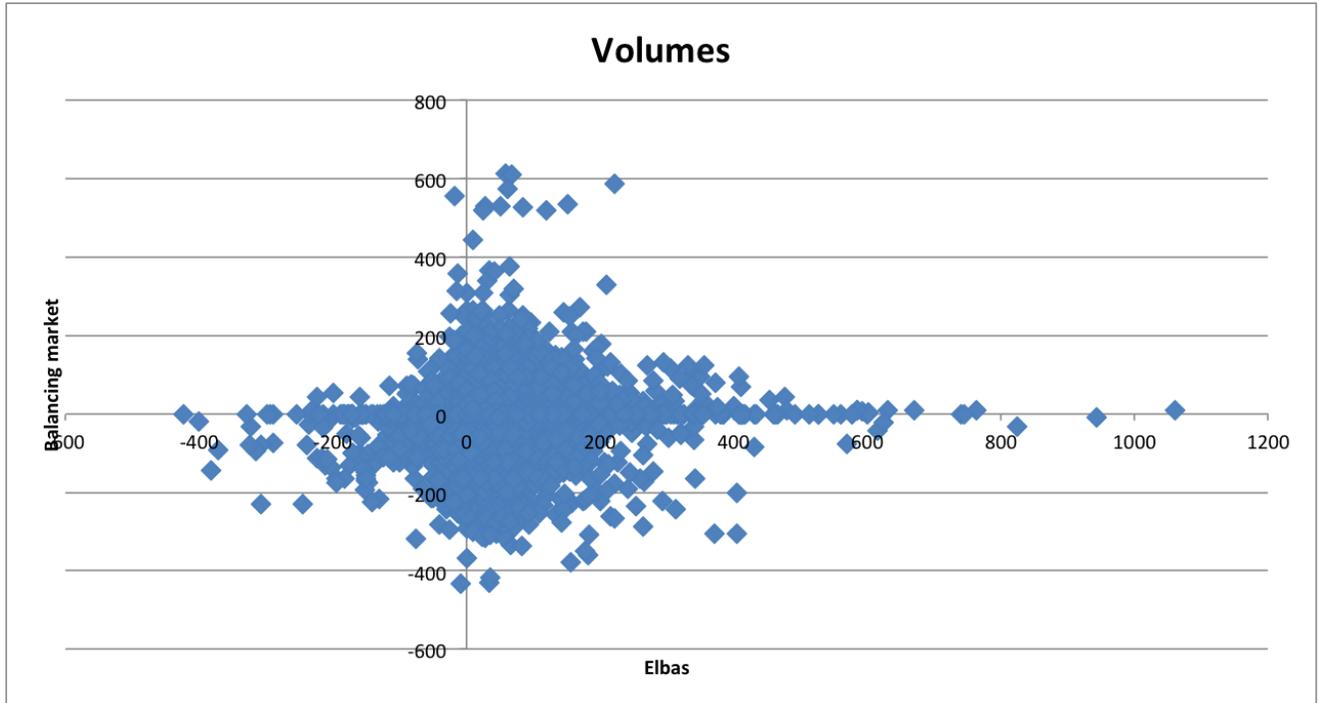
Figure 4.5: Correlation between volumes in Elbas and regulating volume

We see that there is no evident corrolation in the presented data. The correlation between the volumes are found to be 0,0429. The correlation between upwards regulation in the two markets are 0,0734 and downwards regulation is 0,0582. This contradicts the initial assumptions described in Section 4.3.1.

4.3.3   Correlation Between the Prices in Elbas and Prices in the Balancing Market

The prices in Elbas should reflect the expectations of the market, and hence give some price signals for the balancing market. As previously mentioned, the last accepted trade in an hour sets the price in Elbas.
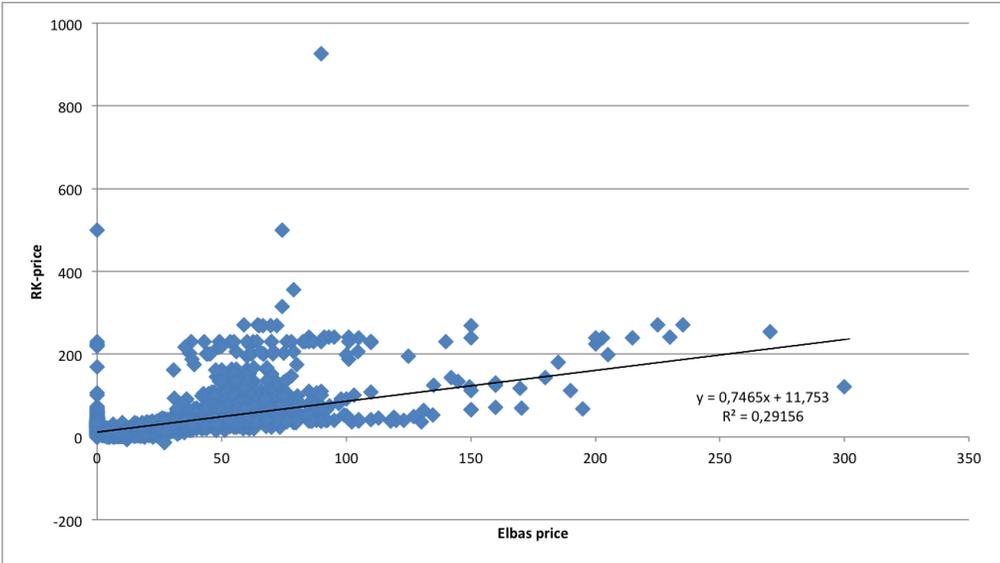
Figure 4.6: Correlation between prices in Elbas and the balancing market

As seen in Fig. 4.6, a linear trend is observed between the prices in Elbas and the prices in the balancing market. In this case the correlation is 0,5400 in total. The correlation of upward regulation is 0,5967 and for downward regulation it is 0,7089. Furthermore, a strong seasonal autocorrelation is observed for the prices in Elbas, as shown in Fig. 4.7.
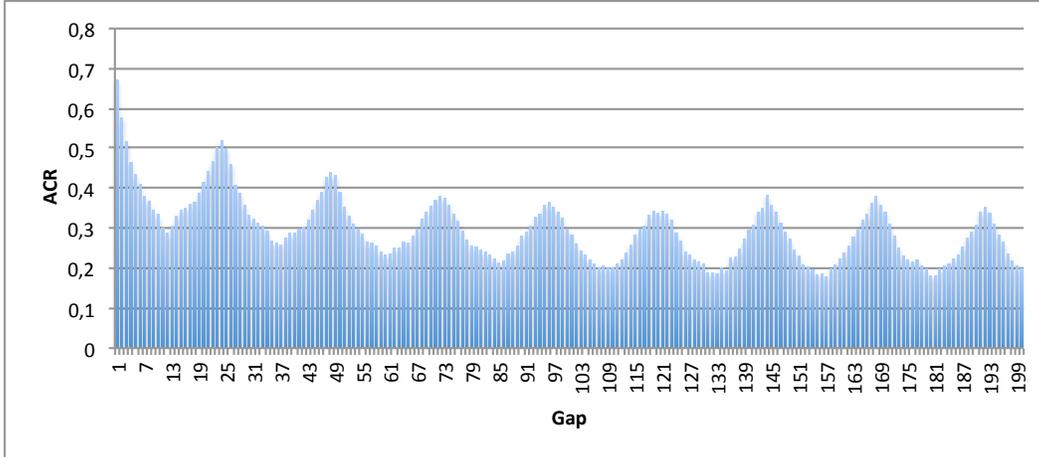
Figure 4.7: Autocorrelation in Elbas

The initial thought was therefore to use the strong autocorrelation in Elbas to predict an Elbas price in the upcoming hours. Thereafter, a linear model model would be constructed using the correlation between the price in Elbas and price of balancing shown in Fig. 4.6. With the proper regression coefficient in place the model would be run a large number of times and the result compared with the actual price of balancing in the hour at hand. With a large number of samples, the expected value and standard deviation of the modelling of the balancing price could be found. The next step would then be to find the error function of the wind power forecast. When this is found a simulation of the best way to handle the balances would have been implemented and the results presented as a probability density function. This is done by creating scenarios combining the the wind forecast error and the price in the balancing market. For each scenario it would be investigated if it is better to handle the balancing intraday or settle it in the balancing market. When this is done for a large number of scenarios a distribution for the cost of balance handling would emerge. One probability density function for handling the balance intraday and one for letting it settle in the balancing market. Whichever function would have the lowest expected value and standard deviation would then be the most promising way to handle the balances.

It was, however, pointed out by Gro Klæboe that the results in Fig. 4.6 were a false positive as both the balancing price and the intraday price is correlated to the spot price. The initial thought was therefore to use the strong autocorrelation in Elbas to predict a Elbas price in the upcoming hours. Thereafter, a linear model model would be constructed using the correlation between the price in Elbas and price of balancing shown in Fig. 4.6. With the proper regression coefficient in place the model would be run a large number of times and the result compared with the actual price of balancing in the hour at hand. With a large sample of results the mean and standard deviation of the balancing price could be found. The next step would then be to find the error function of the wind power forecast. When this is found, a simulation of the best way to handle the balances would have been implemented and the results presented as a probobility density function. This is done by creating scenarios for

the wind forecast error and the price in the balancing market. For each scenario it would be investigated if it is better to handle the balancing intraday or settle it in the balancing market. When this is done for a large number of scenarios a distribution for the cost of balance handling would emerge. One probobility density function for handling the balance intraday and one for letting it settle in the balancing market. Whichever function would have the lowest expected value and standard deviation would then be the most promising way to handle the balances.

As mentioned it was pointed out that the results were a false positive, as both the balancing price and the intraday price is correlated to the spot price. Therefore the same correlation was checked by subtracting the spot price as follows.

$$\Delta pr_{BM} = Balancing_{Price} - Elspot_{Price} \tag{4.3}$$

$$\Delta pr_{Elb} = Elbas_{Price} - Elspot_{Price} \tag{4.4}$$

The scatter plot of Δpr_{BM} and Δpr_{Elb} is shown in Fig. 4.8.
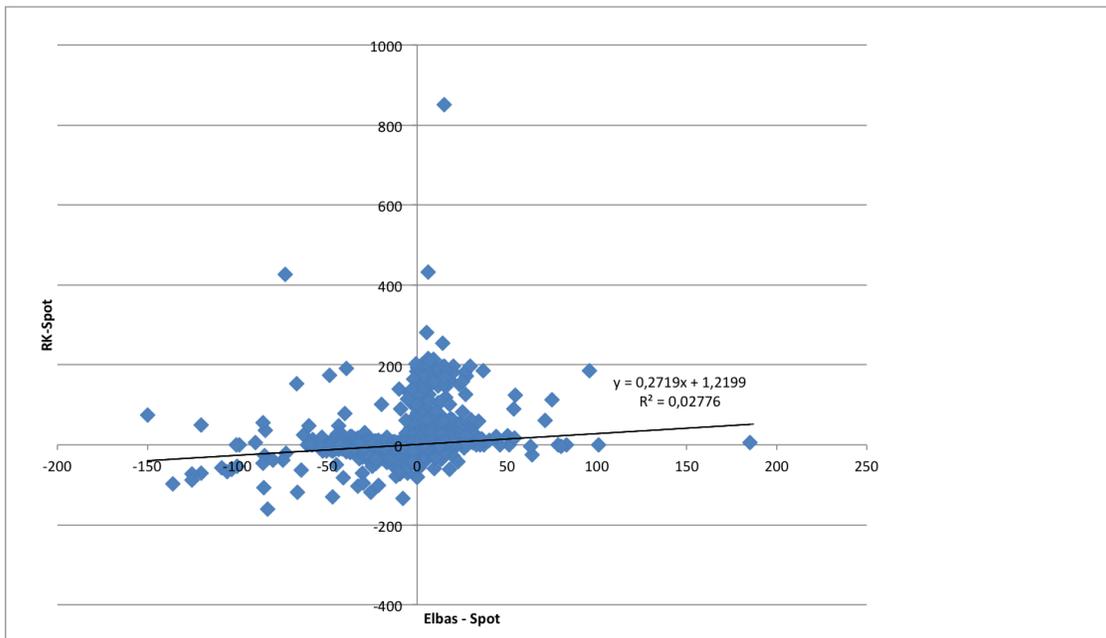
Figure 4.8: Correlation between prices in Elbas and the balancing market, when the spot price is subtracted

As seen in Fig. 4.8, no strong correlation is found between the prices in Elbas and the prices in the balancing market. These results indicate that the trend line found in Fig. 4.6 is a result of the volatility in the spot price. High spot prices are correlated with both the prices

in the intraday market and in the balancing market. Therefore a correlation between the two was found when the spot price of electricity was not subtracted. No correlation between the price in the intraday market and the balancing market tells us that these prices are random when compared to each other. This is a quite peculiar result as it is reasonable to assume that they would have some correlation.

4.3.4 Discussion

An initial explanation of the observed results can be the nature of the two markets. In the physical real-time balancing market, the TSO can trade power in order to balance the system when necessary as a part of the frequency control. In situations where the frequency has dropped, the TSO will accept bids corresponding to increased production in the system. The reason for the drop in frequency can be among other things; increase in demand, tripping of a line into a congested area or the tripping of a producing unit in the system. In its nature such accidents are random, hence the direction and price of balancing power is hard to predict. The same argument is valid for downward regulation. The forecast error for demand and intermittent energy production will vary randomly. There is however, as shown in Fig. 4.3, a autocorrelation for Δpr_{BM}. This suggests that when frequency control is required it is reasonable to assume that it will sustain for some hours. The correlation between the spot price and the price of balancing suggests that if the day-ahead price is high, the marginal cost for producing real-time balancing is high. Therefore, a high spot price will lead to a high balancing price.

The Elbas market is a market that requires a physical delivery. The big difference between Elbas and the balancing market is the auction form. The balancing market is a clearing market, similar to the Elspot market while Elbas is a bay-as-bid market. In [31], an auction game analysis is carried out regarding uniform and pay-as-bid pricing. It is found that in a static setting, the profit level of suppliers will be greater under uniform pricing, and that in the dynamic setting uniform pricing can facilitate collusion. Furthermore, it is pointed out that an entry barrier could exist under a pay-as-bid auction and that it can be harmful in the long run. The study done in [31] states that since most of market players have intra-marginal blocks, they can enjoy profit maximized revenues without any risk by letting players with market power keep the prices high. This would result in extremely high market prices in the short term when supply is tight. In contrast, the market players are subjected to the risk of being "undercut[2]" in a pay-as-bid model, and hence, can not enjoy the profit maximized revenues. This would result in reducing total suppliers revenue in the sort term. This explains why some suppliers of balancing power are reluctant to enter Elbas. On the other hand, buyers of balancing power can, in some situations, find it more favorable to purchase balancing power in the intraday market.

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[2]in this setting undercut reffers to the situation when lower bids then your own is submitted and accepted. This will increase the risk of not getting allocated.

The findings of [31] state that a producer has any spare capacity it would be more beneficial for them to bid into the balancing market. In this case their bid may or may not be accepted. If it is accepted last, the producer would be the price setter in the area. Assuming the bids are properly priced from the producers, an activation of balancing power will have no downside for the producer. If they are not accepted, they do not miss out as the remaining water can be used in the day-ahead market the following period. If they are accepted they have a properly assessed bid and have an upside if any higher bids than their own are activated. Therefore, participating in the balancing market is beneficial for a provider of balancing power.

The risk of being "undercut" can, to some extent, explain some of the low liquidity in the intraday market. However, since the bidding in the balancing market is submitted for the next 24 hours, the intrday market should provide some potential for profit seeking suppliers, especially if they are not committed in the balancing market. When purchasing balancing power the pay-as-bid model can be beneficial for TrønderEnergi, by the same reasoning that it can be unfavorable when selling balancing power.

In [11], a mixed-integer program to support the day-ahead bidding of a price-taker hydropower producer taking into account the possibility of trading energy in the Elbas market is proposed. The value of considering Elbas concept is introduced and the uncertainty in the markets are represented by a set of scenarios generated with an ARMA-GARCH model, calibrated from historical data. The value of Elbas is found by the percentage difference between two results:

1. The optimal expected profit of the proposed model considering Elbas trades

2. The optimal expected profit of the proposed model using fixed day-ahead bids calculated without considering Elbas trades

From this, the value of Elbas $\Delta(\%)$ is calculated by:

$$\Delta(\%) = \frac{(1) - (2)}{(2)} * 100 \tag{4.5}$$

The values found for $\Delta(\%)$ are very low, and never greater then 0.12%. When testing the model with time series from a period with higher volatility the value of Elbas is, in the best case, 0.65%.

The results of this study indicate that when considering Elbas when bidding on the day-ahead market does not impact the profit significantly. Therefore, the day-ahead bidding problem can be modeled without Elbas trading, thus simplifying that operational challenge.

In [16], an analysis of the imbalance costs of wind power for a hydro power producer in Finland is done. Here the intraday correction of forecast error is analyzed. It is stated that the low liquidity will affect the trader proportionally to his balancing volume. Hence, a trader with a large balancing volume will not benefit from trading on Elbas. The article

finds the worst case and the best case of trading in Elbas based on the available bids in a given hour. The base case is defined as settling all of the imbalance volumes in the balancing market. Compared with the base case, the worst case scenario results in overall losses of 24% instead of gains. They further point out that Elbas trading is only cost effective when trading close to average Elbas price levels. When wind power errors are to the opposite of system erros, Elbas trade can only achieve a small gain. To some extent the trade could even be counterproductive as the correction might, at least partly, be to the wrong direction.
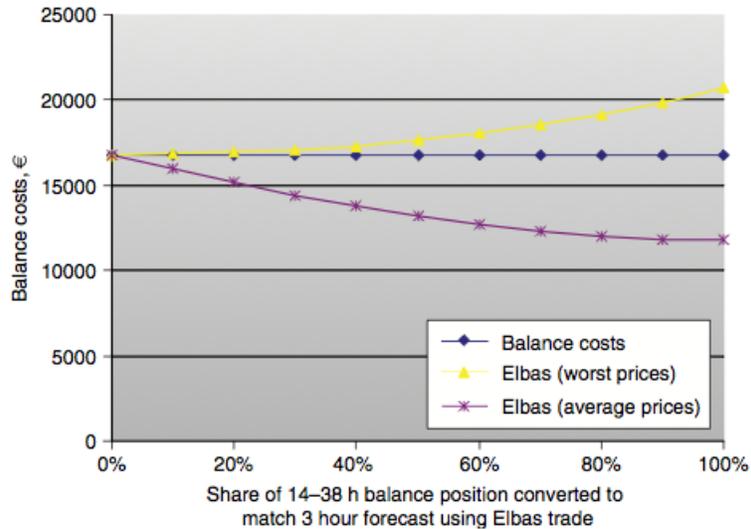
Figure 4.9: The balance costs of 400 MW wind power where production is sold at the spot market 14-38 hours ahead compared to balance costs where the spot position is covered to match a 3 hours ahead forecast using intraday Elbas trade [16].

The work done by [31], [11] and [16] concludes that there is a lower risk for a producer to act in the balancing market compared to Elbas, and that speculations in Elbas should not be considered when optimizing the Elspot bidding. It is found that using Elbas to balance the WPP can lead to losses instead of gains. The reports presented here are an indication of what to expect when investigating the possible options for TrønderEnergi. Some attention should be paid to such repports but it is, however, important to investigate the specific constraints that TrønderEnergi has. On the basis of the statistical analysis presented in Section 4.3, it can be concluded neither the volumes nor prices in Elbas and the balancing correlates in such a scale that Elbas can be used as an indicator of what the prices in the balancing market will be. To be able to provide decision support to TrønderEnergi, the initial thought of using statistical linear regression and a SARIMA model must therefore be altered. An alternative approach is presented in Section 4.4.

4.4 Monte Carlo Analysis of the Respective Markets

4.4.1 Introduction

As presented in Section 4.3 there are not any statistical data that support the inital idea to use prices or volumes in Elbas to predict the prices in the balancing market. After discussions with Professor Gerard Doorman, Ph.D. Hossein Farahmand and Ph.D. student Gro Klæboe a new aproach is found to provide TrønderEnergi with decision support regarding the balance handling of their production portfolio.

This model is based on Monte Carlo analysis and models the respective markets seperately. Based on the correlations found in Section 4.3, it is reasonable to assume that the two markets do not affect each other. Therefore, the modeling of the two markets is done individually. The balancing market and the wind power forecast error are both stochastically modeled based on statistic parameters found by examining the actual data from 2012. For each hour a balancing volume and a price is found and the total yearly costs are calculated. This is done 1000 times and the mean and standard deviation of the costs in the balancing market and the Elbas market is presented. In the following sections each of the parameters are described more thoroughly.

4.4.2 Wind Power Prediction Error

The uncertainty of weather prediction models has on multiple occasions been investigated. The majority of existing wind power forecasting system is based on numerical weather prediction models, as described in Section 3.5. These are typically given with a coarse spartial resolution of 10 x 10 km and are refined considering the local conditions of the specific site, e.g. orography and surface roughness. The NWP's do not provide perfect predictions as "the laws of physics dictate that society cannot expect arbitrarily accurate weather and climate forecasts." [23]. In [23] it is pointed out that there are two main sources of error when predicting the wind power forecast. The uncertainty of the wind speed and the effect of the nonliear power curve. A power curve of a typical wind turbine, and the amplification effect the power curve has on the error of wind speed is shown in Fig. 4.10.

From Fig. 4.10, it can easily be seen that the characteristic shape of the power curve will influence the forecast error of the power prediction. Imagine that the wind speed prediction provides a value that has a small deviation for the actual wind speed. In the steep part of the power curve this small difference will be transferred to a relatively large difference between the corresponding predicted and measured power output. In contrast to this, if a small wind speed forecast error occurs in the flat part of the power curve, the error of power output will be relatively small. Hence, the wind speed prediction error is amplified to power output error according to the local derivative on the power curve.
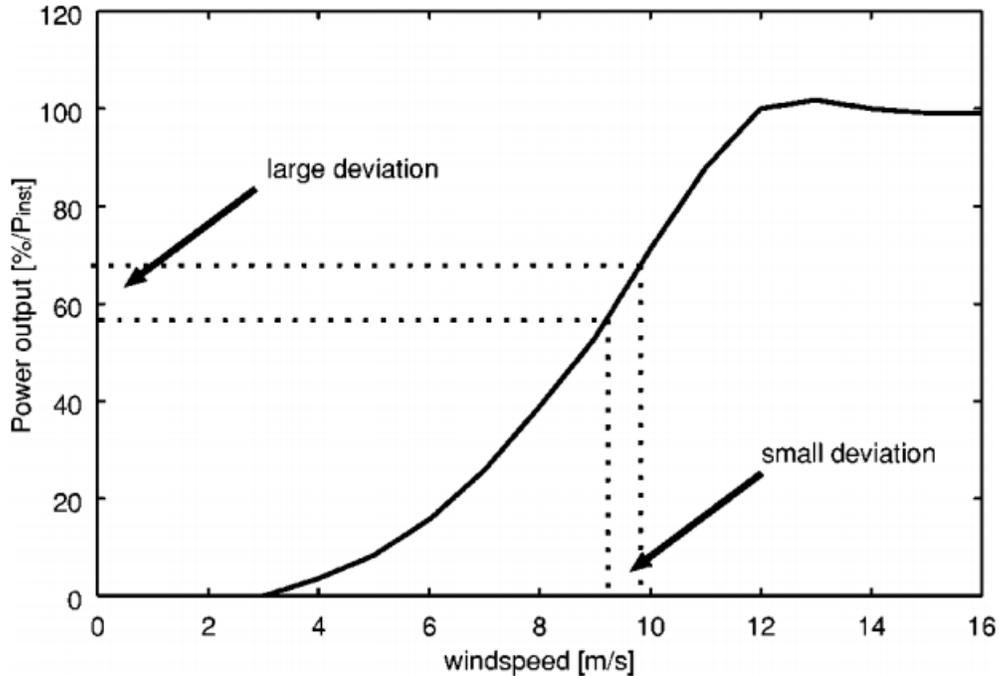
Figure 4.10: Power curve of a typical wind turbine. The amplification of initial errors in the wind speed are aplified according to the slope of the power curve [23].

When dealing with statistical error measure it has to be kept in mind that these measures describe the average deviations between forecast and measurements. The average is normally taken over one year to include all seasons with a chance of covering most of the typical meteorologal situations. Hence, modeling the error measures requires that the data already has been recorded over a certain period of time such that the forecast error represent the error quality of the past. In this thesis data from 2012 is used. The uncertainty is understood as the forecast quality of the past. In contrast to this, the uncertainty of the future is by definition unknown. Under the assumption that the statistics of the wind error forecast is stationary, the historical forecast error is used as an estimate of the uncertainty.

In [5] the statistics of wind power forecast error is analyzed with special regard to the appropriate probability density function (pdf) of the error. It is pointed out that there is not much litterature on the subject. It is stated that the difficulty in finding a proper definition for the forecast error pdf lies in the great variety of its shape depending on the forecast horizon and method, and concluded that the error pdf is fat-tailed with variable kurtosis. Therefore, it cannot be modeled with the normal distribution, and the long term mean value becomes the best forecast for large forecast horizons.

It is pointed out in [17] that wind power production on an hourly level for 1-2 days ahead, is more difficult to predict than any other production forms, or the load. In the article, a wind power production tool (WPPT) has been developed and compared to the persistence of the

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wind. The persistence of wind describes the autocorrelation of the wind from one hour to the next hour. This is the forecast used for the current balance handling[3] as described in section 2.4.2. This is shown in Fig. 4.14.
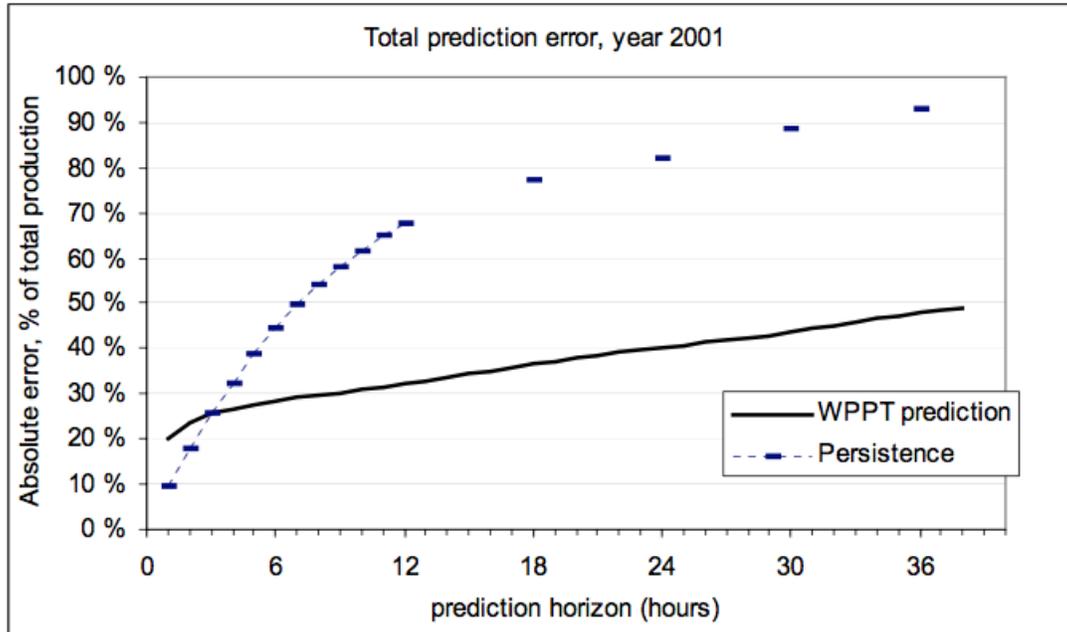
Figure 4.11: Performance of the wind power prediction tool WPPT and the persistence prediction model [17].

It can be seen from Fig. 4.14 that for short time horizons, up to 3 hours, the persistence gives good results for the wind power forecast. According to [17], this is partly due to the fact that so far exact values of space and time have not been crucial for other weather prediction applications. It is, for example, important for a fisherman to know that a storm is coming, but the exact wind speed at a precise location is not of very high importance. For this reason, the balance handling done at TrønderEnergi, the re-bidding procedure, might be a good one.

In this thesis actual hourly data from 2012 is used to fit the statistical property of the parameters. To estimate the wind power forecast error the specific conditions at the windfarms operated by TrønderEnergi[4] are analyzed. For each hour of the year, the energy sold in the day-ahead market and the actual producion is found. The energy sold on the spot market equals the planned production which is found by using wind power prediction models. The difference between the two therefore equals the prediction error and the volume that have to be managed intraday. The time horizon for the error will therefore differ from 12-36 hours. As the objective of this model is to determine whether to balance all of the volume in the

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[3]re-bidding procedure

[4]The analysis include Bessakerfjellet wind farm and Valsneset wind farm

balancing market or on Elbas, the forecast error time horizon is not that crucial as the same volume is evaluated using both markets.

The found forecast errors based on data from 2012 is presented in Fig. 4.12 and Fig. 4.13.
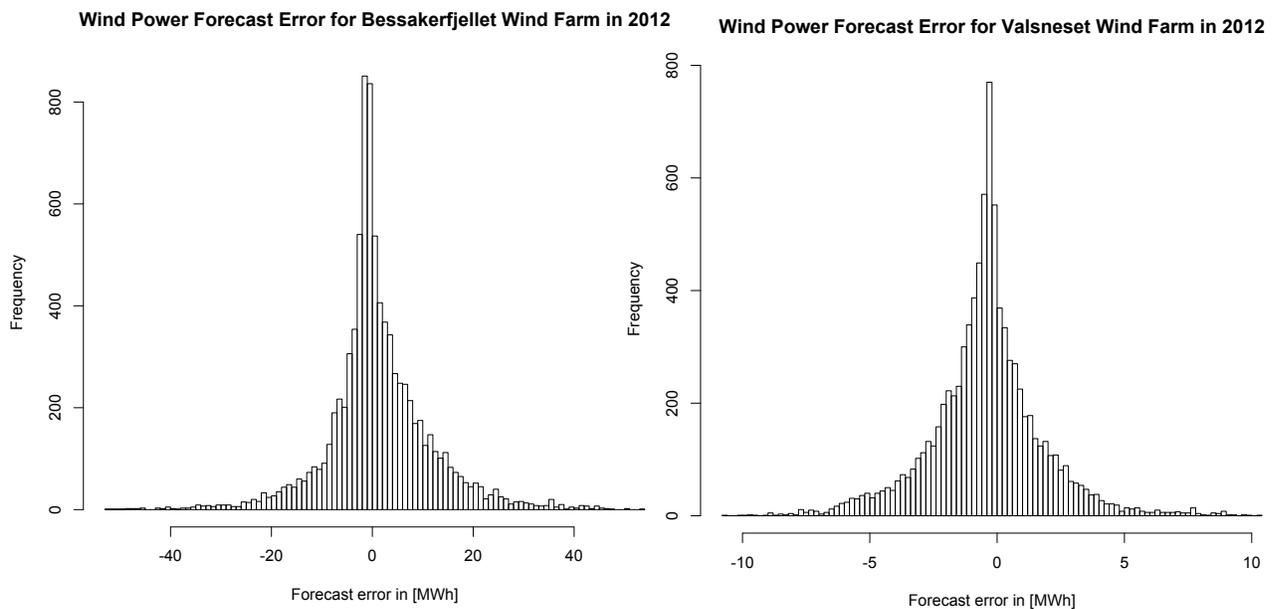
Figure 4.12: Wind power forecast error for Bessakerfjellet Wind Farm in 2012.

Figure 4.13: Wind power forecast error for Valsneset Wind Farm in 2012.

As seen in the respective figures, and Table 4.1, the mean of the wind power forecast error is slightly positive for Bessakerfjellet and negative for Valsneset. The x axis of the figures should be noticed as Valsneset wind farm is bigger then Bessakerfjellet wind farm, and thus the forecast error at this location is more crucial then at Bessakerfjellet. As the total balancing volume is the sum of the balancing volume from Bessakerfjellet and Valsneset, the total balancing volumes is shown in Fig. 4.14

Total Wind Power Forecast Error in 2012
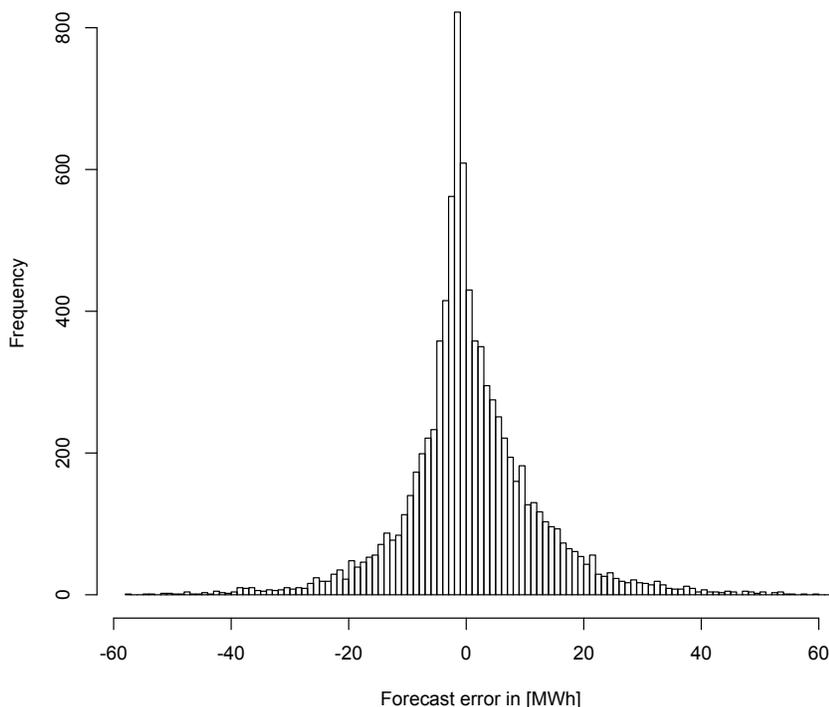
Figure 4.14: Total wind power forecast error in 2012.

With a similar assumptions as presented in [23], the wind prediction forecast error is assumed to be stationary. Furthermore one year data is used to model the statistichal behavior, similar to the work done in [17]. Using R[5], the mean and standard deviation of the wind forecast error is found. This is presented in Table 4.1.

	Mean	Standard Deviation
Bessakerfjellet Wind Farm	1.1626	10.3801
Valsneset Wind Farm	-0.4291	2.2107
Total	0.7335	11.4390

Table 4.1: Statistichal parameters for wind farms operated by TrønderEnergi.

The histogram shown in Fig. 4.14 somewhat contradicts the conclusions of [5]. The distribution has a fatter tail than what is shown in the article. This can, to some extent, be explained by the differece in the forecast horizon. When plotting data from Bessakerfjellet

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[5]R is a language and environment for statistical computing and graphics

and Valsneset, the forecast horizon is 12-36 hours, while the article has a fixed forecast horizon of 24h when investigating the probability distribution of the forecast error. Furthermore some geographical smoothing can be expected as the wind farms are situated about 80 kilometers from one another. The data shown in Fig. 4.14 is in this thesis modeled as a normal distribution with the parameters shown in Table 4.1.

To measure the accuracy of the wind power forecast error, some goodness of fit tests have been run. The results are shown in Fig. 4.15 and Fig. 4.16.
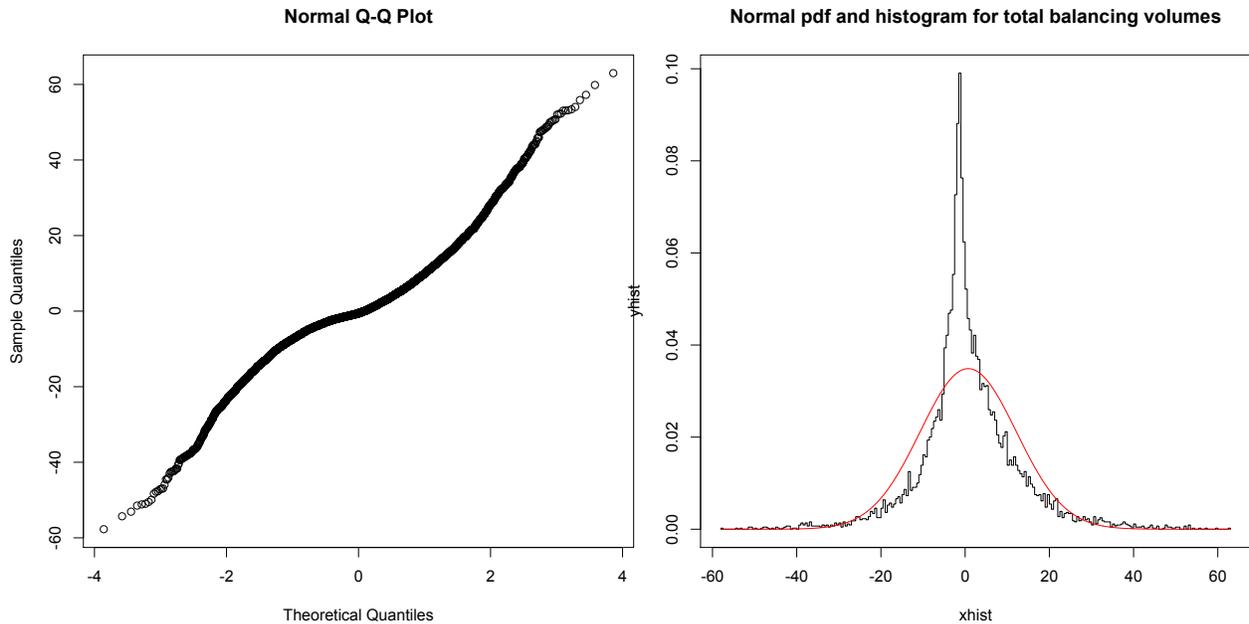
Figure 4.15: Q-Q plot for goodness of fit for total balancing volumes.

Figure 4.16: Normal pdf and histogram for total balancing volumes.

In Fig. 4.15 a Q-Q plot of the fitted distribution in presented. This is a graphical method for comparing two probability distributions by plotting their quantiles against eachother. If the two distributions beeing compared is a good match, the points in the Q-Q plot will lie on the line y=x. If the distributions are linearly related, the points in the Q-Q plot will lie on a line, but not nexessarily on the line y=x. This can be seen on as a non-parametric approach to comparing their underlying distributions. A Q-Q plot is generally a more powerful approach to doing this then the common technique of comparing histograms. Nevertheless the histogram of the balancing volumes are compared with a normal distribution in Fig. 4.16.

It has been concluded in conversations with the supervisors that the found distribution is an axeptable fit for the purpose of this thesis, considering the time constraint and sensitivity of the modeling. Even if the fitting is not perfect, the same balancing volumes will be used to compare the costs in the balancing market and in Elbas. As the purpose of this thesis is

to evaluate which of the two markets will be more profitable, not to accurately describe the wind power forecast error, the value of the balancing volume are not crucial.

4.4.3 Balancing Market Model

In this section the model used to calculate the costs in the balancing market is described. This is done by modeling the wind power forecast error, which will be the balancing volume, and by modeling the prices in the balancing market. This is done by using data from 2012. When the model is fitted, simulations for a year are done on a hourly basis. This is then repeated 1000 times and the average sum of the yearly balancing costs is presented as a probability density function.

4.4.3.1 Modeling the Balancing Market Price

To properly estimate the upcoming balancing price has proven to be a difficult task. As mentioned the nature of the random faults and load in the system is a sound explenatnion for this. This is further explained in [19]. In the literature there is, however, some work done to model the balancing prices. In [30] the prices are modeled by using a SARIMA model of the balancing volumes to find the regulating state of the system, and a statistical linear model based on statistics from previous years is used to calculate the prices. [25] proposes a model based on SARIMA and Markov Processes. In this paper the balancing price is forecasted without regard to the balancing volumes. It seems that the predictability of the balancing price has been reduced over the past couple of years. The mentioned articles [30] and [25] had promising results for forecasting the balancing price, but the statistical analysis done in Section 4.3 show that there are no applicable correlation for a solid forecasting of the balancing price when using data from 2012. It is beyond the scope of this thesis to provide an explanation for this, but it is conceivable that the increased integration of intermittent energy sources is a factor for this development.

In the model proposed in this thesis, the expected value of the balancing price is used. This is done by splitting the 24 hours of a day into day and night, as the upward, downward and no regulating state is found to differ in the two time periods. Each of the three regulating states are modeled stochastically by using historic data. The hourly prices are then found by multiplying the prices in each state by the probability of that state occuring. Therefore it is the expected value of the balancing price that is found. The macro used to find the regulating state for each hour throughout the year is shown in Fig. A.11. This is an if loop that counts the regulating state for each hour throughout the year. In Fig. 4.17 and Fig. 4.18 the frequency of upward regulation, no regulation and upward regulation for each hour of the year is shown. Based on these graphs it is found valid to separate the 24 hour period into day and night, and find the probability for each state to occur seperately. As data for 2012 is used to model the balancing prices and to find the Elbas prices, data from 2012 is

used here for concistency. The numbers found for 2011 are used to support the assumption that the different regulating states differ from day to night.
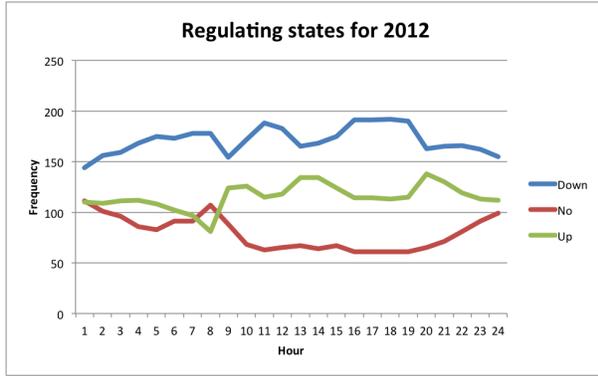
Figure 4.17: Regulating states for 2012.   Figure 4.18: Regulating states for 2011
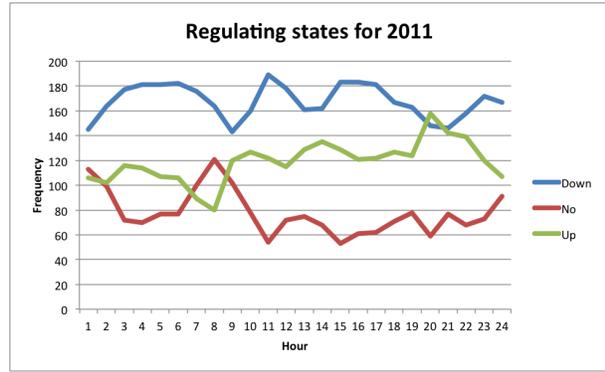
Based on these figures, the day is defined as from hour 9 to hour 23 and night from hour 1 to hour 8 pluss hour 24. For the respective hours the number of regulating states is divided by the number of that hour over the year. As 2012 was a leap year this number is 366. In other words there are for example 366 hours with the value 1 over the year, and this transfers to the hour from 00:00 to 01:00. Of these 366 hours 144 had downward regulation, 111 had no regulation and the remaining 110 had upward regulation. Hence the probability for the respective states become:

$$\mu_{Up} = \frac{Upward \quad regulating \quad hours}{Total \quad hours} = \frac{110}{366} = 0.3005 \tag{4.6}$$

$$\mu_{No} = \frac{No \quad regulating \quad hours}{Total \quad hours} = \frac{111}{366} = 0.3033 \tag{4.7}$$

$$\mu_{Down} = \frac{Downward \quad regulating \quad hours}{Total \quad hours} = \frac{144}{366} = 0.3934 \tag{4.8}$$

In Eq. 4.6, Eq. 4.7 and Eq. 4.8, μ denotes the probability of the respective regulating state for the hour used in this example. To find the probability of regulating state in the defined periods day and night, the average regulating state for that period is found. This is shown in Eq. 4.9. At first sight the equation seems a bit messy due to the notations. μ is used to denote the probability and notations for day and upward regulating is used in this example. The bar above μ_{UP}^{Day} denotes average. The number 15 is used as the day is defined as of hour 9 to hour 23, which is 15 hours.

$$\overline{\mu_{UP}^{Day}} = \frac{1}{15} \sum_{i=1}^{15} \mu_{UPi}^{Day} \tag{4.9}$$

The similar calculations are done for all regulating states during the day and night. For simplicity not all of the formulas are included. The results are shown in Table 4.2.

	Down	*No*	*Up*	*Sum*
Day	0.4781	0.1883	0.3336	1
Night	0.4512	0.2627	0.2861	1

Table 4.2: Statistichal parameter of downward regulating, no regulating and upward regulating.

For each state the price of balancing is modeled. As the price in the balancing market is strongly correlated to the spot price, it is Δpr_{BM} as defined in Eq. 4.3 that is modeled. As the developed tool is meant to give decision support on the long term basis, the extreme values of balancing are removed. These often occur due to extreme situations in the system, which are hard to predict. Such situations are therefore disregarded in this thesis. Values that lie outside of 3 standard deviations (σ) of the mean are therefore deleted. In total 125 values for Δpr_{BM} are removed. Values for Δpr_{BM} are shown in Fig. 4.19. The unit on the x-axis is [€/MWh].

In Fig. 4.19 the bars which are above zero on the x-axis is the frequency of hours with positive Δpr_{BM}, which means upward regulation. The bars below zero account for hours with downward regulation. From the figure, we see that the data presented is consistent with the data presented in Fig. 4.17. Number of hours with downward regulation is higher than with upward regulation.

As mentioned, the upward and downward regulation has to be modeled individually. Therefore a histogram for each state is shown in Fig. 4.21 and Fig. 4.20.

From the presented histograms it is clear that a normal distribution cannot be used to model Δpr,BM. As the density function changes drastically with the value of x, a Weibull distribution is chosen after consulting with the supervisors. The scale and shape parameters are found using R, and are presented in Table 4.3.

	Scale parameter	*Shape parameter*
Upward Regulation	7.1756	1.0298
Downward Regulation	9.0485	1.4831

Table 4.3: Statistical properties of Δpr_{PM}.

To evaluete the goodness of fit, the proposed model is plotted with the theoretical Weibull distribution with the same parameters. The Q-Q plots are shown in Fig. 4.24 and Fig. 4.25.
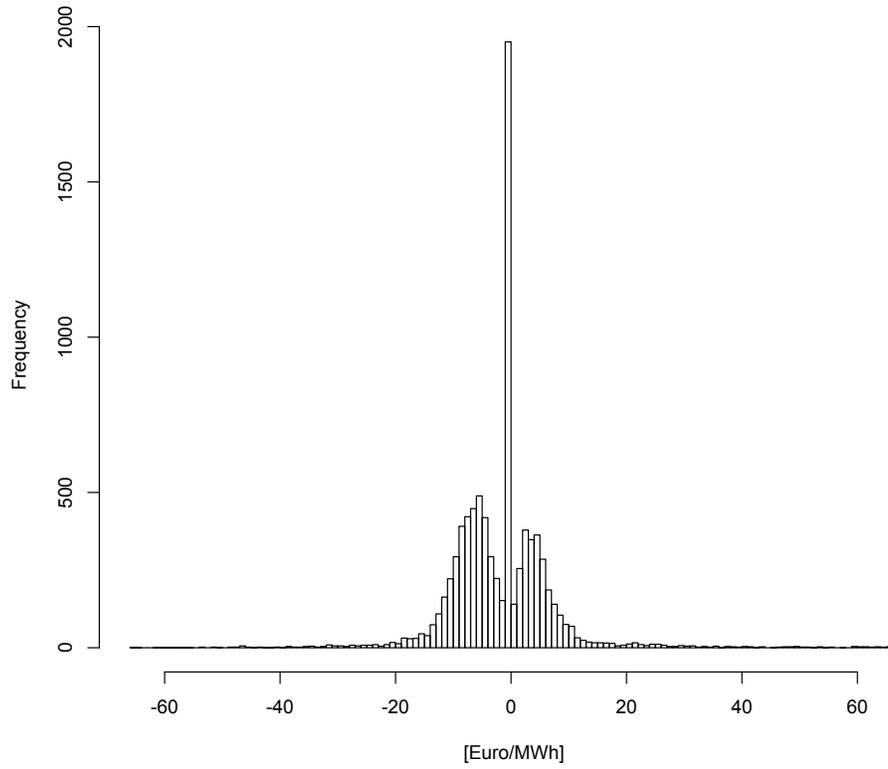
Figure 4.19: Histogram of Δpr_{BM} in 2012.
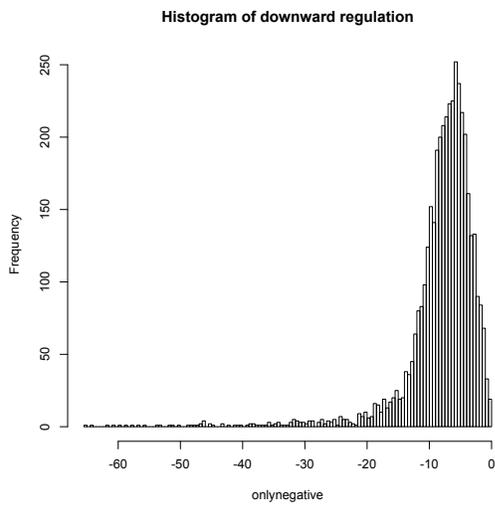
Figure 4.20: Negative Δpr_{BM} in 2012.

Figure 4.21: Positive Δpr_{BM} in 2012

Weibull pdf and histogram of downward balancing price

Weibull pdf and histogram of upward balancing price
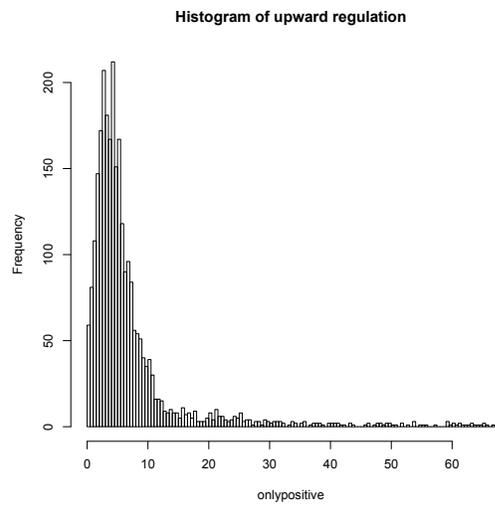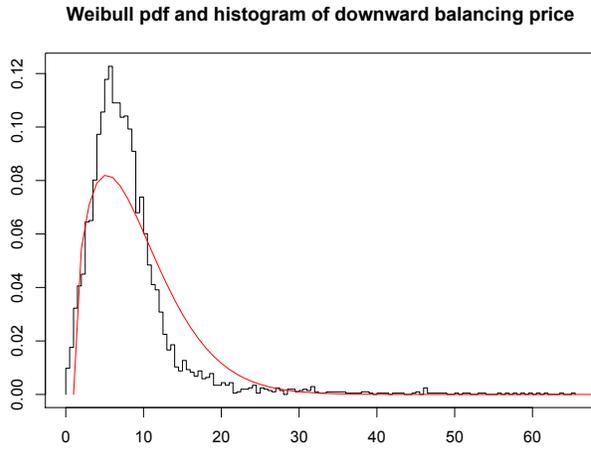
Figure 4.22: Q-Q plot for downward reg-
ulating model.
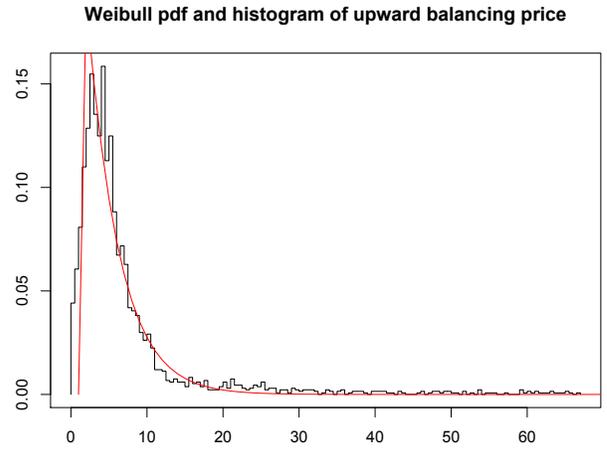
Figure 4.23: Q-Q plot for upward regu-
lating model.

Q-Q plot downward regulation

Q-Q plot upward regulation
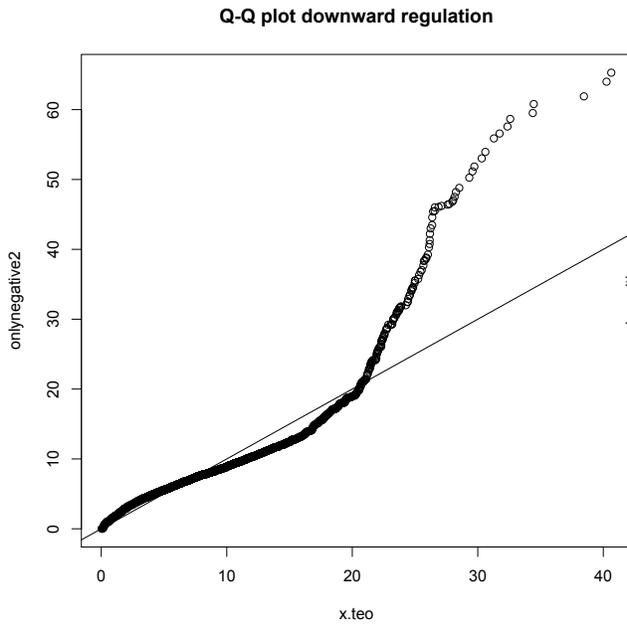
Figure 4.24: Weibull pdf and histogram
of downward balancing price.
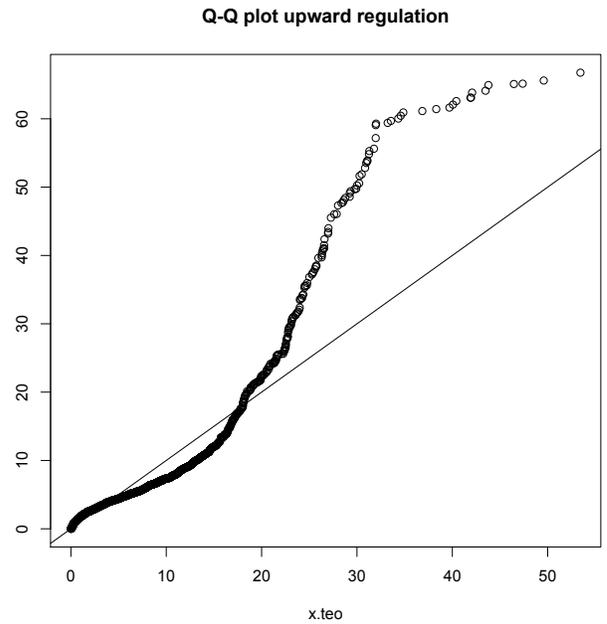
Figure 4.25: Weibull pdf and histogram
of upward balancing price.

From the respective Q-Q plots we see that this model is a good fit up til values around 20.
This transfers to that the overall fitting of the model is good, but the tails of the distribution

may be inacurate. As seen in Fig. 4.22 and Fig. 4.23 this is due to prices that occure rarely. However as stated in [19] modleing of the balacing prices has proven to be a difficult task, so the proposed model is accepted for this thesis.

The purpose of modeling the wind power forecast error and the balancing prices is to determine wether to settle the balancing volumes in the balancing market or to trade them in Elbas. In the model described here the wind error and balancing prices is drawn stochastically on a hourly basis and the yearly costs of handling the balances in the balancing market is found. When this is repeated 1000 times and a distribution that describes the bundling of wind error forecast and balancing prices are found.

To calculate the total costs of handling the balances in the balancing market, hourly balancing prices has to be modeled. This is done by using the probability of the regulating state and randomly drawing a price for each state. The drawing of a random number according to the weibull distribution is dentoted wblrnd(scale parameter, shape parameter). This is chosen as it is the syntax in MatLab[6]. The expected value of the balancing price is found for each hour. This is done according to the probability trees shown in Fig. 4.26 and Fig. 4.27. The expected value is calculated as shown in Eq. 4.10 and Eq. 4.11. To be clear a balancing price is drawn for each regulating state for each hour. Then these prices are wheighted after whether the current hour is during the day or during the night. The hourly balancing prices are then gathered into a vector. The vector of the balancing prices will then have 8784 values, one modeled balancing price for each hour throughout the year.
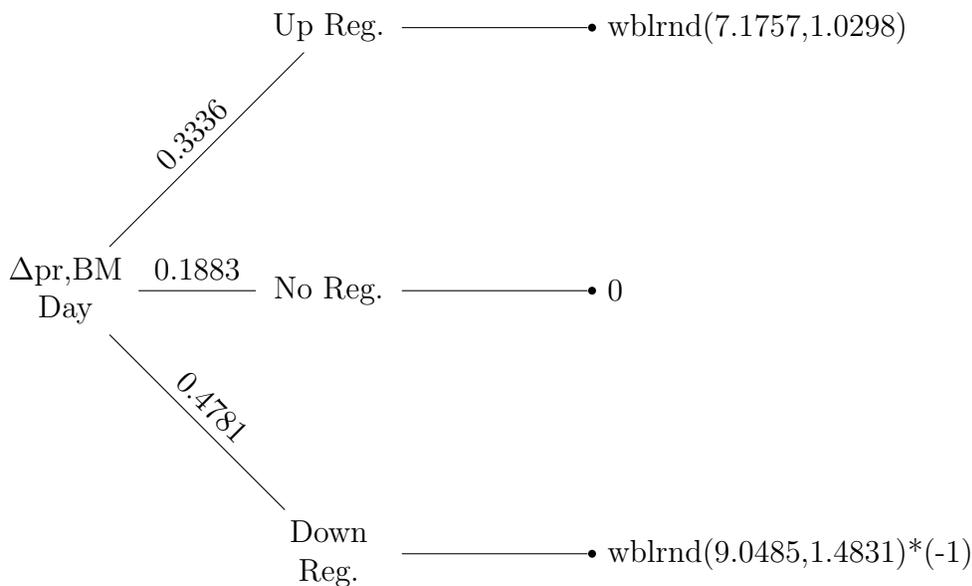
Figure 4.26: Balancing price during daytime

As seen in the Fig. 4.26, the price of balancing during the daytime is found as the expected

---

[6]wlbrnd is short for weibull random.

value seen from the first node, to the left. This is mathematically denoted in Eq. 4.10.

$$E(\Delta pr_{BM,Day}) = 0.3336*wblrnd(7.1757, 1.0298)+0.1883*0+0.4781*wblrnd(9.0485, 1.4831)*(-1)$$
(4.10)
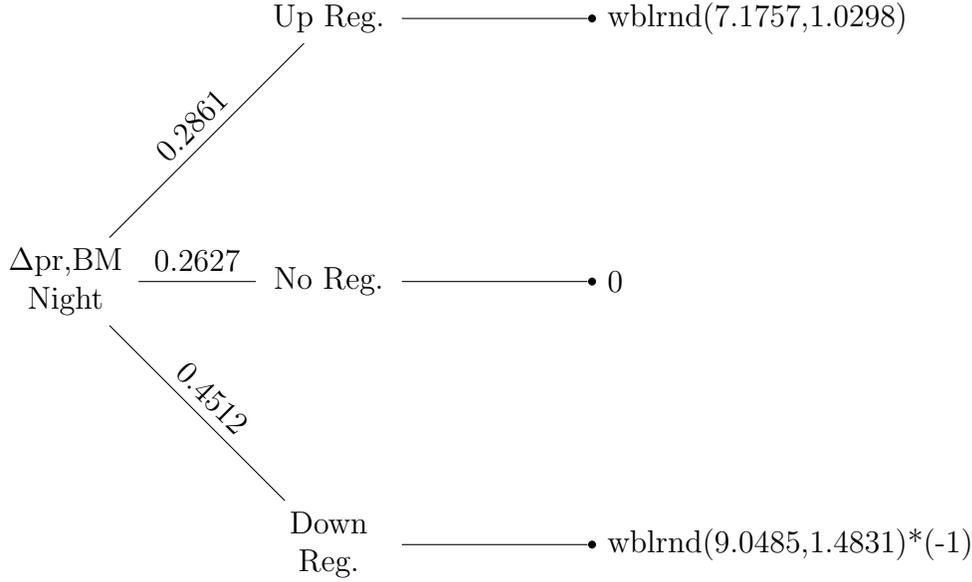
Figure 4.27: Balancing price during the night

The price of balancing during the night is shown in Fig. 4.27. This is mathematically denoted in Eq. 4.11. No values can be below zero in the Weibull distribution. As Weibull is found to be the best distribution to model the balancing prices, this is solved by drawing a random number according to the parameters of downward regulation price and multiplying the drawn number by (-1). This is shown in Fig. 4.26, Fig. 4.27, Eq. 4.10 and Eq. 4.11.

$$E(\Delta pr_{BM,Night}) = 0.2861*wblrnd(7.1757, 1.0298)+0.2627*0+0.4512*wblrnd(9.0485, 1.4831)*(-1)$$
(4.11)

As described in Section 2.4.2, the two-price system is implemented in the Norwegian balancing market and that Δpr_{BM} is defined as the balancing price minus the Elspot price. This has to be accounted for when calculating the costs of balancing. In brief, the two-price system is designed so that if the imbalances of the BRP support the balancing requirements of the system at the time, the balancing volume of the producer will be priced after the spot price. The imbalance costs will therefore be zero in such an hour, hence $\Delta pr_{BM} = 0$. If the balancing position of the BRP does not support the system requirements the price of balancing will induce a loss with the BRP, hence $\Delta pr_{BM} < 0$. In MatLab this is solved by checking if the drawn price in the balancing market and the volume of balancing are both positive or

negative. If this is the case, offering balancing volume to the market would gain a surplus. As mentioned this will not give a surplus in the two-price system, but the imbalance costs would be zero. This is offset by introducing a vector, called the check vector, where the element of the hour in hand will be 0 if the balancing position of the BRP supports the systems needs, and 1 if the balancing position contradicts the system. An example of the check vector is shown in Eq. 4.12. In the example the first with vector with numbers [-10,3,12,-4,-7,6,2,-5]' represents the balancing volume and the second vector represents Δpr_{BM}.

$$
\begin{bmatrix} Check_1 \\ Check_2 \\ Check_3 \\ Check_4 \\ Check_5 \\ Check_6 \\ Check_7 \\ Check_8 \end{bmatrix} = \begin{bmatrix} -10 \\ 3 \\ 12 \\ -4 \\ -7 \\ 6 \\ 2 \\ -5 \end{bmatrix} \neg \begin{bmatrix} -2 \\ 3 \\ -1 \\ -3 \\ 5 \\ 2 \\ 1 \\ 4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{4.12}
$$

With stochastic representation of the wind power prediction error, the price of balancing and correction according handling the two-price system, hourly values of the cost of balancing are found. This is shown in Eq. 4.13. The $\odot$ denotes elementwise multiplication of the vectors. The notation from 1 to 8784 reffers to the hours throughout the year. The number 8784 is due to the fact that 2012 was a leap year.

$$
\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_{8784} \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_{8784} \end{bmatrix} \odot \begin{bmatrix} \Delta pr_{Bal1} \\ \Delta pr_{Bal2} \\ \Delta pr_{Bal3} \\ \vdots \\ \Delta pr_{Bal8784} \end{bmatrix} \odot \begin{bmatrix} Check_1 \\ Check_2 \\ Check_3 \\ \vdots \\ Check_{8784} \end{bmatrix} \tag{4.13}
$$

With hourly costs of balancing in a vector, the yearly cost is found quite easily by the sum of the vector. A loop is introduced that runs this procedure one thousand times and the yearly balancing costs are placed in a new vector. Plotting a histogram of this vector will show the density function of the cost occuring when settling the imbalances in the balancing market.

4.4.4 Re-bidding Procedure

The current balance handling used by TrønderEnergi is also modeled. This is to be able to make a conclusive decition for TrønderEnergi of how to handle their balances in the short run, before the intra-day market in Norway matures. The re-bidding procedure is described in Section 2.4.2. In short this procedure consists of updating the production plan 45 minuites

before the hour of operation. This is done to move some volumes from the two-price system in the production balance into the one-price system in the consumer balance. The equations describing the calculation of the respective balances are included here.

$$Production \quad imbalance = Actual \quad production - planned \quad production$$
$$+ active \quad regulations_{production} \quad (4.14)$$

$$Consumer \quad balance = Planned \quad production + Actual \quad consumption$$
$$+ Trade_{prior \quad to \quad the \quad operating \quad hour} + regulations_{consumption} \quad (4.15)$$

By changing the production schedule prior to the hour of operation the producer changes the planned production. In the consumer balance the actual consumption and regulations are neglected. How these parameters affect the balancing are outside the scope of this thesis.

To properly describe the re-bidding model, an example is included. Assuming that the wind power forecast predicts a production of 50 [MWh] in the hour at hand. This is sold in the day-ahead market, so the terms "planned production" and "trade prior to the opering hour" is 50 [MWh]. At the hour of operation the actual production is 40 [MWh]. The balance sheet will in this case be:

Production balance =	40 [MWh]	- 50 [MWh]	= -10 [MWh]
Consumer balance =	50 [MWh]	- 50 [MWh]	= 0 [MWh]

Table 4.4: Balance sheet example No. 1. Ref Eq. 4.14 and Eq. 4.15.

By using the re-bidding procedure the producer changes the producion schedule assuming that the wind power production will be the same as the hour before. Assuming that the production before the hour at hand was 44[MWh], the updated balance sheet will be:

Production balance =	40 [MWh]	- 44 [MWh]	= -4 [MWh]
Consumer balance =	44 [MWh]	- 50 [MWh]	= -6 [MWh]

Table 4.5: Balance sheet example No. 2. Ref Eq. 4.14 and Eq. 4.15.

By taking measures the production balance is reduced by 6 [MWh] and hence, the consumer balance is increased by 6 [MWh]. In this case 60% of the balancing volume is settled in

the consumer balance and 40% are settled in the production balance. When modeling the re-bidding procedure the weighting of the markets is used. As the wind power forecast error is modeled stochastically, and hence has no autocorrelation, this is found to be the best approach. The actual weighting of the markets is found by using data from 2012. Weigthing the markets refers to what share of the balancing volume that is settled in the one-price system and in the two-price system. This is found by studying the data from 2012. It is asumed that 8784 values is sufficient to represent the weighting of the markets. α is denoted for the percentage of the volume settled in the two-price system and β is used to denote the percentage of volume settled in the one-price system.

When the weighting of the two markets is emplemented, the total costs of balancing using the re-bidding procedure is found, as shown in Eq. 4.16. By using this approach some of the volume is priced after the one-price system and TrønderEnergi might see some hourly surplusses on their imbalances.

$$
\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_{8784} \end{bmatrix} = \alpha \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_{8784} \end{bmatrix} \odot \begin{bmatrix} \Delta pr_{Bal1} \\ \Delta pr_{Bal2} \\ \Delta pr_{Bal3} \\ \vdots \\ \Delta pr_{Bal8784} \end{bmatrix} \odot \begin{bmatrix} Check_1 \\ Check_2 \\ Check_3 \\ \vdots \\ Check_{8784} \end{bmatrix} + \beta \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_{8784} \end{bmatrix} \odot \begin{bmatrix} \Delta pr_{Bal1} \\ \Delta pr_{Bal2} \\ \Delta pr_{Bal3} \\ \vdots \\ \Delta pr_{Bal8784} \end{bmatrix} \qquad (4.16)
$$

Based on data from previous years, the α, is found to be 0.15, and the β, is found to be 0.85. A peculiarity of this procedure is that the re-bidding can give higher balancing volumes by settling all of the balances in the producer balance. If the updated production scheme has a larger error than the initial wind power forecast, the balancing volumes will be increased. An example is shown in Table 4.6. Assuming that the initial forecast was a forecast error of 10 [MWh], similar to the example shown in 4.5.

Production balance =	40 [MWh]	- 35 [MWh]	= 5 [MWh]
Consumer balance =	35 [MWh]	- 50 [MWh]	= -15 [MWh]

Table 4.6: Balance sheet example No. 3. Ref Eq. 4.14 and Eq. 4.15.

In this case the direction of the two balancing volumes is opposite. In this example there is a surplus in the production balance and a deficit in the consumer balance. However, the sum of the two are similar to the original balancing volume of -10 [MWh]. In this case α= -0.5 and β= 1.5. This is included when calculating the average α, and β.

Intuitively this approach should perform better then settling all of the volumes in the balancing market. This is sound even if there is only one hour in which TrønderEnergi has

balances according to the systems requirements and gets paid more then the spot price with a positive balance or can buy back a negative balance to a lower price than it was initially sold for. The purpose of calculating the costs of such a system is to see how the Elbas market performs compared to an "optimal" balance handling of only using the balancing market.

4.4.5   Elbas Market Model

An alternative to settling the balances in the balancing market is to adjust the balancing position in Elbas. The markets structure of Elbas differs from the clearing structure used in the balancing market. As mentioned Elbas is a pay-as-bid market. It is the purpose of this thesis to evaluate whether to clear the volumes of balancing in the balancing market or in Elbas. As the trade on Elbas closes one hour ahead of the hour of operation, the needed volumes in Elbas are not exact. The wind power forecast one hour ahead is however significantly better than the 24 hours ahead.

It has numerous times been pointed out that the liquidity in the Norwegian Elbas market is too low. With deficiency of data, using the Norwegian Elbas market as comparison will lead to unjust results. To compare the cost of balancing in Elbas, a well functioning market has to be present. For this reason, the Elbas market in Sweden, more particulary SE3 has been used as a reference in this thesis. This also includes the investigated correlations in subsequent sections. SE3 has been chosen as this price area has some of the highest traded volumes in the system. With a high easyness of trade a well functioned marked can be represented. Furthermore, SE3 has close connection to the Norwegian system, where TrønderEnergi can participate. Therefore it should be elaborated that the results presented in the thesis are based on data from SE3. Currently trading in a well functioning intraday market is not an alternative for TrønderEnergi, but as elaborated in Section 3.3 the volumes in the Norwegian Elbas market are rising and are expected to rise in the future. The work done here will therefore be relevant when the liquidity in the Norwegian Elbas market approaches the level of liquidity seen in Sweden. This being said, there will still be opportunities for more cost-efficient balancing of the wind power, as the traded volumes in the market rises.

To calculate the costs of balancing in the balancing market the wind power forecast error and the balancing prices are modeled based on data collected from 2012. A similar procedure could be implemented to model the Elbas market. After discoussions with the supervisors this has been rejected. The costs of balancing in Elbas has been calculated by modeling the balancing volume with the same procedure as described in Section 4.4.2. The modeled balancing volume has then been multiplied with the actual price in Elbas for the hour at hand. This implies that the cost of balancing in Elbas assumes that the Elbas market will continue to perform as it has in 2012. The calculation of the costs of balancing is done on a hourly basis and elementwise multiplication is used. A large distinction between the costs of balancing in Elbas and in the balancing market is that in Elbas the BRP has an opportunity to beat the market, meaning that Δpr_{Elb} can be positive, meaning that the sold

balancing power can be sold at a higher price then the spot price. Similarly, if the balancing volumes are negative, the volume can be bought back at a lower price than what it was initially sold for in the Elspot market. This is similar to the one-price model used in the consumer balance. Therefore, there is no use for a Check vector when calculating the costs of balancing in Elbas.

When adjusting the balances in Elbas the price is known beforehand but the actual balancing volume is uncertain. The one hour gate closure makes it possible to trade volumes so that the producer is in balance one hour before the hour of operation. The balancing volumes that occur the last hour before the hour of operation must also be taken into account. This volume of balancing will be priced after the two-price system. In this thesis it is found feasible to model this volume similar to the volume settled in the two-price system when modeling the re-bidding procedure. In the re-bidding procedure the production schedule is updated 45 minutes before the hour of operation, without any human intervention. As the gate closure in Elbas is 15 minutes earlier then in the re-bidding procedure the α is adjusted to 0.18 and the β to 0.82.

The calculation of cost of balancing in Elbas is shown in Eq. 4.17.

$$
\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_{8784} \end{bmatrix} = \alpha \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_{8784} \end{bmatrix} \odot \begin{bmatrix} \Delta pr_{Bal1} \\ \Delta pr_{Bal2} \\ \Delta pr_{Bal3} \\ \vdots \\ \Delta pr_{Bal8784} \end{bmatrix} \odot \begin{bmatrix} Check_1 \\ Check_2 \\ Check_3 \\ \vdots \\ Check_{8784} \end{bmatrix} + \beta \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_{8784} \end{bmatrix} \odot \begin{bmatrix} \Delta pr_{Elb1} \\ \Delta pr_{Elb2} \\ \Delta pr_{Elb3} \\ \vdots \\ \Delta pr_{Elb8784} \end{bmatrix} \quad (4.17)
$$

Like in the balancing market model, the hourly costs over a year will be stored in a vector. Yearly costs are found by summing this vector, and the procedure is repeated 1000 times.

To investigate whether the gate closure in Elbas has any effect, the same procedure is done using prices two hours ahead. However, a source of error here is that there in a large number of hours are no trade. In the model, hours with no trades have been deleted. As it is not possible to trade the product at hand, this will lead to an error in the results. As the gate closure in this case is 2 hours ahead of the hour of operation, the α is adjusted to 0.25 and β to 0.75.

4.4.6 Results

In this section the results of the described models are presented. The MatLab code is found in the electronically attached zip file. As described yearly simulations are done one thousand times. The results are presented as histogram and as cumulative distribution functions. The mean and standard deviation is used to compare the different results.
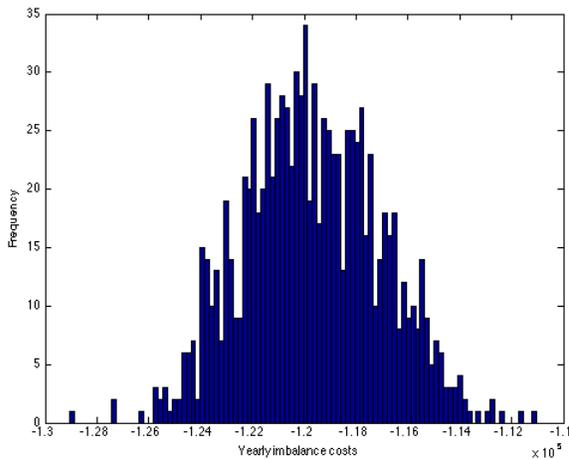
Figure 4.28: Histogram for total costs in the balancing market.
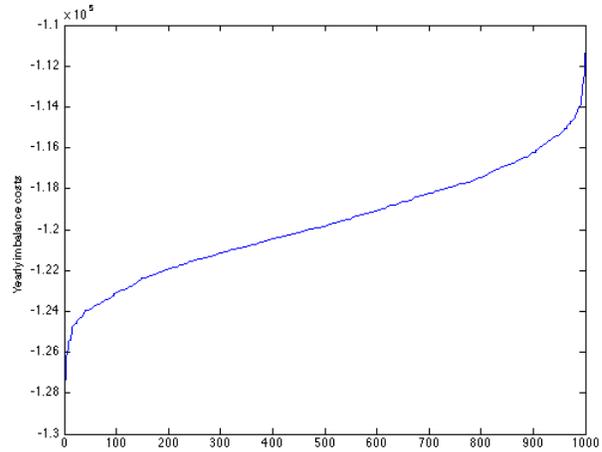
Figure 4.29: Cullmulative distribution function for settling in the balancing market.

4.4.6.1 Balancing Market

The results of settling all the balances associated with the wind power forecast error in the balancing market is presented here. In this case the producer does not attempt to shift some volumes into the trade balance, hence all of the volumes are settled according to the two-price system. By definition, there can be no gains on the balancing volume in this case. The histogram resulting from running the model thousand times is shown in Fig. 4.28. In Fig. 4.29 the yearly results are sorted. The years with the highest costs are shown to the far left, and the years with lowest costs are shown to the right in the figure.

The mean and standard deviation of the distribution shown in Fig. 4.32 is found, and presented in Table 4.7.

	Mean	*Standard Deviation*
Settling in the Balancing market	- 119 700	2 626

Table 4.7: Mean and standard deviation for settling in the balancing market.

The presented results show that an annual cost of 119 700[€] is to be expected when settling all of the balance in the balancing market, without taking any measures to improve the balancing volume. With the aproximation that the histogram shown in Fig. 4.32 follows a normal distribution, the standard deviation tells us that for 68.2% of the time the annual costs will be within [117 074 ,122 326] [€] and for 95,5 % of the time the annual costs will be within [114 448, 124 952][€].

More exact precentiles can be found by studying the cummulative distribution function, as no asumptions have to be made here. From Fig. 4.33 it can be stated that there always will be costs acosiated with balancing all of the balancing volume in the two-price system. This is consistent with the theory presented. Furthermore, it can be seen that fifty percent of the time the settlement costs will be above approxomately 120 000 [€/year], which is presistant to the mean of the distribution. Ten persent of the time the settlement will be -123 500 [€/year] or more and the other ten percentile shows an annual settlement of less then 116 000 [€/year]. These percentiles can easily be found in Fig. 4.29. The x-axis will then be per thousand. If dividing the x-axis by then the percentage is found.

4.4.6.2 Re-bidding Procedure

As opposed to settling all of the volume in the two-price system, the re-bidding procedure transfers a rather large amount of the total balancing volume to the consumer balance, where the one-price system is used. The simulated costs by using this method is presented in Fig. 4.32. To properly address the costs in the production balance and the trade balance in such a modified settling procedure, the settlement in each price system is shown. The settlement in the trade balance, which is calculated according to the one-price system is shown in Fig. 4.30. The settlement in the production balance, calculated after the two-price system is shown in Fig. 4.31.
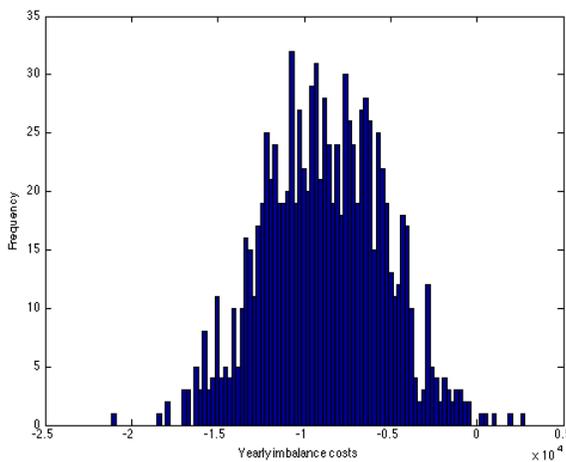
Figure 4.30: Histogram for costs in one-price system.
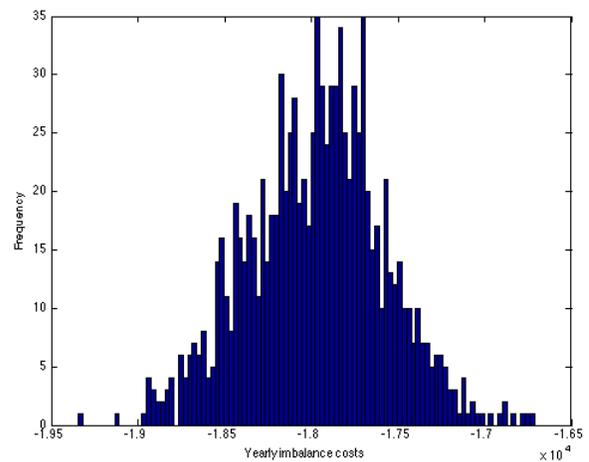
Figure 4.31: Histogram for costs in two-price system.

From Fig. 4.32 and Fig. 4.31 it is clear that settling the balances in the consumer balance, according to the one-price system, is more benefitial than settling the volumes in the two-price system. However, Fig. 4.30 show that a deficit still can be expected when settling in

the one price system. This follows from the statistichal properties of the wind power forecast error and the direction of balancing. As shown in Fig. 4.19 the price of downward balancing is expected to have a larger difference from the spot price then the upward regulating price. Furthermore it is shown in Fig. 4.18 and Fig. 4.17 that the percentage of hours with downward regulation is larger then the percentage of hours with no regulation or upward regulation. As shown in Fig. 4.14 and table 4.1 the wind power forecast error for the wind farms operated by TrønderEnergi statisticly tend to predict a higher wind power production than what is actually produced. This will lead to a tendency that TrønderEnergi will have a negative balancing volume.
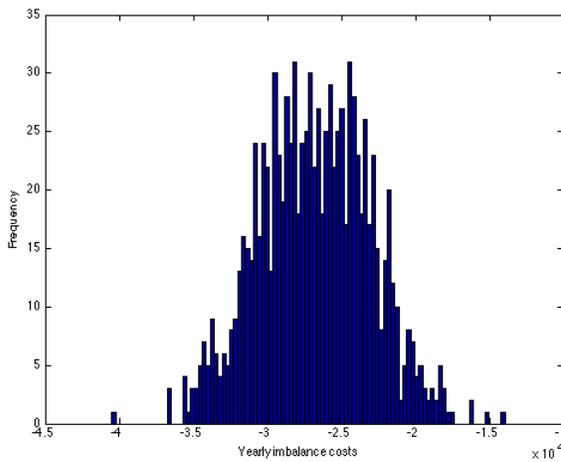
Figure 4.32: Histogram for total costs using the re-bidding procedure.
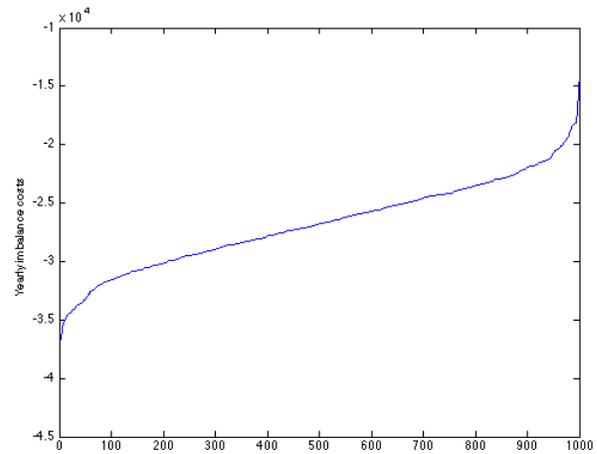
Figure 4.33: Sorted results for total costs using the re-bidding procedure.

The total results of settling the balancing volumes by using the re-bidding procedure is shown in Fig. 4.32, and the cummulative distribution function is shown in Fig. 4.33. From the two figures it is obvious that settling the balances by using the re-bedding procedure will give lower deficits when balancing the unpredictable wind power production. The parameters for the histograms for settling in the one-price system, settling in the two-price system and the total settlements are shown in Table 4.8.

	Mean	Standard Deviation
Setteling in One Price	- 8831	3455
Setteling in Two Price	- 17 970	394
Total settlement using the re-bidding procedure	- 26 802	3776

Table 4.8: Mean and standard deviation for the re-bidding procedure.

4.4.6.3 Elbas

The results of settling the simulated balancing volume with the prices in Elbas during 2012 is presented. As the wind power forecast error and the balancing prices for 2012 is found by using data from 2012, this procedure is found to be a good way to reference the costs of balancing. Opposed to the balancing market, the prices in Elbas are known ahead of the hour of operation. For a BRP this is beneficial as the risk of unpredictably high prices are not present. As the balancing market is closely connected to the physical condition of the power grid, price spikes could occur. These are, however, not included in the modeling of the balancing market, as they are random and very hard to predict. If such random high prices were included when comparing the markets, trading on Elbas could be found to be even more benefital then settling the balancing volumes in the balancing market.
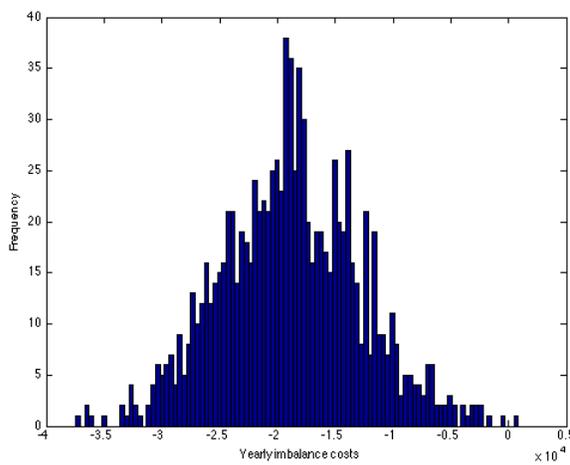
Figure 4.34: Histogram for total costs Elbas.
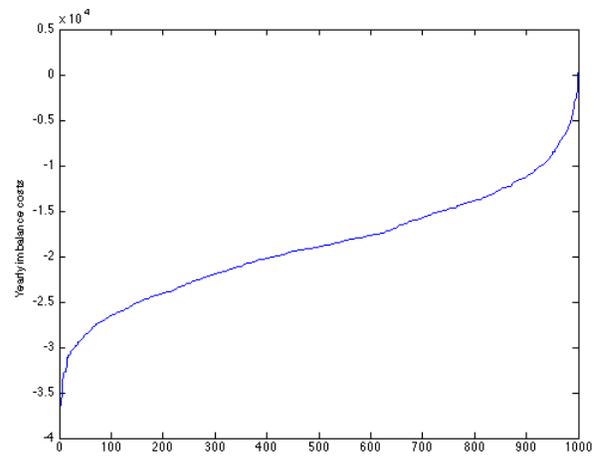
Figure 4.35: Sorted results for total costs in Elbas.

As shown in Fig. 4.34 and Fig. 4.35, by using Elbas to adjust the balances some surplus can be achieved. With a lower mean than the other alternatives trading in Elbas seems to be the most benefitial alternative. This requires, however, that there is sufficient liquidity in the market, so that a producer has this alternative. When modeling the intraday market, the hours with no trade are deleted, and hence not taken into account. With gate closure one hour before the hour of operation a total of 1625 hours have been removed, which means that in 18% of the time, trading in Elbas is not an option. When the prices in the market two hours before the hour of operation are used, a total of 2901 hours are removed from the analysis, which corresponds to 33% of the time.

When using one hour gate closure the price of the last trade done prior to the hour of operation is used as the price of the whole hour. This is correct according to a normal representation of the market, but as the decision for the BSP must be done in such a

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perspective that it is possible to trade, a two hour "gate closure" is introduced. Now the decision maker at TrønderEnergi has one hour to evaluate the two opportinities. The results of trading on Elbas with prices two hours ahead of the hour of operation is shown in Fig. 4.36 and the cummulative distribution is shown in Fig. 4.37.
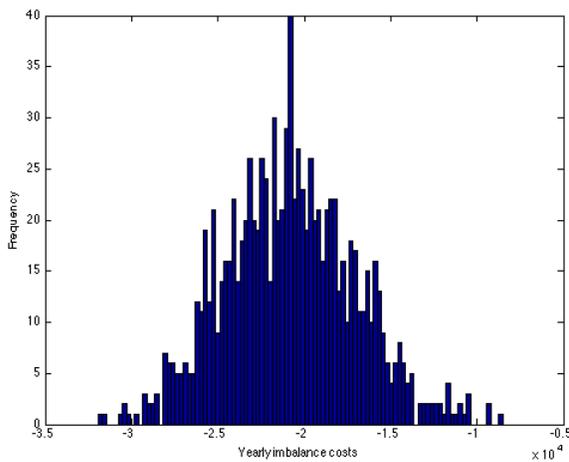
Figure 4.36: Histogram for total costs Elbas.
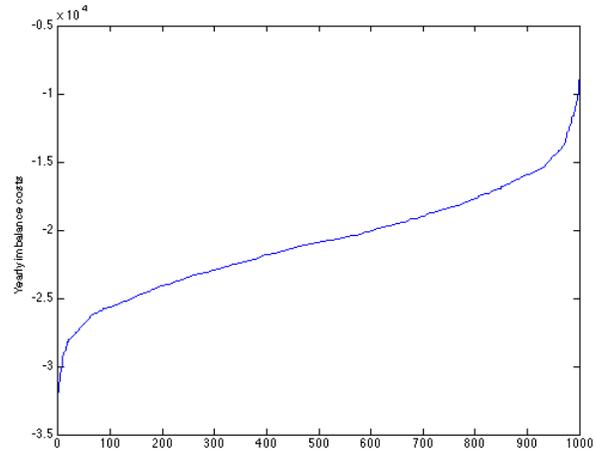
Figure 4.37: Sorted results for total costs in Elbas.

By closing the market one hour early a rise in the costs of balancing is observed. This rise is however only slight. This can be explained by the behaviour of the traders. It is reasonable to assume that two hours before the gate closure the traders will submit bids with a higher spread, to get a better price. As the hour of operation approaches the behavior of the traders may shift from profit seeking to actual get the volumes sold.

4.4.6.4 Summed Results

The results of all simulations are presented in this section. The cummulative distribution function for all of the assesed balancing methods is shown in Fig. 4.38.
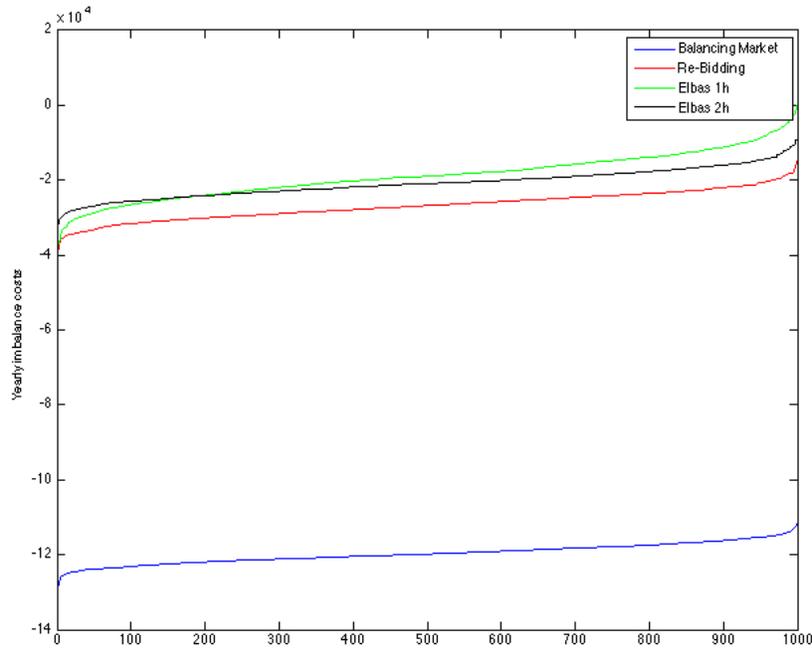
Figure 4.38: Sorted results.

Fig. 4.38 show that trading in Elbas would be the best alternative for TrønderEnergi. This is the only strategy that could lead to a surplus when handling the balances associated with the uncertainty of WPP. The difference of settling in Elbas one and two hour before the hour of operation should be noticed. However, the penetration of WPP is small in the area at hand, so it might not have a large say. The found result could be an indication that the behavior of the trades in the market can have a large say. If a BRP has an imbalance close to the hour of delivery, a trader may clear its positions with less regards to the price in the market.

The mean and standard deviation of the different balancing strategies are summed up in Table 4.9.

	Mean	Standard Deviation
Settling in Balancing market	- 119 700	2 626
Settling using re-bidding procedure	- 26 802	3776
Settling in Elbas	-18 840	6044
Settling in Elbas (2h)	- 20 855	3768

Table 4.9: Mean and standard deviation for the different models.

The results presented give conclusive evidence of how to most cost efficiently handle the balancing volume, with the assumptions done in this thesis. It is found precurial that regardless of how the balances are handled, no surplus can be expected when the spot price is used as a reference. This will give a clear incentive for the producers to comply with the production schedule.

Chapter 5

Discussion

In Chapter 3 the development of the balancing market and the Elbas market has been presented. The benefits and drawbacks of internal balancing of own hydro power has been elaborated and the expectation of more accurate weather forecasts using numerical weather predictions have been examined. The main goal of this report is to analyze how TrønderEnergi with 70 [MW] wind power capacity and 640 [MW] hydro capacity can best handle the uncertainty of the wind power production. Based on the presented literature, it is safe to assume that the European balancing markets will merge so that balancing power can be imported or exported. When this is implemented it is expected that the flexibility that the Nordic, and especcialy the Norwegian system can provide will be utilized so that a larte amount of balancing power will be precured in Norway. This, combined with an increase in the installed WPP capacity, both in Norway and internationally, will lead to higher volatility in the Norwegian balancing market.

The wind power forecast error and the balancing prices have been modeled in Chapter 4. In this work it has been proven that there is a very small correlation between the balancing market and the intraday market. The different alternatives to aproach the handling of imbalances have been derived and results show that settling the imbalances in the intraday market will be most beneficial for TrønderEnergi.

Some initial assumptions that the modeling are based on should, however, be discussed. First of all, it should be made abundantly clear that the data used in this thesis, are recorded data from the price area SE3 during 2012. Both when modeling the balancing market and Elbas, data from Sweden is used. This is done to properly represent a well functioning intraday market. To be able to draw a sound conclusion, the balancing market data is also gathered from Sweden. Using Norwegian numbers is possible, but investigating correlation and sound decision making by comparing the balancing market in Norway and intraday market in Sweden is of very little use. It has numerous times been pointed out that the traded volumes in Norway currently are too low. Therefore, efficient intraday trading is not an option for TrønderEnergi. The development of the Norwegian intraday market is

described in Section 3.3. From the presented material and especially the key points made by [22], a well functioning intraday market is on the horizon. When this is implemented the different trends in analysing the two markets can be transferred into the Norwegian system. There is, however, a possibility that the conclusions drawn by investigating the Swedish market can not be fully trusted in the Norwegian market. This is due to difference in the two countries. This includes, but is not limited to:

- The production portfolio

- The national transmission grid

- The installed production capacity

- The flexibility of production units in the two markets

The future development of the balancing market has been described in Section 3.2. It is predicted that the volatility in the balancing market will rise. With higher volatility in the balancing markets, the respective producers will see a higher risk when settling their balances in the balancing market. With the implemented two-price system the upside in the market will be zero, while a larger downside will be observed. By using the re-bidding procedure TrønderEnergi can see a larger upside, but the drag of the volumes settled in the two-price system will still be present. Furthermore, [40] points out that the re-bidding procedure currently used by TrønderEnergi is illegal. The interpretation of illegal can, however, be discussed, as it seems unreasonable to charge a producer when the wind speed does not match the predictions. It should however be mentioned that when using the re-bidding procedure the producers escape the initial objective of implementing the two-price system, to reduce the balancing volumes. This has not been enforced so far, but with increasing integration of WPP and a more volatile balancing market this may change. As described in Section 3.2.1 the political risk in the power markets can be high. With a stroke of a pen decisions with a large impact for the actors in the market are implemented. If the regulations on system responsibility are enforced, TrønderEnergi could suddenly be forced to balance all of their volumes coming from the wind power forecast error in the two-price system. This will, as presented, have a large economic impact.

From the statistichal analysis done in Section 4.3, a remarkable result is found. There is a very small correlation between the balancing market and the intraday market. It has been discussed that this is due to the nature and physical boundary of the two markets. The independency of the two markets can actually provide some opportunities for a BRP. As they are random, compared to each other, a favorable price can be found at different times in the different markets. Therefore a sound understanding and monitoring of both markets is recommended.

When analyzing the results presented here, it is natural to point out some sources of error, and how the results may differ from the actual case. It should be elaborated that the modeling of the different parameters in the balancing market is very difficult. This is supported by the findings in the literature. It has been mentioned that modeling the prices in the balancing

market is a challenging task. In this thesis a Weibull distrobution is chosen to represent these prices. It has been shown that the representation chosen here, fits the main part of the distribution of 2012 data, and have some deviation at the tails. This can somewhat affect the results presented here. The Q-Q plot presented shows that the actual data of the tail is more dispersed than the theoretical presentation of the data. This could have an impact on the presented results. With a more dispersed distribution a higher volatility in the presented results would be expected. This implies that the slope of the lines representing the balancing market and the re-bidding model in Fig. 4.38 would be higher. However as the majority of the stochastic data is modeled with a good fit, therefore the mean of the presented results can be used to draw a confident conclusion.

The representation of the balancing volume occuring from Bessakerfjællet and Valsneset wind farm are found by modeling the netted imbalances of the two wind farms during 2012. In this representation a normal distribution is used, which according to the presented literature, is an unconventional way of representing the balancing volumes. This representation is found applicable in this thesis, as it is the balancing volume for two geographical separated wind farms that are found. When combining the individual properties of the two wind farms the goodness of fit of the representation is found to be sound. As the balancing volume is used in all simulations when assessing the different aproaches for handling balances, the deviation will be the same for every trial.

The results from the simulations done in this thesis show that settling the balancing volumes in the two-price system is the most costly way to handle the imbalances. The re-bidding procedure that is implemented has proven to be a substantially better way of handling the imbalances associated with the WPP. The intraday market provides opportunities to better handle the balancing volumes. Some drawbacks of the presented models should, however, be presented. As it midways in the time frame of this thesis was found that the initial model had to be shelved some simplifications had to be made. Nevertheless, it is concluded that the presented model is a good representation of the actual situation and should provide decision support for TrønderEnergi. The model can, however, be improved if the models are improved. Especially the autocorrolation in the wind speed should be utilized and modeled in some other way then weighting of the markets. This becomes more relevant when models with shorter time horizons than one year is developed. The extreme values occuring in the balancing market should be included when assesing the costs in the markets.

No modeling has been done when assesing the Elbas market. Instead actual hourly prices are used to calculate the costs of balancing. The differences in yearly results are due to the stochastic wind power forecast error. Therefore the presented results can be evaluated as the performance of Elbas in 2012 with changing balancing volumes. Alternatively, the results can be interpreted as 1000 different BRPs with different balancing positions. It should, however, be mentioned that Elbas is a dynamic market, where the bidding of the actors will change in line with the expectaions and positions of the traders. Furthermore, when evaluating Elbas, the last accepted trade is used as a reference. In this way, TrønderEnergi is assumed to be a price taker in the market. The potential upside of being a price setter, hence submitting bids

and assuming they are accepted, is not accounted for. This could also present a downside. To be able to exploit this upside, sound knowlegde and experience is advantageous. Therefore aquiring knowledge and experience at an early stage is recommended.

The purpose of this thesis is to give TrønderEnergi decision support of how to handle their imbalances asociated with their wind power production. It is found that settling the imbalances in the intraday market, when this matures in Norway, will give lower costs when handling the balances and even provide opportunities for surpluses. If these gains are large enough to defend reallocation of human resources is left to TrønderEnergi to decide. It is, however, strongly recommended to address the issue, either set up internal office or outsource the balance handling to companies, which have specialized expertise in the area. For example Bergen Energi or Axpo Nordic. By setting up an internal office, the opportunities at hand could also include allocation of hydro power resources in the intraday market for profit seeking. This is a decision that beyond of the scope of this thesis. It is, however, strongly recommended to gain further knowlegde on the issue, as a new market for intraday trading emerges and gaining knowledge at an early stage can be very beneficial.

Chapter 6

Conclusion

It is the purpose of this thesis to evaluate the opportunities to optimize production balance, taken specifically into account the uncertainty in wind power production. Based on the presented literature it is safe to assume that the cross-border integration of balancing market is in the making. This is backed by statements from the regulatory organs. With cross-border integration of the balancing markets, the flexibility of the Norwegian hydro-based power system will be exploited and more balancing reserves will be procured in the area. This will provide opportunities for greater earnings when offering hydro power to the market, but with no control over the production a wind power producer is likely to see larger costs in handling their imbalances. With the implemented two-price system no gains will come from the imbalances.

As the liquidity in the Norwegian Elbas market evolves, this intraday market will provide opportunities to better handle the imbalances asociated with the wind power production forecast error. The results presented in this thesis show that settling the imbalances in Elbas, instead of the balancing market will reduce the costs of balancing. Furthermore, the intraday market will provide possibilities for a larger income when offering flexible hydro power production.

The current approach used by TrønderEnergi to manage their imbalances is found to be very successful compared to settling in the two-price system. The yearly costs can however be reduced by approximately 8 000 [€/year] by settling in Elbas, using 2012 numbers from SE3.

With increased function of Elbas TrønderEnergi should increase their knowledge of the market and exploit the benefits of intraday trading. This could almost certainly reduce the losses of their WPP portfolio and provides opportunities to beat the market and earn excess returnes compared to the settlement in the balancing market. Until the intraday market matures in Norway, the re-bidding procedure should be used.

Chapter 7

Further work

The main objective of this report was to investigate various methods to improve the production balance for TrønderEnergi.

It is mentioned that the internal grid in Norway has many bottlenecks, which makes the handling of balances more challenging. In the Grid Development Plan [35] it is stated that during the next 10 to 20 years large investments can be expected in the internal grid. A proposal for further research is to investigate how these investments will affect the balancing market, the intraday market and if the bidding areas in the day-ahead market will be changed.

In Chapter 5 some limitations of the presented models are mentioned. This includes a better representation of the balancing volume occuring from Bessakerfjællet and Valsneset wind farm, exploit the autocorrolation in the WPP and including extreme values in the balancing market. Furthermore block bids in Elbas are not assesed. This should be included in any further work.

In this thesis it is assumed that TrønderEnergi is a price taker in both the balancing market and in Elbas. With proper computational tools and experience, properly assesed bids can be submitted, with the intention to gain a surplus. This is a business area that TrønderEnergi is encouraged to exploit.

It is mentioned that the internal grid in Norway has many bottlenecks, which makes the handling of balances more challenging. In the Grid Development Plan [35] it is stated that during the next 10 to 20 years large investments can be expected in the internal grid. A proposal for further research is to investigate how these investments will affect the balancing market, the intraday market and if the bidding areas in the day-ahead market will be changed.

Appendix A

Apendices

A.1   Collecting Input Data

In this thesis data for the electric intraday market, ELBAS[1] is used to see if the prices and volumes in this market correlates to the volumes and prices in the balancing market. The data from Elbas is extracted from a FTP server from Nord Pool Spot. To be able to process these datas, they first have to be extracted and sorted according to the parameters used in this thesis. This has proven to be a challenging and time consuming task, which is described here.

A.2   The data

In the FTP[2] server all of the trades in Elbas is stored in a CSV[3] file format. Here values for the trade time, product code, price quantity, buy area and sell area is stored with comma as a separator. Data for 2012 is stored in 366 files, one for each day.[4] It is not trivial to import and extract the relevant data from such a file format. To be able to start to work with the data it first had to be extracted from the server and sorted after the desired parameters that fits the thesis.

An example of a cdv file shown in a text edit program is shown in Fig. A.1

---

[1] Electrical balancing adjustment system
[2] File Transfer Protocol
[3] Comma-separated values
[4] 2012 was a leap year

```
Trade Time,Product Code,Price,QTY,BArea,Sarea
2012/12/22:22:47:17,PH01121223,36,15,FIN,FIN
2012/12/22:20:11:10,PH01121223,36.1,4,FIN,NO2
2012/12/22:22:33:41,PH01121223,36,10,FIN,FIN
2012/12/22:22:37:48,PH01121223,36.3,20,FIN,FIN
2012/12/22:22:57:27,PH01121223,37.5,10,FIN,SE2
2012/12/22:20:03:18,PH01121223,36,6,SE2,SE3
2012/12/22:21:52:27,PH01121223,36.5,5,SE2,SE2
2012/12/22:22:24:58,PH01121223,36.1,2,FIN,SE3
2012/12/22:22:24:58,PH01121223,36,13,FIN,SE3
2012/12/22:22:51:17,PH01121223,37,5,FIN,SE3
2012/12/22:22:53:40,PH01121223,37,23,FIN,SE2
2012/12/22:16:18:21,PH01121223,33.1,21,FIN,KT
2012/12/22:22:50:18,PH01121223,36.5,28,SE3,SE2
2012/12/22:22:48:22,PH01121223,36,10,FIN,FIN
2012/12/22:15:51:16,PH01121223,32.6,10,SE2,KT
2012/12/22:17:22:40,PH01121223,36,4,SE2,SE3
2012/12/22:22:52:21,PH01121223,37,7,SE3,SE3
2012/12/22:22:52:22,PH01121223,37,33,SE3,SE2
2012/12/22:16:08:34,PH01121223,35.1,5,NO4,KT
2012/12/22:20:11:10,PH01121223,36,5,FIN,SE3
2012/12/22:20:17:12,PH01121223,36.1,3,FIN,NO2
2012/12/22:20:03:29,PH02121223,36,6,SE2,SE3
2012/12/22:21:52:37,PH02121223,36.5,5,SE2,SE3
2012/12/22:22:44:41,PH02121223,35,5,FIN,SE3
2012/12/22:22:44:41,PH02121223,35,10,FIN,SE3
2012/12/22:22:47:35,PH02121223,35,15,FIN,FIN
2012/12/22:22:13:42,PH02121223,36,1,SE2,SE3
2012/12/22:23:14:17,PH02121223,36.5,30,FIN,SE2
2012/12/22:23:19:11,PH02121223,36.5,3,FIN,SE2
```

Figure A.1: Example of .CSV file in text edit

As mentioned in section **??** it was decided that data from SE3 should be used, as this area has the highest volatility and are closely connected to NO3, where TrønerEnergi operates. With help from Gunnar Aaronsen, a senior market analyst at TrønedrEnergi a macro was written to extract and sort the data. This is done by developing VBA macros in Excel.

A.3   Extracting the data

In this section the macro used to extract the data is described. The macro "HentDataFraSVC()" is used to gather all of the relevant data and import it into excel. The data is sorted after the hour of operation (1-24). This macro imports the trades from all areas and at all times. The macro for sorting the imported data is further described in section **??**

```vb
Sub HentDataFraSVD()
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' HENTER INN DATA FRA SDV-FILER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Angir hva som er filen det jobbes fra.
    Set AnalyseFil = Workbooks("ElbasFraNordpool.xlsm")
    AnalyseFil.Activate
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Slår av windowsbeskjeder og skjermoppdatering.
    Application.DisplayAlerts = False
    Application.ScreenUpdating = False
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Oppretter ett filsystem objekt  - Mangler en pakke på mac "Microsoft Scripting runtime"
    Dim fso As New FileSystemObject
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Angir variable.
    Dim HenteAdresse   As String   ' Adresse hvor svd-filene ligger.
    Dim LagreAdresse   As String   ' Adresse hvor dataene skal lagres
    Dim LagreFilNavn   As String   ' Navnet på filene som dataene skal lagres i.
    Dim SdvFilNavn     As String   ' Svdfilene som dataene hentes fra.
    Dim DelFilNavn     As String   ' Første delen av filnavnet som ikke endres innom året.
    Dim ForsteUke      As Integer  ' Første uken som dataene skal hentes fra.
    Dim SisteUke       As Integer  ' Siste uken som dataene skal hentes fra.
    Dim ForsteAar      As Integer  ' Første året som dataene skal hentes fra.
    Dim SisteAar       As Integer  ' Siste året som dataene skal hentes fra.
    Dim DataNavn(2)    As String   ' Navnet på dataene som skal hentes.
    Dim Startid        As Double   ' Timer som lagrer dataene med jevne mellomrom.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Kode og område indeks for dataene som skal hentes ut.
    Dim ProduktKode    As String
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Diverse teller som brukes i makro
    Dim DataTeller(1 To 24) As Integer  ' Holder rede på hvilken linje vi er på i utdatafilen
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Setter verdier som angir filnavn og stier.
    HenteAdresse = "Macintosh HD:\Brukere\Gjert\Dokumenter\Master\Elbas vs RK\2012\"
    LagreAdresse = "Macintosh HD:\Brukere\Gjert\Dokumenter\Master\Elbas vs RK\"
    LagreFilNavn = "ElbasData2012.xlsx"
    DelFilNavn = "elbas_ticker_report_12"
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Lukker lagringsfilen om den er åpen.
    For Each File In Workbooks
        If Not File.Name Like AnalyseFil.Name Then
            File.Close
        End If
    Next
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Lager filene som dataene skal lagres i.
    Workbooks.Add
    For i = 24 To 1 Step -1
        Sheets.Add
        ActiveSheet.Name = IIf(i < 10, "Time0" & i, "Time" & i)
    Next
    ActiveWorkbook.SaveAs Filename:=LagreAdresse & LagreFilNavn _
    , FileFormat:=xlWorkbookDefault, Password:="", WriteResPassword:="", _
        ReadOnlyRecommended:=False, CreateBackup:=False
    Set LagreFil = ActiveWorkbook
    AnalyseFil.Activate
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Figure A.2: Screenshot of the first part of HentDataFraSVD()

```
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Åpner filene som data skal hentes fra
    For Måned = 1 To 12
        For Dag = 1 To 31
            FilNavn = DelFilNavn & IIf(Måned < 10, "0" & Måned, Måned) & IIf(Dag < 10, "0" & Dag, Dag) & ".csv"
            FulltNavn = HenteAdresse & FilNavn
            If Not fso.FileExists(FulltNavn) Then GoTo IngenFil
            Workbooks.OpenText Filename:=FulltNavn, StartRow:=1, DataType:=xlDelimited, TextQualifier:=xlTextQualifierNone, ConsecutiveDelimiter:=False, _
            Tab:=False, Semicolon:=False, Comma:=True, Space:=False, Other:=False, OtherChar:=False, DecimalSeparator:=".", Local:=False:
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
' Leser data som skal skrives til filen som lagrer data.
        Cells(2, 1).Select
        Range(Selection, ActiveCell.SpecialCells(xlLastCell)).Select
        Set Inndata = Selection
        For RadNr = 1 To Inndata.Rows.Count
            SkrivTilArk = "Time" & Mid(Inndata(RadNr, 2), 3, 2)
            ArkNr = CInt(Mid(Inndata(RadNr, 2), 3, 2))
            DataTeller(ArkNr) = DataTeller(ArkNr) + 1
            For KolNr = 1 To 6
                If KolNr = 1 Then
                    Temp = Inndata(RadNr, KolNr).Value
                    Temp1 = Left(Temp, 10)
                    Temp1 = Right(Temp1, 2) & "." & Mid(Temp1, 6, 2) & "." & Left(Temp1, 4)
                    Temp2 = Right(Temp, 8)
                    Temp = CDate(Temp1 & " " & Temp2)
                    LagreFil.Sheets(SkrivTilArk).Cells(DataTeller(ArkNr), KolNr).Value = Temp
                Else
                    LagreFil.Sheets(SkrivTilArk).Cells(DataTeller(ArkNr), KolNr).Value = _
                                        Inndata(RadNr, KolNr).Value
                End If
            Next
        Next
        Workbooks(FilNavn).Close


IngenFil:
        Next
    Next
End Sub
```

Figure A.3: Screenshot of the second part of HentDataFraSVD()

As seen from Fig.A.2 and Fig.A.10 the macro "HentDataFraSVD()" opens the CSV file for each day separately and sorts them after the hour of the product.

A.4   Sorting

After having imported all of the values into excel, they are sorted after the product hour. To be able to property analyze the data, they have to be sorted after the desired parameters. This means that the volumes in the area at hand must be summed and the price noted. In this case the last accepted price in the market determines the price of that hour. This is the market clearing price and is normally used in the financial markets.

Developing the macro that sorts the data has proven to be a challenging and time consuming task. The macro used is presented below.

```vba
Sub SamleAlleTrades()
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Macro for å sortere og summere voluet i Elbas med tanke på område.
'For å endre område må ein endre "Område" på 4 plasser, dobbeltsjekk!
'NB! Macroen skriver til "Sheet2" Sjekk at det er eit tomt ark som heiter dette i excel og husk å endre navnet på arket til området når macroen har kjørt.
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Deklarerer variable
Dim Rad As Long
Dim AntallRader As Long
Dim KolonneTeller As Integer
Dim RadTeller As Long
Dim AntallWorksheets As Integer
Dim MySheet As String
Dim i As Integer




RadTeller = 1
KolonneTeller = 0
'AntallWorksheets = ActiveWorkbook.Worksheets.Count

'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'AntallRader Teller rader i det aktuelle inndata arket
'Førstee For/If/For skriver data for Sarea for det ønskede området til eit nytt ark

'ThisWorkbook.Sheets("Sheet" & "AntallWorksheets").
'ThisWorkbook.Sheets("Sheet2").

For i = 1 To 24
MySheet = IIf(i < 10, "Time0" & i, "Time" & i)
For Rad = 1 To 10400
    If ActiveWorkbook.Sheets(MySheet).Cells(Rad, 5).Value = "SE3" Then
        For j = 1 To 6
            ActiveWorkbook.Sheets("Sheet2").Cells(RadTeller, j).Value = ActiveWorkbook.Sheets(MySheet).Cells(Rad, j).Value
        Next
            RadTeller = RadTeller + 1
    End If
Next


'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Førstee For/If/For skriver data for Sarea for det ønskede området til eit nytt ark
'Må unngå duplikater, dvs trades innenfor området, dei ville blitt importert to gonger dersom koden ovenfor hadde blitt kopiert og ikkje modifisert

For Rad = 1 To 10400
    If ActiveWorkbook.Sheets(MySheet).Cells(Rad, 6).Value = "SE3" And ActiveWorkbook.Sheets(MySheet).Cells(Rad, 5).Value <> "SE3" Then
        For j = 1 To 6
            ActiveWorkbook.Sheets("Sheet2").Cells(RadTeller, j).Value = ActiveWorkbook.Sheets(MySheet).Cells(Rad, j).Value
        Next
            RadTeller = RadTeller + 1
    End If
Next

Next i
```

Figure A.4: Screenshot of the first part of SamleAlleTrades()

```
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Gir time-referanse til til produktet (PH12mmdd)
'NB! dobbelsjekk "Sheet2"
'Deklarerer

'Dim Rad As Integer
'Dim AntallRader As Integer
Dim Days As Integer
Dim Teller As Integer
Dim StartMaanedTimer As Long
Dim HourReference As Integer

StartMaanedTimer = 0
'AntallRader = ActiveSheet.UsedRange.Rows.Count

For Rad = 1 To 58624
Temp = Worksheets("Sheet2").Cells(Rad, 2).Value
temp1 = Mid(Temp, 7, [2])                            'månad
temp2 = Right(Temp, 2)                               'dag
temp3 = Mid(Temp, 3, [2])                            'time
' Må korrigere for dager i ein måned, NB! 2012 var skuddår

    For Teller = 1 To (Val(temp1) – 1)                   ' gir timene til begynnelsen av måneden
        If Teller = 1 Then
            Days = 31
            ElseIf Teller = 2 Then
            Days = 29                                    ' skuddår
            ElseIf Teller = 3 Then
            Days = 31
            ElseIf Teller = 4 Then
            Days = 30
            ElseIf Teller = 5 Then
            Days = 31
            ElseIf Teller = 6 Then
            Days = 30
            ElseIf Teller = 7 Then
            Days = 31
            ElseIf Teller = 8 Then
            Days = 31
            ElseIf Teller = 9 Then
            Days = 30
            ElseIf Teller = 10 Then
            Days = 31
            ElseIf Teller = 11 Then
            Days = 30
            ElseIf Teller = 12 Then
            Days = 31
        End If
StartMaanedTimer = StartMaanedTimer + Days * 24               ' sum timer i begynnelsen av måneden. Feks i mai er dette summen t.o.m. april
    Next

HourReference = StartMaanedTimer + (24 * Val(temp2) – 24) + Val(temp3)     ' Trekker frå 24 fordi timene i den aktuelle dagen ikkje skal teljast to gonger
Worksheets("Sheet2").Cells(Rad, 8).Value = HourReference
StartMaanedTimer = 0                                 ' Nulstiller telleren for kvar rad
Next
```

Figure A.5: Screenshot of the second part of SamleAlleTrades()

```vba
"%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

'Gir time-referanse til til tiden for trade
'NB! dobbelsjekk "Sheet2"

HourReference = 0              'Nulstiller tellerene frå forige løkke
StartMaanedTimer = 0

'AntallRader = ActiveSheet.UsedRange.Rows.Count

For Rad = 1 To 58624

Temp = Worksheets("Sheet2").Cells(Rad, 1).Value
temp1 = Month(Temp)                                'månad
temp2 = Day(Temp)                                  'dag
temp3 = Hour(Temp) + 1                             'time Angivninga for Time i Elbas og i Excel er forskjellig. Kl 02.00-03.00 (feks 02.30) er Time 3 i Elbas
temp4 = Year(Temp)
' Må korrigere for dager i ein måned, NB! 2012 var skuddår
   For Teller = 1 To (Val(temp1) - 1)                         ' gir timene til begynnelsen av måneden
      If Teller = 1 Then
         Days = 31
         ElseIf Teller = 2 Then
         Days = 29                                ' skuddår
         ElseIf Teller = 3 Then
         Days = 31
         ElseIf Teller = 4 Then
         Days = 30
         ElseIf Teller = 5 Then
         Days = 31
         ElseIf Teller = 6 Then
         Days = 30
         ElseIf Teller = 7 Then
         Days = 31
         ElseIf Teller = 8 Then
         Days = 31
         ElseIf Teller = 9 Then
         Days = 30
         ElseIf Teller = 10 Then
         Days = 31
         ElseIf Teller = 11 Then
         Days = 30
         ElseIf Teller = 12 Then
         Days = 31
      End If
StartMaanedTimer = StartMaanedTimer + Days * 24               ' sum timer i begynnelsen av måneden. Feks i mai er dette summen t.o.m. april
   Next
HourReference = StartMaanedTimer + (24 * Val(temp2) - 24) + Val(temp3)       ' Trekker frå 24 fordi timene i den aktuelle dagen ikkje skal teljast to gonger

If temp4 = 2011 Then                                          ' if setning som korrigerer for trades gjort i 2011. Desse får negativ referanseverdi.
HourReference = HourReference - 8784
End If

Worksheets("Sheet2").Cells(Rad, 9).Value = HourReference
StartMaanedTimer = 0                                ' Nulstiller telleren for kvar rad
Next
```

Figure A.6: Screenshot of the third part of SamleAlleTrades()

```
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Sorterer etter dato
'Sorteringsmacro funnen på internett, funka som fjell
' Pass på at det er rett rad i starting Row og i range (J).

Dim StRw As Long, EndRw As Long
    StRw = 1 ' Starting Row
    EndRw = Range("H65500").End(xlUp).Row
    Rows(StRw & ":" & EndRw).Select
    Selection.Sort Key1:=Range("H1"), Order1:=xlAscending
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Sletter linjer der handelen sjedde meir enn tre timer før hour of operation
'Må begynne nederst og gå oppåver fordi dersom ein begynner på topp vil macroen hoppe over neste linje. Usikkert kvifor dette skjer, meiner det er ein innebygd bug

For Rad = 58624 To 1 Step −1
Worksheets("Sheet2").Cells(Rad, 10).Value = Worksheets("Sheet2").Cells(Rad, 8).Value − Worksheets("Sheet2").Cells(Rad, 9).Value
    If Worksheets("Sheet2").Cells(Rad, 8).Value − Worksheets("Sheet2").Cells(Rad, 9).Value >= 4 Then
        Worksheets("Sheet2").Rows(Rad).Delete
    End If
Next
```

Figure A.7: Screenshot of the forth part of SamleAlleTrades()

```vba
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Summerer volum for kvart produkt (PH12mmdd)
'Sjekker om referanseverdien er lik for neste rad, dersom den er det summeres volumet og neste rad slettes
'For å unngå forvirring slettes pris og området som er tradet med som ikkje er relevant.

'Kolonne A: Tiden produktet er tradet. Har sett begrensning på 3 timer før hour of operation
'Kolonne B: Produktkode
'Kolonne C: Pris
'Kolonne D: Volum
'Kolonne E: Buy Area
'Kolonne F: Sell Area
'Kolonne G: Blank
'Kolonne H: Time i året for produktet
'Kolonne I: Time i året for handel. Negative timer er fra 2011
'Kolonne J: H-I, for å sortere ut handler som ikkje er relevante

'Siste bud bestemmer prisen. Derfor må eg finne ut kva trade som er den siste.

Do While Worksheets("Sheet2").Cells(Rader, 11) <> ""
If Worksheets("Sheet2").Cells(Rader, 11).Value = Worksheets("Sheet2").Cells(Rader + 1, 11).Value Then

    'Summerer volumet
    Volum = Worksheets("Sheet2").Cells(Rader, 4).Value + Worksheets("Sheet2").Cells(Rader + 1, 4).Value
    Worksheets("Sheet2").Cells(Rader, 4).Value = Volum

    'gir prisen, prisen bli satt av den siste traden, som vanlig i finansielle markeder.
    TempPris = Worksheets("Sheet2").Cells(Rader, 3).Value

        'Sjekker hvilken pris som ble klarert sist.
        TimeValueRad = TimeValue(Worksheets("Sheet2").Cells(Rader, 1).Value)
        TimeValueNesteRad = TimeValue(Worksheets("Sheet2").Cells(Rader + 1, 1).Value)

        If TimeValueNesteRad > TimeValueRad Then
         TempPris = Worksheets("Sheet2").Cells(Rader + 1, 3).Value
        Worksheets("Sheet2").Cells(Rader, 3).Value = TempPris
        End If

    'skriver siste pris
    Worksheets("Sheet2").Cells(Rader, 3).Value = TempPris
    Worksheets("Sheet2").Rows(Rader + 1).Delete

    If Worksheets("Sheet2").Cells(Rader, 5).Value = "SE3" Then
        Worksheets("Sheet2").Cells(Rader, 6).Value = "-"
    Else
        Worksheets("Sheet2").Cells(Rader, 5).Value = "-"
    End If
Else
Rader = Rader + 1
End If
Loop
```

Figure A.8: Screenshot of the fifth part of SamleAlleTrades()

```
'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%'%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
'Koden ovenfor tek ikkje med timer der det ikkje var noko handel. Dette må korrigerast for då volum=0 òg er eit resultat.
Dim Temp, Rader As Integer

Rader = 2
Do While Worksheets("Sheet2").Cells(Rader, 8) <> ""
Temp = Worksheets("Sheet2").Cells(Rader, 8).Value – 1

If Worksheets("Sheet2").Cells(Rader – 1, 8).Value <> Temp Then
    Worksheets("Sheet2").Cells(Rader, 8).EntireRow.Insert
    Worksheets("Sheet2").Cells(Rader, 8).Value = Temp
    Worksheets("Sheet2").Cells(Rader, 4).Value = 0

Else
Rader = Rader + 1
End If
Loop


End Sub
```

Figure A.9: Screenshot of the sixth part of SamleAlleTrades()

A.5   Misc

I addition to the macros presented above, other macros have been written to handle various problem that have occurred during the development of the two main macros. The assorted macros are shown below:

```
Sub TrimMellomrom()
'macro for å slette mellomrom i tekststrengene slik at dei blir lettare å behandle.

Cells(1, 1).Select
    Range(Selection, ActiveCell.SpecialCells(xlLastCell)).Select

    For Each Cell In Selection
Cell.Value = Trim(Cell.Value)
    Next

End Sub
```

Figure A.10: Screenshot of the macro that removes spaces in the text strings

```
Sub RegTilstand()
'Goal: Find statistichal properties of the regulating state for a cluster of hours.
' First find for each hour.

'Declerations

Dim DownCounter As Integer
Dim UpCounter As Integer
Dim NoCounter As Integer
Dim Hour As Integer

For Hour = 1 To 24

DownCounter = 0
UpCounter = 0
NoCounter = 0

For Rad = Hour To 8784 Step 24

If ThisWorkbook.Sheets("Sheet1").Cells(Rad, 7).Value = -1 Then
DownCounter = DownCounter + 1

ElseIf ThisWorkbook.Sheets("Sheet1").Cells(Rad, 7).Value = 0 Then
NoCounter = NoCounter + 1

ElseIf ThisWorkbook.Sheets("Sheet1").Cells(Rad, 7).Value = 1 Then
UpCounter = UpCounter + 1
End If
Next

ThisWorkbook.Sheets("Sheet1").Cells(Hour + 1, 9).Value = Hour
ThisWorkbook.Sheets("Sheet1").Cells(Hour + 1, 10).Value = DownCounter
ThisWorkbook.Sheets("Sheet1").Cells(Hour + 1, 11).Value = NoCounter
ThisWorkbook.Sheets("Sheet1").Cells(Hour + 1, 12).Value = UpCounter

Next
End Sub
```

Figure A.11: Screenshot of the macro that finds the regulating state for each hour of the year

A.5.1 The model used in the Case study

In the case study in section 3.1 the losses in the balancing market is found for Bessaker wind farm. Here the method and calculations used to find these losses are presented. The volume in the consumer balance, the production balance, the current balancing price and the current spot price is found using the mentioned program written by G. Aaronsen. The gains or deficit in the trade balance is found by using a if sentence, using the built in excel function IF:

$$= IF(F14 > 0; F14 * (G14 - H14); ABS(F14) * (G14 - H14)) \quad (A.1)$$

Where F14 is the cell containing the trade balance volume, G14 is the cell containing current balance price and H14 is the cell containing the current spot price. The sentence first checks if there is a positive or negative balance. If it is negative it multiplies the volume with the difference between the spot price and the balancing price. If it is false it multiplies the

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volume with the absolute value of the difference between the spot price and the balancing price. In other words, if the volume is positive the losses or gains is the difference between the balancing price and the spot price. With a balancing price higher then the spot price there is a gain and with lower balancing price it is a loss. If the volume is negative the opposite is true. With a balancing price lower then the spot price it is a gain, and with a balancing price higher then the spot price it is a loss. The reason for this is that one have to buy back the balancing volume.

The losses in the production balance is found by nesting if-sentences:

$$= IF(E14 > 0; IF(G14 > H14; 0; E14*(G14-H14)); IF(G14 < H14; 0; E14*(G14-H14)))$$

$$(A.2)$$

Where E14 is the cell containing the production balance volume, G14 is the cell containing current balance price and H14 is the cell containing the current spot price. The first if sentence checks if the production balance volume is positive or negative, hence, if TrønderEnergi have to buy back production or if excess production is sold. Whether this is true or not, the function goes into another if sentence that checks if the balance supports the system or not. This is done by comparing the spot price and balancing price. If the balance supports the system as a whole, there is no losses and zero is returned. If it does not support the system the loss is found by multiplying the volume and the difference between the balancing price and spot price, or the difference between the spot and balancing price. This depends on whether the system is under supplied or over supplied.

The found values is found and summarized for the trade balance and the producer balance. The results are shown in table 3.1. Different screenshots from Excel is shown in Fig.A.12 and Fig.A.13,

Handel ubal.	Reg.kraft.pris	Spotpris	Prod.ubal	Handel ubal
-1,80	281,09	248,18	0	59,238
0,90	232,95	232,38	-0,42025	0,513
1,80	225,57	225,02	-0,251539	0,99
-1,60	221,69	221,15	-3,03464	0,864
2,00	215,40	214,87	-15,19887	1,06
2,50	214,78	214,25	-22,06995	1,325
1,00	162,97	212,47	0	-49,5
1,30	165,00	205,66	0	-52,858
-1,00	162,97	189,00	0	-26,03
2,60	145,21	189,00	0	-113,854
3,10	142,05	207,52	0	-202,957
3,00	145,00	225,02	0	-240,06
2,60	150,00	226,96	0	-200,096
2,80	165,00	224,71	0	-167,188
2,20	165,00	226,26	0	-134,772
3,00	232,48	231,92	-13,00082	1,68
2,70	270,00	240,51	-640,8612	79,623
2,10	297,40	255,62	-911,0978	87,738
2,20	297,40	261,66	-811,0648	78,628
0,70	297,40	255,93	-809,8081	29,029

Produksjonsubalansen	-778 444,42
Forbruksubalansen	-361 415,40
Sum	-1 139 859,82

Figure A.12: Screenshot of Excel - Case study model.

Prod.ubal	Handel ubal.	Reg.kraft.pris	Spotpris	Prod.ubal	Handel ubal
1,94540351867682	-1,8	281,09	248,18	=IF(E14>0;IF(G14>H14;0;	=IF(F14>0;F14*(G14-H14);ABS(F14)*(G14-H14))
-0,737280044555639	0,899999999999999	232,95	232,38	=IF(E15>0;IF(G15>H15;0;	=IF(F15>0;F15*(G15-H15);ABS(F15)*(G15-H15))
-0,457344207763683	1,8	225,57	225,02	=IF(E16>0;IF(G16>H16;0;	=IF(F16>0;F16*(G16-H16);ABS(F16)*(G16-H16))
-5,61970428466801	-1,59999999999999	221,69	221,15	=IF(E17>0;IF(G17>H17;0;	=IF(F17>0;F17*(G17-H17);ABS(F17)*(G17-H17))
-28,677120513916	2	215,4	214,87	=IF(E18>0;IF(G18>H18;0;	=IF(F18>0;F18*(G18-H18);ABS(F18)*(G18-H18))
-41,641418838501	2,50000000000001	214,78	214,25	=IF(E19>0;IF(G19>H19;0;	=IF(F19>0;F19*(G19-H19);ABS(F19)*(G19-H19))
-43,492135925293	1	162,97	212,47	=IF(E20>0;IF(G20>H20;0;	=IF(F20>0;F20*(G20-H20);ABS(F20)*(G20-H20))
-37,2811051177979	1,3	165	205,66	=IF(E21>0;IF(G21>H21;0;	=IF(F21>0;F21*(G21-H21);ABS(F21)*(G21-H21))
-30,3240692901611	-1	162,97	189	=IF(E22>0;IF(G22>H22;0;	=IF(F22>0;F22*(G22-H22);ABS(F22)*(G22-H22))
-28,4476459503174	2,60000000000001	145,21	189	=IF(E23>0;IF(G23>H23;0;	=IF(F23>0;F23*(G23-H23);ABS(F23)*(G23-H23))
-22,2655150604248	3,1	142,05	207,52	=IF(E24>0;IF(G24>H24;0;	=IF(F24>0;F24*(G24-H24);ABS(F24)*(G24-H24))
-22,2903255462646	3	145	225,02	=IF(E25>0;IF(G25>H25;0;	=IF(F25>0;F25*(G25-H25);ABS(F25)*(G25-H25))
-23,6833452606201	2,6	150	226,96	=IF(E26>0;IF(G26>H26;0;	=IF(F26>0;F26*(G26-H26);ABS(F26)*(G26-H26))
-22,9057172393799	2,8	165	224,71	=IF(E27>0;IF(G27>H27;0;	=IF(F27>0;F27*(G27-H27);ABS(F27)*(G27-H27))
-21,8689556121826	2,2	165	226,26	=IF(E28>0;IF(G28>H28;0;	=IF(F28>0;F28*(G28-H28);ABS(F28)*(G28-H28))
-23,2157481384277	3	232,48	231,92	=IF(E29>0;IF(G29>H29;0;	=IF(F29>0;F29*(G29-H29);ABS(F29)*(G29-H29))
-21,7314736175537	2,7	270	240,51	=IF(E30>0;IF(G30>H30;0;	=IF(F30>0;F30*(G30-H30);ABS(F30)*(G30-H30))
-21,8070332336426	2,1	297,4	255,62	=IF(E31>0;IF(G31>H31;0;	=IF(F31>0;F31*(G31-H31);ABS(F31)*(G31-H31))
-22,6934761810303	2,2	297,4	261,66	=IF(E32>0;IF(G32>H32;0;	=IF(F32>0;F32*(G32-H32);ABS(F32)*(G32-H32))
-19,5275653076172	0,700000000000003	297,4	255,93	=IF(E33>0;IF(G33>H33;0;	=IF(F33>0;F33*(G33-H33);ABS(F33)*(G33-H33))
-18,7214218139648	0,199999999999996	289,63	239,51	=IF(E34>0;IF(G34>H34;0;	=IF(F34>0;F34*(G34-H34);ABS(F34)*(G34-H34))
-18,7574825286865	1,1	228,14	227,58	=IF(E35>0;IF(G35>H35;0;	=IF(F35>0;F35*(G35-H35);ABS(F35)*(G35-H35))
1,17455184936519	2,40000000000001	218,2	217,66	=IF(E36>0;IF(G36>H36;0;	=IF(F36>0;F36*(G36-H36);ABS(F36)*(G36-H36))
-1,03507910766604	3	191,17	190,71	=IF(E37>0;IF(G37>H37;0;	=IF(F37>0;F37*(G37-H37);ABS(F37)*(G37-H37))

Produksjonsubalansen	=SUM(I$14:I$1048576)
Forbruksubalansen	=SUM(J$14:J$1048576)
Sum	=SUM(M14:M15)

Figure A.13: Screenshot of Excel -Case study model, showing formulas.

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