Norwegian School of Economics
Bergen, Spring 2013

Economic solutions to improve frequency quality

A discussion of Statnetts challenges in the power system

Fredrik Vigeland Christoffersen

Supervisor: Linda Rud

Master Thesis within the main profile of Energy, Natural Resources and the Environment (ENE)

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

The frequency of a power system can be compared to the heartbeats of a human. However, unlike for the human heart rate, it is vital that the frequency is kept stable at all time. Frequency deviations occur when the frequency is not kept stable. The deviations are used to measure frequency quality, which is an indication of the quality of power supply. The frequency quality has decreased the last ten years. This thesis identifies challenges of providing a sufficient frequency quality, and discusses economic solutions that Statnett as the TSO can implement to meet these challenges. The first part of the thesis presents the energy system. Based on this discussion we identify that rapid load changes, light system operation and wind power production represent important challenges in providing a sufficient frequency quality. We further discuss various solutions to deal with these challenges, focusing on economic based solutions of market design and incentives, rather than new technical solutions. As the energy system is interlinked and complex, the thesis takes a broad perspective. Thus, the thesis identifies and discusses several possible measures that we argue will benefit the future frequency quality of the system: - changing the time of trading units and interconnector ramping rules, - strengthening the intraday market, - introducing wind power brokers, - introducing new products in the option market for manual reserves, and - facilitate for flexible consumption.

Foreword

In the summer of 2012, I was so lucky as to be a part of the KUBE-project by Statnett. KUBE is an interdisciplinary project where six students construct a scientific report regarding a research topic of Statnett´s choice. The subject of KUBE 2012 was “System operations in 2020” with a main focus on frequency quality. I found working with the subject both challenging and interesting, and the experience inspired me to study frequency quality in depth in this master thesis.

Chapter 5 presents much of the same arguments and findings that part 2 of KUBE 2012 does. Leiv Erik Ødegaard and I wrote this part of KUBE 2012, and I would like to thank Leiv Erik for the collaboration. I would also like to thank the rest of KUBE 2012; Tove Rømo Grande, Martha Marie Øberg, Tine Handeland and Jonas Nøland for sharing knowledge and ideas through the summer of 2012, some of them which I have built upon or used in this thesis. Working interdisciplinary through KUBE 2012 gave me an insight into the complexity of the electricity system and the understanding that economic thinking must be combined with other disciplines. I will also like to thank the employees at Statnett who helped us with KUBE 2012 and shared their time and knowledge.

Several numbers and figures that are presented in chapter 5 are taken from KUBE 2012. These were done by me in the project and the calculations and assumptions are presented in appendix.

Last, but not least, would I like to thank my supervisor Linda Rud for all the help, time and ideas she has given through the work on this thesis. It would not have been possible to make this report without her help and patience with my questions.

Bergen, 31.05.2013
Fredrik Vigeland Christoffersen

Content

Figure list

Table list

List of abbreviations, organizations and technical terms

TSO	Transmission System Operator
Statnett	Norwegian TSO
Energinet.dk	Danish TSO
Svenska Kraftnät	Swedish TSO
Fingrid	Finish TSO
TenneT	Dutch TSO (also TSO in a region of Germany)
NVE	Norges Vassdrag og Energidirektorat (Norwegian Water Resources and Energy Directorate)

ELSPOT	Joint Nordic spot market
ELBAS	Joint Nordic intraday market
FCR	Frequency Containment Reserves
FRR	Frequency Restoration Reserves
RKM	Regulating Power Market
RKOM	Regulating Power Option Market

1 W	One Watt of instant effect
1 Wh	One Watt of energy provided over one hour

1 kW = 1000 W
1 MW = 1000 kW
1 GW = 1000 MW
1 TW = 1000 GW

1 kWh = 1000 Wh
1 MWh = 1000 kWh
1 GWh = 1000 MWh
1 TWh = 1000 GWh

1. Introduction

1.1. Frequency – the heartbeat of the power system

The frequency of a power system can be compared to the heartbeats of a human. However, unlike for the human heart rate, it is vital that the frequency is kept stable at all time. A too high or a too low frequency can cause severe damage or, in the worst case, make the electricity system collapse (Statnett SF 2012a). Deviations from the frequency can in this way be seen as a weakening of the security of power supply. In general, the term frequency is defined as the number of times a specific incident occurs within a amount of time (TechTerms.com 2011). For electricity, frequency is measured in hertz (Hz). Hertz is used to quantify the amount of times that energy changes direction within one second (Statnett SF 2012b). Most power systems, including the Norwegian system has a frequency of 50 Hz.

We can think of the energy system as a pair of scales in order to understand the concept of frequency. Production and import is on one scale, and consumption and export on the other. The balance between the amount of electricity fed into the system and taken out has to be exactly the same at all time in order for one of the scales not to tip the other over (Statnett SF 2012b). If more electricity goes into the system than out, even for a moment, the frequency increases. If more electricity is taken out of the system than fed in, the frequency decreases. Balancing power must be used if there are imbalances between the two scales. Balancing power is available production capacity allocated for the purpose of balancing the frequency.

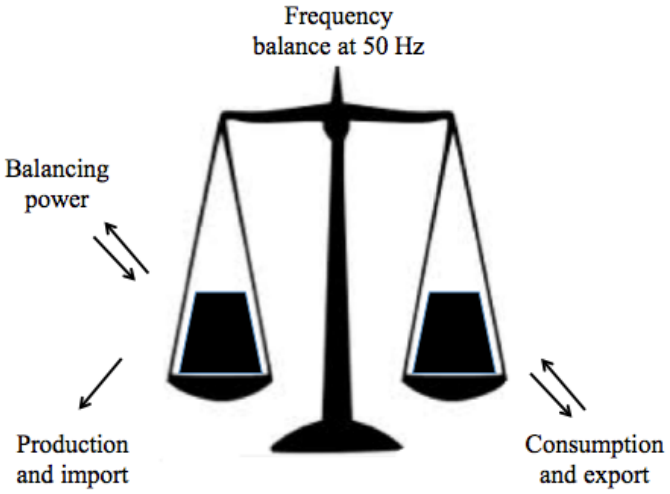

Figure 1: The frequency as a pair of scales. Own figure

1.2. Falling frequency quality

A frequency deviation occurs whenever there is an imbalance in the system. If the frequency falls or rises more than 0,1 Hz from 50 Hz, its defined as a frequency deviation. The frequency quality of a power system can be measured as the accumulated minutes of frequency deviations within a given time frame, or alternatively, the number of times the frequency deviates within a given timeframe (Statnett SF 2012b). An increase in frequency deviations indicates falling frequency quality.

Norway is part of a joint power system called the Nordic synchronous system with Sweden, Finland and Eastern Denmark. The system has a joint frequency, as it is one interlinked system. (Statnett SF 2012b) Figure 2 shows that the minutes of frequency deviations in the Nordic synchronous system has been increasing gradually the last ten years. The result is a decreasing frequency quality and a weakened security of power supply.

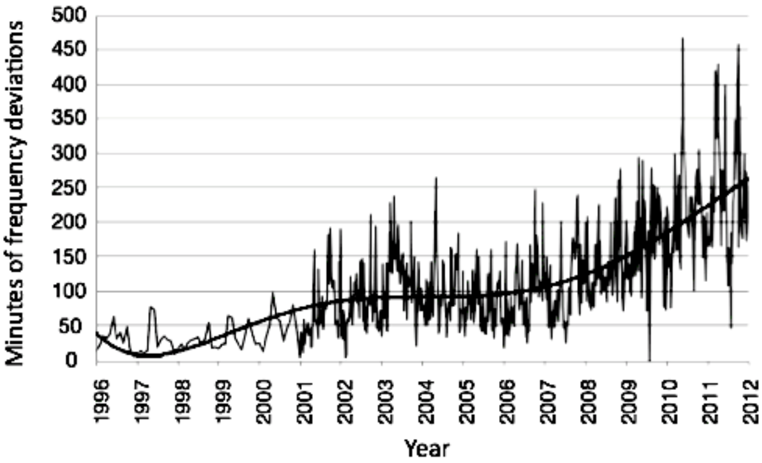

Figure 2: Development of frequency deviations (1995 - 2011). (Statnett SF 2012b)

It is the Transmission System Operators' (TSO) responsibility to handle energy imbalances by the use of balancing power. The TSO´s are the operators of the national transmission grid, which are natural monopolists. Statnett is TSO in Norway, and share the balancing responsibility with the TSOs in the other Nordic countries. (Statnett SF 2012b) This thesis will limit its focus to Statnett's part of the balancing responsibility.

1.3. Challenges and solutions

The power system is growing in complexity. Figure 3, which is adapted from Statnett (2012a), shows how the development of different factors is expected to increase the complexity of the power system between 2012 and 2020. Changes in production and consumption, political conditions, international integration, weather, technology and cross border trading are all a part of this growing complexity. This is also the main reason why it has become harder to balance the power system. This development is expected to continue in the future (Statnett SF 2012a). It is expected that the frequency quality will continue to decrease if actions are not made (Statnett SF 2012b).

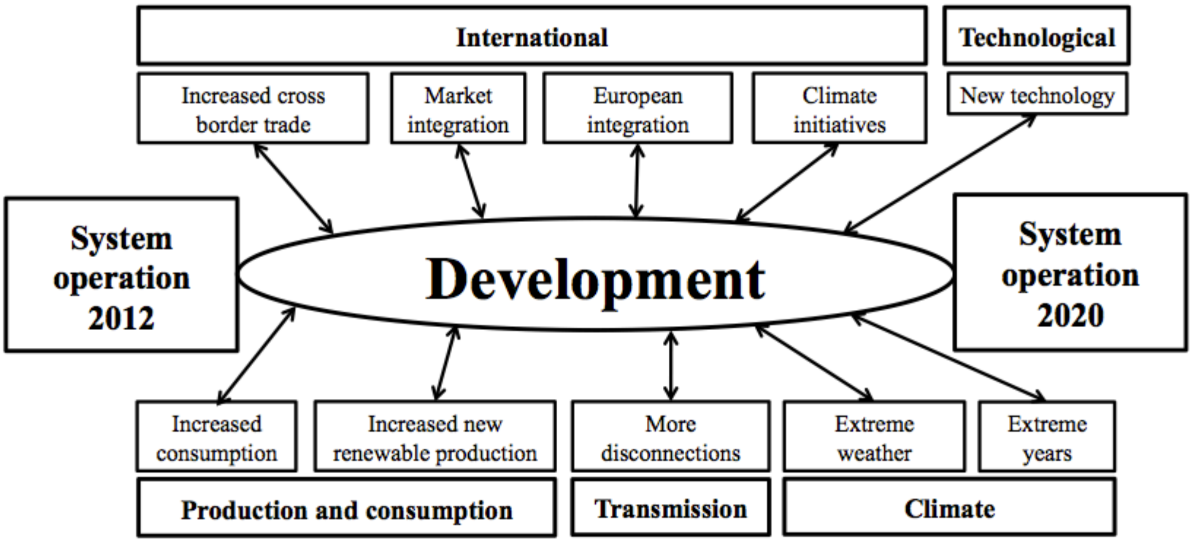

Figure 3: Main development for system operation between 2012 and 2020. Adapted from (Statnett SF 2012a)

The subject of frequency quality is interesting and important because the frequency is so vital to the power system. The thesis first identifies main challenges of maintaining a sufficient frequency quality in the future, and then discusses economic measures that Statnett can introduce to improve the frequency quality in the future. These include modifications of already existing market solution, as well as new ideas. The main challenges and the suggested solutions of the thesis may be summarized as follows:

- Rapid load changes in the system are increasingly contributing to imbalances. The markets for planned trade of power are insufficient in handling load changes. This may be improved by a market design based on shorter trading units in the markets for planned trade combined with continuous ramping on the interconnectors.

- Light system operation occurs when the system is operated with a low amount of balancing power capacity. The system becomes less robust to handle energy imbalances in these situations. The introduction of down-regulating options for manual reserves may increase the bids and the capacity available in RKM and thereby provide more available capacity.
- Wind power is unregulated and highly unpredictable. More wind power can cause increased energy imbalances in the future. The undesired features of wind power can be addressed by increasing trade in the intraday market, introducing brokers for wind power, implementing shorter trading units in the markets for planned trade and implementing down-regulating options for manual reserves.
- Flexible demand can contribute to increased frequency quality. This solution does not derive from a specific challenge for the frequency, but can contribute by providing manual reserves and a more even load pattern.

1.4. Structure

The Norwegian energy system and the markets for planned trade of power is presented in chapter 2, providing an understanding of the system which is necessary in addressing solutions for providing an increased frequency quality. Chapter 3 focuses on balancing power, as well as markets for balancing power where Statnett obtain the necessary services to balance the power system. We discuss three main challenges for providing an improved frequency quality in chapter 4. Possible solutions, based on economic theory, to the three main challenges, will be discussed in chapter 5 – 7. Chapter 5 will address the challenge of rapid load changes and frequency deviations around hourly shifts. In chapter 6 wind power will be discussed, as it is expected that wind power will contribute to increased system imbalances. This chapter also addresses the aspect of light system operation. Chapter 7 discusses the advantages of flexible demand in maintaining the frequency quality. Chapter 8 gives a summary of the thesis.

2. The electricity system

The energy balance in the power system and the need for frequency regulations are determined by the actions of the system participants. The producers produce electricity, which the consumers use. In addition, cross border trading affects the energy load. All the actions add up to the net balance of energy in the system at any given time and they determine if the pair of scales is kept leveled or tips in one direction. This will cause a frequency deviation that must be handled to restore the frequency. (Statnett SF 2012b)

The structure of the power system can be seen in Figure 4 where the main system participants are presented. Produced electricity is transported into the transmission grid, which is operated by the system operators[1]. It is then distributed to consumers. The producers and consumers trade in open markets for planned trade of electricity, called the spot- and intraday markets. (Statnett SF 2012b) The transmission grids are natural monopolies, operated by regulated transmission companies. This deregulated market system makes it possible for producers and consumers to act in open markets, which gives a more economically efficient system. We will look at system participants and their actions in chapter 2.1 and the markets for planned trade in 2.2.

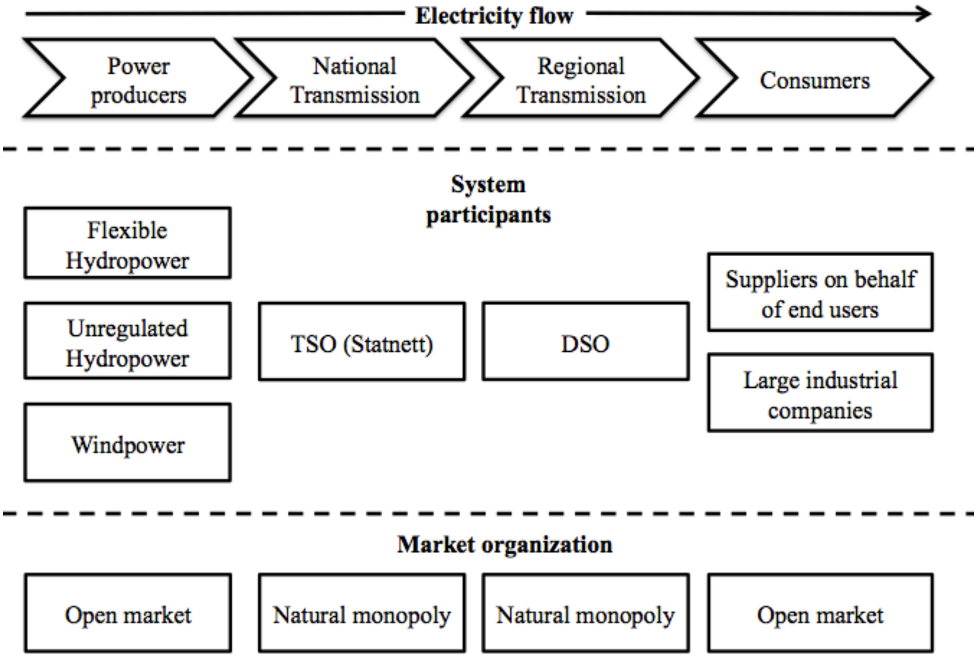

Figure 4: The electricity system with electricity flow, system participants and market organization. Own figure.

2.1. System participants

2.1.1. Consumers

This thesis has chosen to divide consumers into two main groups of interest, given their differences in size, consumption pattern and market participation:

The industrial industry is one of the two main consumer groups of electricity. The group's total energy consumption in a normal year is approximately 600 GWh per week, and not dependent upon season (Olje- og energidepartementet 1998). This accounts for roughly 25 % of the total Norwegian energy consumption in a year. The industrial firms are active market participants, as electricity is one of their most important factor inputs.

Individual consumers, such as households, office buildings, malls and other power users of less energy intensive scale, are the other main group of consumers. They do not directly trade in the markets for electricity, but purchase from an electricity provider. The electricity providers trade in the electricity market and act as aggregated consumers on behalf of all their clients. The consumer group use from 1000 to 3000 GWh/week (Statnett SF 2012b), and account for approximately 75 % of Norway's energy consumption in a year (Olje- og energidepartementet 1998). Unlike the industrial consumers, the individual consumer group has a distinct pattern of consumption for years, weeks and days. The patterns can be seen in Figure 5, 6 and 7:

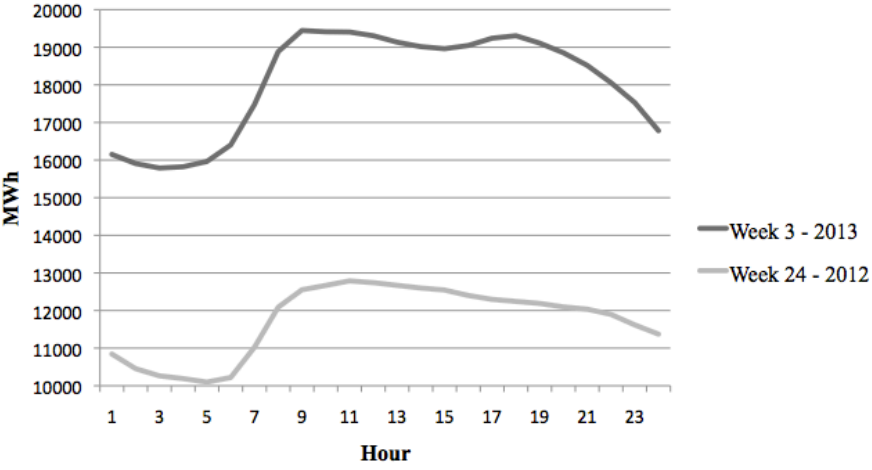

Figure 5: Average daily consumption pattern for week 3, 2013 and week 24, 2012. (Nord Pool Spot 2013a)

---

[1] Local Transmission Operators (LSO) are not included in the figure.

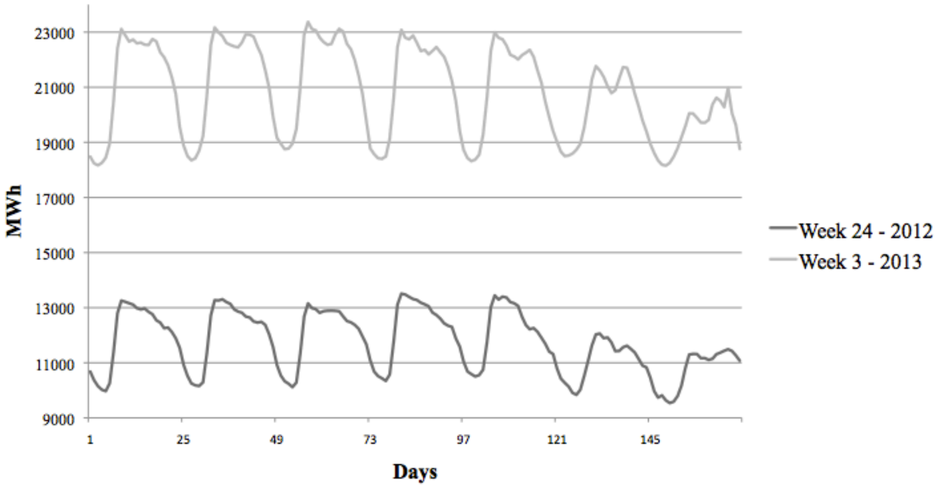

Figure 6: Consumption pattern for week 24, 2012 and week 3, 2013. (Nord Pool Spot 2013a)

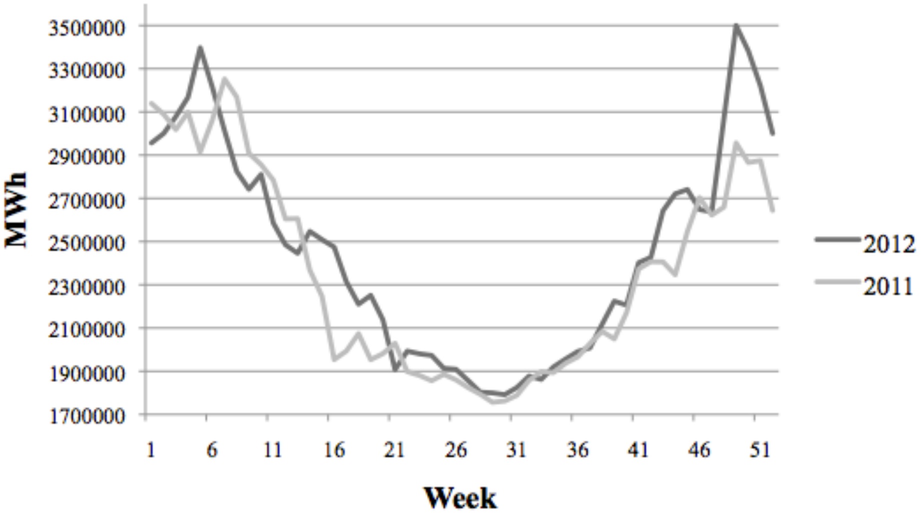

Figure 7: Yearly consumption in weekly numbers for 2012 and 2013 (Nord Pool Spot 2013a)

- The daily consumption starts at a low level in the night, spikes in the morning, is kept high during the day and then falls in the evening. This pattern follows the daily rhythms of society.
- The weekly consumption pattern consists of seven-day patterns where the weekend has a lower level of energy usage than the weekdays.
- The yearly consumption pattern is negatively correlated with outside temperature, as heating is an important usage of electricity in Norway. This gives high consumption in the winter, falling in the spring, low in the summer and rising in the fall.

There are three important aspects regarding the group's consumption of energy:

- Consumption has high uncertainty and is difficult to forecast.
- The consumption load changes continuously.
- Consumption has rapid changes in the morning and in the evening.

The combination of the three implies that it can be difficult to know what actual consumption of electricity will be before the operating moment. This is a challenge for keeping a stable energy balance in the system.

2.1.2. Producers

This thesis has chosen to divide producers into three groups, based on their differences in production regulation possibilities and technology:

Hydropower producers with storage capacity, also called flexible producers, generate about 70% of Norway's power in a normal year (Olje- og energidepartemenet 2012a). The storage is done in large dams or lakes, called reservoirs, and electricity is produced by tapping water from the reservoirs into tubes with turbines. Production plants have high investment costs, but low marginal costs since the "fuel" of hydropower is rainwater. However, the water used in hydropower production does have a value called water value. The water value represents the opportunity cost of saving water for production on a later occasion when prices are higher, compared to using the water for production now at current prices. The water value makes out most of the producers' marginal costs and is therefore an important parameter in their production decisions. (Olje- og energidepartementet 1998)

Hydropower producers without storage capacity, also called unregulated hydropower, account for 27 % of Norway's power production in a normal year (Olje- og energidepartemenet 2012a). Unlike the hydropower producers with storage capacity this group consists of producers without any possibility to decide when to produce or not to produce electricity. The plants are located in rivers where the water flow is converted into energy, using turbines. The investment costs of the unregulated hydropower plants are high, but their marginal costs are close to zero and do not include water value as water cannot be stored. This implies that the producers have an inelastic supply curve.

Figure 8 shows the production pattern over a year for both groups of hydropower production and a graph indicating water inflow into their reservoirs and water pathways.

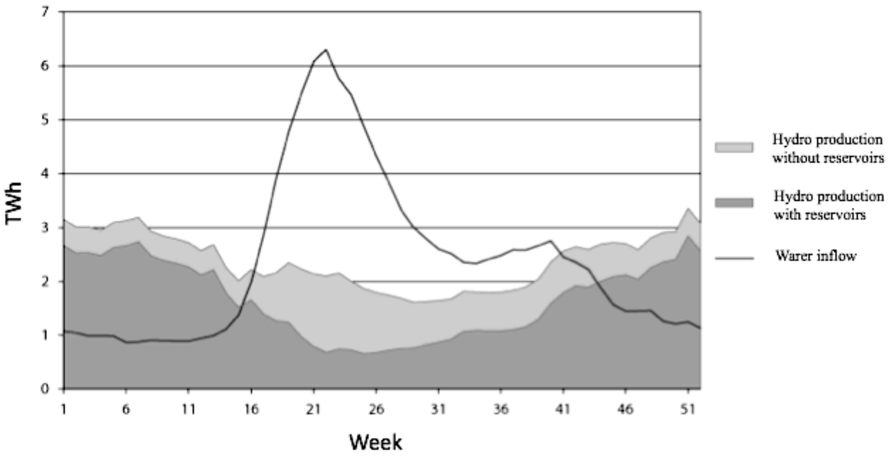

Figure 8: Graphs for hydropower production and water inflow in a typical year. (Olje- og energidepartemenet 2012a)

- The unregulated hydropower production is correlated with the inflow graph, as the inflow is what determines their production.
- Flexible production is negatively correlated with water inflow. This is because water inflow is highest in the summer months, while the electricity demand and prices are highest in the winter months. The producers can, given their storage capacity, hereby build up reservoir levels in the warm months to meet consumption needs in the colder months when water inflow is low.

Wind power production is the third producer group of interest in the Norwegian electricity system. Although wind power only has a share of approximately 1% of the total production capacity in Norway, they are included in this thesis because they are expected to gain significance in the future due to the green certificate market for electricity (Statnett SF 2011a) (Olje- og energidepartementet 2012b). Wind power is produced by transforming wind into energy using windmills. The production is unregulated and dependent upon wind speed. Like for unregulated hydropower production the investment costs in wind power are high, but the marginal costs are close to zero. However, unlike for unregulated hydropower, wind power production is a much less predictable power source. (Nilssen, et al. 2010)

2.1.3. Electricity export and import

In addition to producers and consumers cross border trading also affects the energy balance. Norway has several connections, both to countries within the Nordic synchronous system and outside of it. Capacity information by country is summarized in Table 1. (Olje- og energidepartementet 2012c)

Country	**Import capacity (MW)**	**Export capacity (MW)**	**Within the Nordic synchronous system**	
Installed capacity				
Sweden	3 695	3 545	x	
West-Denmark	1 000	1 000		
The Netherlands	700	700		
Finland	80	120	x	
Russia	56			
Planned capacity				Completed
West-Denmark	700	700		2014
Germany	1 400	1 400		2018
Great Brittan	1 400	1 400		2020

Table 1: Cross border trading capacity. Own figure based on (Olje- og energidepartementet 2012c)

Cross border trading between Norway and countries outside of the Nordic synchronous system will be of main interest for this thesis. This is because these trades affect the net energy loads in the system, something that cross border trading within the synchronous system doesn’t do. Electricity exchange outside the Nordic synchronous system is done using interconnectors, which are cables connecting countries in different synchronous systems. (Statnett SF 2012a) The cable is usually a high voltage direct current cable (a HVDC-cable). Changes in the load on an interconnector, called ramping, may potentially have a great impact on the balance of the energy system. As of today is the total transmission capacity of the interconnectors linking Norway with countries outside of the Nordic synchronous system 1700 MW. In 2020 is this capacity expected to be 5200 MW (Statnett SF 2012b).

The countries connected to Norway through interconnectors are mainly thermal dominated production systems. These systems have a more defined and volatile price structure over the day than Norway has, mainly because of significant start- and stop costs for thermal power production facilities (Olje- og energidepartemenet 2012a). This often results in import to Norway during the night and export in the daytime. Thus, the interconnectors are often turned two times a day. (Statnett SF 2012b)

Cross border trading is important for Norway because the variations in domestic power production can be large between wet and dry years. Norway is dependent upon net import in dry years, to secure their energy supply, but can take advantage of the cables for export in wet years to avoid spillage of water. (Olje- og energidepartemenet 2012a) It is expected that Norway will be net exporter of power for most years by 2020, given investments in new renewable energy. (Statnett SF 2012b). The interconnectors are important so that excess power can be exported in the future (Hope 2011).

2.1.4. Important elements regarding system participants

We have seen that the energy balance in the system depends upon the actions of system actors and cross border trade. There are five key elements that we need to keep in mind for the rest of this paper:

- Consumption varies a lot over the day and within the year. This implies that production loads must change in the same way.
- Flexible hydropower production has the ability to regulate their production, which the unregulated hydropower and wind power does not.
- Wind power production is highly unpredictable and difficult to forecast.
- The differences in price patterns between Norway and thermal dominated power systems most often lead to export from Norway during the day and import during the night.
- The total cross border transmission capacity between Norway and countries outside of the Nordic synchronous system are expected to increase by 3500 MW the next eight years.

The actions of producers and consumers furthermore follow from trade in electricity markets, and thus also enforced by the incentives of these markets.

2.2. Markets for planned trade

There are different markets connected to trade of electricity. We have commodity markets for energy, financial markets and markets where ancillary services are traded. This part of the thesis will look into the commodity markets for electricity. These are markets where trade occurs ahead of the operating moment, and where production is planned to meet real consumption so that the energy balance is maintained. The markets can be called markets for planned trade, i.e. planned production and consumption, and consist of the spot market, which is a day-ahead market, and the intraday market (Statnett SF 2012b). The spot- and intraday markets are open Nordic power markets covering Norway, Sweden, Finland, East-Denmark, Lithuania and Estonia. However, market participants from other countries are also allowed to trade. Most of the trade is done on the commodity exchange Nord Pool Spot, owned by the TSOs of the countries in the market (Nord Pool Spot 2013c).

In addition to the spot- and intraday market there also is bilateral trade in form of agreements between actors in the system. (Statnett SF 2012b) These agreements can be defined as a part of markets for planning, even though the trade does not occur through organized markets.

2.2.1. The spot market

The spot market, called ELSPOT, is the main market for trade of electricity in the Nordic power market. The commodity trade was 432 TWh in 2012, by 320 companies from 20 countries (Nord Pool Spot 2013b). ELSPOT is operated on a daily basis covering the following 24 hours of the next day, for which 24 different hourly contracts are traded, that is 24 units each covering 60-minute of the next day. The market is cleared using a market algorithm that aggregates supply and demand curves based upon bids from producers and consumers. The algorithm also incorporates transmission constraints in the grid. NordPool Spot is responsible for publishing information regarding price, volume and cross border trading quantities after the markets is cleared. Accepted bids become binding contracts for physical delivery and reception of electricity for the next day. (Statnett SF 2012b)

Figure 9 shows the timeline for trade in the spot market:

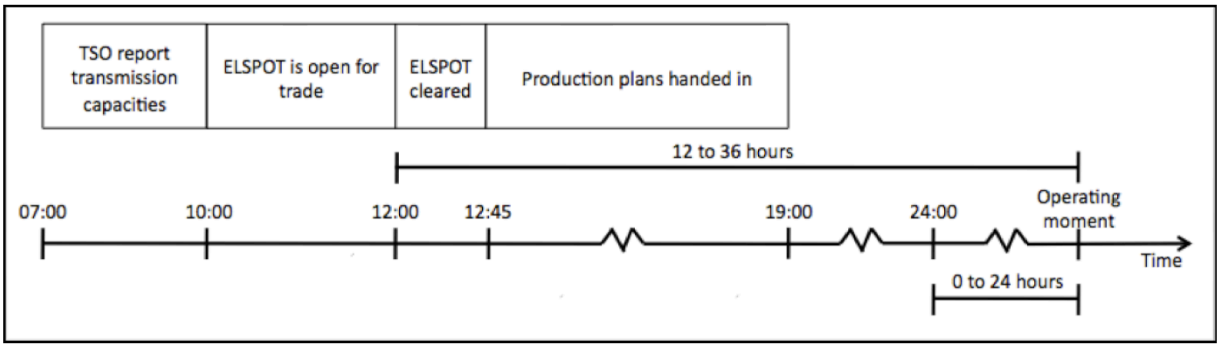

Figure 9: Timeline for trade in the spot market. Own figure

- The capacity constraints in the transmission grid are reported by the TSOs between 07:00 and 10:00 in the morning.
- The market opens for bids from producers and consumers at 08:00 and closes at 12:00.
- The cleared market information is made public between 12:30 and 12:45.

- The producers are obligated to hand in production plans for the following day within 19:00. These plans are important for the planning that Statnett needs to do in order to adjust production to consumption for the next day. Large producers, with capacity over 200 MW, are obligated to define their plans in 15-minute units. Statnett has the possibility to move production in the plans, within the interval of one quarter of an hour. For example, if a producer has planned to start production at 08:00, Statnett can order them to move the production start within the time interval of 07:45 to 08:15. The producers are compensated for these movements according to spot market prices. (Statnett SF 2012c)

The design of the spot market holds three features that create challenges for keeping a stable balance in a way that is economically desirable:

- The binding contracts for delivery and reception of electricity are made from 12 to 36 hours before actual delivery. Important parameters that affect consumption or production can change during this time period.
- Consumption load, and therefore also production, changes continuously. However, the market is cleared in 60-minute units where the producers and consumers are obligated by the market to be in balance within each hour. The mismatch between market structure and continuous load changes is the main reason why Statnett is dependent upon exercising production movements.
- Statnett can make production movements after the large producers hand in their production plans. However, Statnett doesn’t have perfect information to make these production movements in an economically optimal way.

All these challenges are important with respect to the frequency quality of the system, and will be discussed in great detail later in this thesis.

2.2.2. The intraday market

The intraday market, called ELBAS, is designed as a supplementary market to ELSPOT. It opens after the spot market is cleared and is used so that producers and consumers can alter their spot market obligations if new information occurs. Trade in ELBAS is done on a continuous basis and contracts are entered into at varying prices, depending on the bids. It is only possible to trade in ELBAS if there is spare capacity available in the transmission grid. This might not be the case after the spot market is cleared, especially not for cross border trading. Like for ELSPOT, the contracts in ELBAS are binding contracts that require physical delivery or reception of electricity. (Statnett SF 2012b)

Figure 10 shows the timeline of trade in ELBAS:

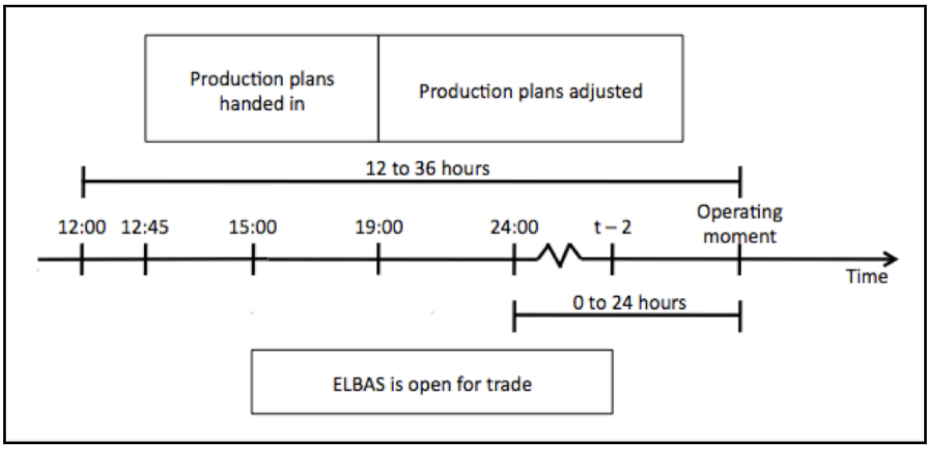

Figure 10: Timeline for trade in the intraday market

- The market opens at 15:00.
- ELBAS closes two hours before operating hour for Norwegian market participants. Closing time in most other countries in the market is one hour before operating hour. Statnett is expected to adapt this gate closure time in 2015. (Statnett SF 2012a)
- After ELBAS is closed producers must hand in any alterations they may have done in their production plans. These altered production plans must be handed in not later than 45 minutes before the operating hour.

The intraday market provides two important advantages for the system:

- Market participants can aim to maximize their profit as information changes over time.
- It is easier for the for system actors to uphold their balancing obligations. If a market participant obtains new information regarding production or consumption implying that he will not be able to fulfill his contract obligations, then these imbalances can be traded off in ELBAS. Foreseen imbalances can in this way be dealt with ahead of the operating moment, instead of when they occur. (Statnett SF 2012a)

Norwegian producers and consumers seldom use ELBAS, regardless of the advantages that it provides both market participants and Statnett. There are several reasons for this, but the most obvious reason is that production sources in Norway today are highly predictable. (Statnett SF

2012a) However, we might expect this to change in the future, given investments in new renewable energy.

2.2.3. Price development in the markets for planned trade

How prices in these markets will develop in the future will have important effects on the outcome of the discussions made later in this thesis. This is because a lot of the arguments made in the text are affected by expected prices. There are two important questions regarding price development for electricity, which we need to address. The first is a question of price level and the other of price structure.

The price level in the markets for planning is expected to change in the future for two reasons:

- Investments in new renewable energy production indicates that prices for electricity will decrease, everything else held constant. (Bye 2003)
- The building of interconnectors indicates that prices for electricity will increase, given the current lower price levels in Norway than surrounding countries. (THEMA, Pöyry 2010)

The report "Challenges for the Nordic Power – How to handle the renewable electricity surplus" by THEMA Consulting Group and Pöyry Management Consulting (THEMA, Pöyry 2010) indicates that the future holds a decrease of energy prices in the short run (before 2018 -2020), and a increase in the long run (after 2018-2020). Other articles also underline this development as the most probable in the future (Hope 2011).

The price structure within each day is closely related to consumption, as can be seen in Figure 11, where prices for electricity in Oslo are displayed for the same periods as in Figure 5, which displayed consumption. We can conclude with a strong positive correlation between consumption and prices within days. It's expected that the price pattern will become more volatile in the future, given an increase in cross border trade. (IPA Consulting, Econnect Ltd & Martin Energy 2006). We can, on the other hand, expect that the price pattern will become less specific, due to the fact that wind power production will affect prices from day to day randomly, depending upon the weather.

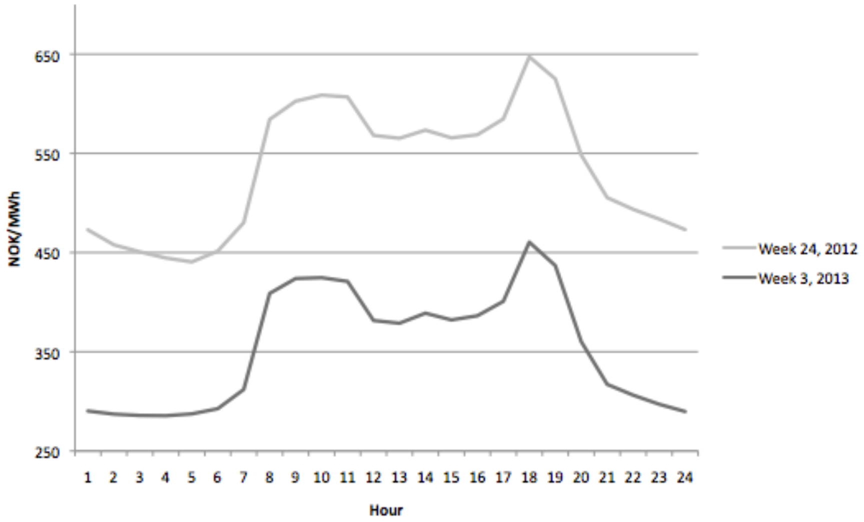

Figure 11: Average price for one day in week 24, 2012 and week 3, 2013. (Nord Pool Spot 2013e)

2.3. Imbalances may occur

It is the combination of all actions that system participants make that determine the energy balance in the system at any given time. However, their actions are determined by the obligations they make in the day-ahead and intraday markets. So, how can we use this insight to provide an improved frequency quality? To be able to answer this question, we first need to obtain information regarding how the energy balance is restored if the system participants tip the pair of scales out of balance.

3. Maintaining frequency balance

The day-ahead and intraday markets are cleared in balance for the 60-minute units that are traded. However, consumption changes continuously within the hour, and actors are not always able to meet their market obligations, due to forecasting error or operational problems. This can result in energy imbalances that must be handled so that the frequency can be restored at 50 Hz. Statnett, as TSO, is responsible for balancing the frequency and monitors the situation continuously. They use ancillary services involving different kinds of reserves to keep a stable balance in the system. Statnett does not own the reserves, but obtains them through markets specially designed for this purpose, where they operate as the only buyer. Producers and some consumers operate as sellers. The different types of reserves will be presented in chapter 3.1 and the markets for the reserves in 3.2.

3.1 Types of reserves

Statnett uses three types of reserves to balance the frequency. These are Frequency Containment Reserves (FCR)[2], Frequency Restoration Reserves (FRR)[3] and regulating reserves, also called manual reserves. FCR and FRR are rotating automatic reserves, which implies that only large hydro producers with reservoir capacity can supply them in Norway.[4] This is because a physical momentum is needed for rotating automatic reserves (Statnett SF 2012b). A reserve is rotating if the aggregate providing the reserve capacity is in use (rotates). The manual reserves are, however, not rotating and can in theory be supplied by all producers and consumer with the desired flexibility (Statnett SF 2012b).

Figure 12 gives a good picture of how frequency is balanced, using the three types of reserves:

- The FCRs starts balancing the frequency within seconds after a frequency deviation occurs. The turbines that produce electricity in hydropower plants are attached to frequency monitors and will automatically increase or decrease production as the frequency changes. FCRs are designed to help restore the frequency balance from zero to two minutes after the frequency deviation occurs. (Statnett SF 2012b)

---

[2] FCR consist of two types of reserves. These are FNR and FDR.

[3] Often referred to as LFC, as LFC accounts for a significant share of FRR.

[4] Thermal power can also provide automatic reserves, but this is not a part of Norway's production mix.

- The FRRs takes over the balancing responsibility from FCRs within 120-210 seconds after the frequency deviation occurs. They are designed to function up to five minutes after the deviation and are important because they make it possible for the FCRs to reset and be ready to handle new potential imbalances. Unlike the FCRs, Statnett must activate the FRRs even though they are automatic rotating reserves. FRR was implemented in the Norwegian power system in 2012. (Statnett SF 2012b).
- The regulating reserves are operated manually by the employees in charge at the system operator's central at Statnett. The choice of reserves is based on bids from producers and consumers offering to reduce or increase their production or consumption. They are activated from two to fifteen minutes after the frequency deviation occurs and should be used until the frequency is stabilized on 50 Hz. (Statnett SF 2012b)

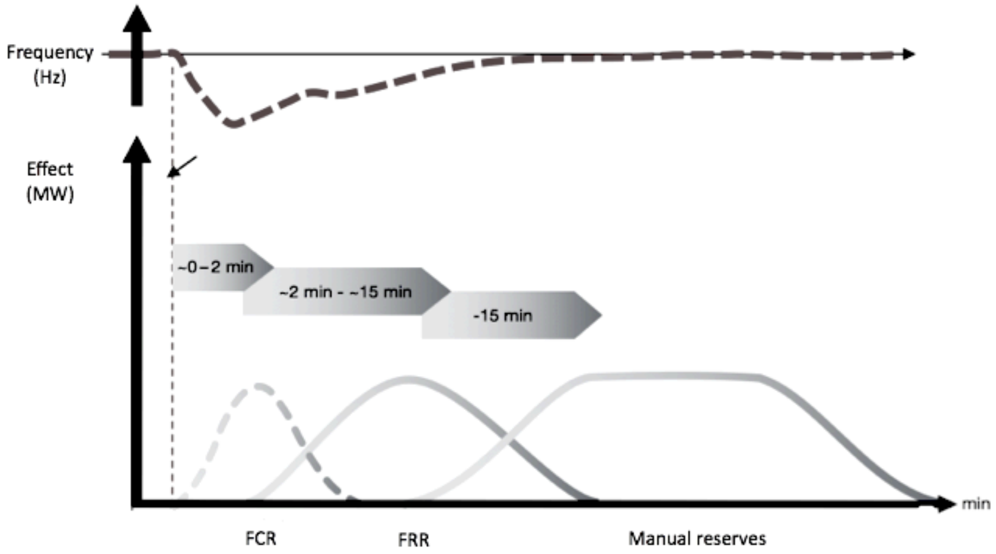

Figure 12: The usage of the different types of reserves. (Statnett SF 2012b)

3.2 Markets for ancillary services

3.2.1. The market for Frequency Containment Reserves (FCR)

FCRs are automatic reserves and the system's first defense when frequency deviations occur. The market is a pure Norwegian market, as FCRs need to be evenly distributed geographically around in the power system, and thus normally will not be traded across country borders (Statnett SF 2012b). However, it is possible to trade FCRs between TSOs when this is required. In this case the TSOs trade reserve capacity with each other, and not through market participants in the market for FCR. (Statnett SF 2010) To be able to provide FCR capacity, the producers need to have entered into binding obligations for supply in the markets for planned trade. This is because they need to have running production in order to produce FCR. (Statnett SF 2012b)

The FCR market consists of a week-based and a day-based market. The timeline displayed in Figure 13 shows when bidding and delivery is done in the market:

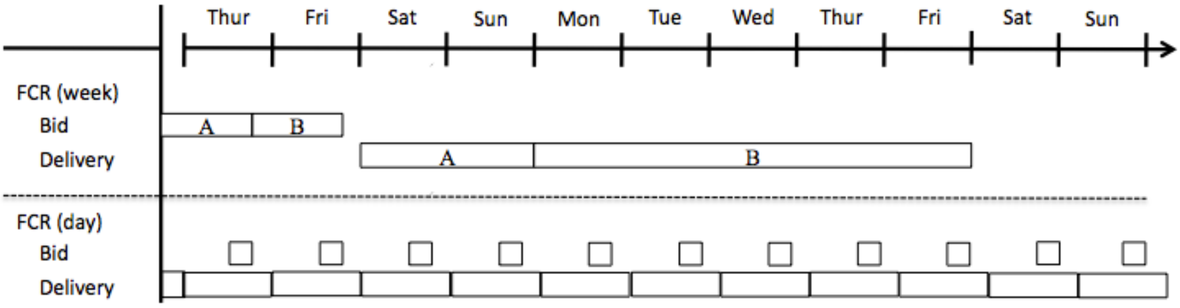

Figure 13: Timeline for bids and delivery in the market for FCR. Own figure based upon (Statnett SF 2011b)

The week-based market deals with the supply of FCR covering either the weekdays, or the weekend period. Bidding closes on Thursdays for the following weekend (A in the figure) and on Fridays for the following weekdays (B in the figure). All days in the week-based market consists of three units, night (00:00 – 08:00), day (08:00 – 20:00) and evening (20:00 – 24:00). The market is opened for bids eight days before it closes. (Statnett SF 2011b)

The day-based market for FCR opens the day before delivery and closes at 19:00. The producers receive information regarding the outcome of the market at 20:00. The day is split into 24 60-minute units. The daily market is important because it provides the producers with the opportunity to act in the market for FCR after they have received information regarding the clearance of the spot market (Statnett SF 2012b). All bids in the market can be done actively or passively, where a passive bid implies that the bidder accepts whatever price provided. (Statnett SF 2010) The prices in both the week-based and day-based markets are set at prices of the marginal accepted bids (Statnett SF 2011b).

Figure 14 shows the price pattern in the week-based market for FCR in the price zone NO2 in 2012 (Nord Pool Spot 2013d). The prices in the market are negatively correlated with power consumption. This is because FCRs are produced by flexible hydropower where production is positively correlated with consumption. The prices in the market for FCR will increase when production from flexible hydropower is low because this limits the capacity to provide the reserves. Remember that the producers must have accepted bids in the market for planning in order to deliver FCR capacity. (Statnett SF 2012a) The prices for FCR are mostly higher in the weekends than weekdays. This is because power demand is usually lower in weekends.

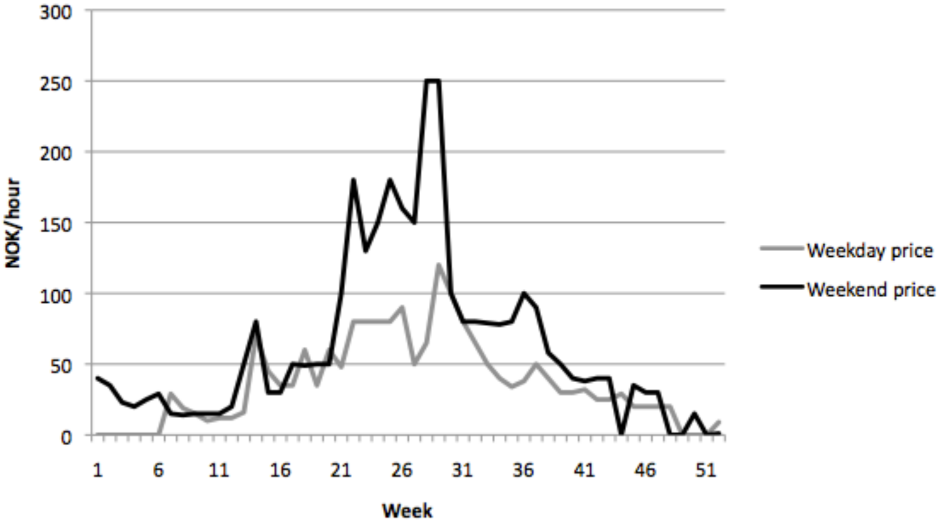

Figure 14: Prices in the week-based market for FCR in 2012 from price zone NO2. (Nord Pool Spot 2013d)

3.2.2. The market for Frequency Restoration Reserves (FRR)

FRRs are automatic reserves and represent the system's second line of defense when frequency deviations occur. The FRR market has only been in operation since 2012, since the use of this reserve is new. Research indicates that FRRs make an important contribution to improved frequency quality. This is mainly because use of the FRRs enables resetting the FCRs, thus making them available to tackle new imbalances. (Statnett SF 2012a) The FRR market is a national market, but Statnett can make bids available for other TSOs in the Nordic synchronous system. At the same time Statnett can use bids made available by the other TSOs. (Statnett SF 2012d) Like for FCR, producers need to have binding production obligations in the markets for planned traded to be able to provide FRR capacity. (Statnett SF 2012b)

The FRR market is a week-based market and the timeline displayed in Figure 15 shows bidding and delivery information:

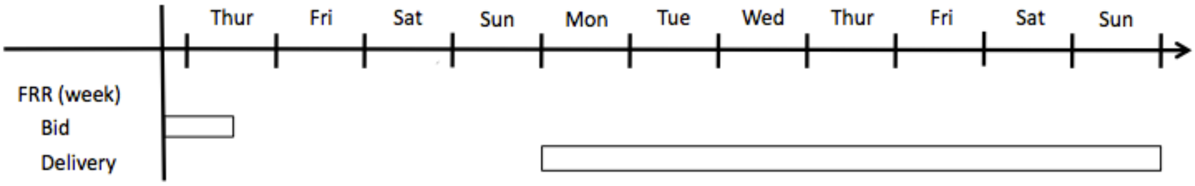

Figure 15: Timeline in the market for trade of FRR. Own figure based upon (Statnett SF 2012d)

This week-based market closes at 13:00 on Thursdays, where bids for delivery the following week are submitted. All days in the market are divided into night-, day- and evening units, with the same time frame as in the week-based market for FCR. Prices are set to be the price level of the marginally accepted bid. Bids are normally accepted in their entirety, or not at all. The bids in the market are separate for up- and down regulation of production, and are cleared at different prices. (Statnett SF 2012d) Even though the market has not been run for a full year, we can assume that the price pattern in the market will be as the pattern in the market for FCR. This is because FCRs and FRRs have the same price drivers.

3.2.3. The market for regulating reserves

The manual reserves are the system's third line of defense when frequency deviations occur, and it is their responsibility to restore frequency at 50 Hz. The market for manual reserves is called the Regulating Power Market (RKM), and is a joint Nordic market. All producers and consumers can in theory make bids in RKM as long as they fulfill the technical requirements. However, flexible hydropower producers and industrial consumers are the only actors involved today, given their flexibility to regulate. (Statnett SF 2012b).

RKM is a day-based market, and the timeline displayed in Figure 16 shows bidding and delivery information:

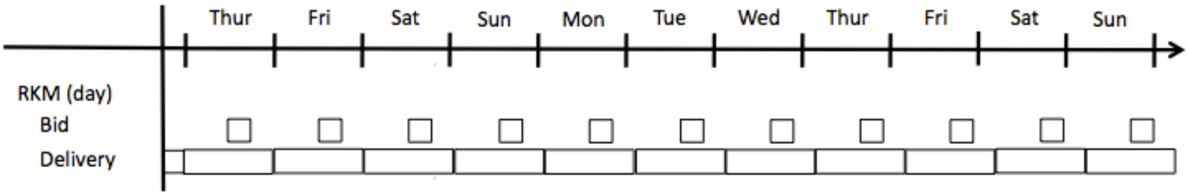

Figure 16: Timeline for trade in RKM. Own figure based upon (Statnett SF 2009)

This day-based market closes at 20:00 every day for delivery the next day. All bids are made on basis of compensation for producers or consumers in order to alter their production or consumption within 15 minutes notice. The bids in the market are separate for up- and down regulation, and are cleared at different prices. If there is a need for up-regulation within the hour, then the price of the marginally accepted bid sets the up-regulating price and is used for all accepted bids. The same approach to pricing applies to down-regulation. If there is a need for both up- and down regulation within the same hour, the price for the net value of the most utilized regulation will be used. (Statnett SF 2009) The bidding units in the market are 60-minute units.

Although Statnett is the only buyer in RKM, they are not responsible for the payment of all utilized reserves. If manual reserves are used for balancing purposes when consumers or producers deviates from their plans (energy obligations per hour), then these actors will be charged for the regulation. The settlements are done according to a specter of conditions and will include a percentage of the cost of FCR and FRR, as well as the cost of manual reserves and a fixed imbalance fee. (Statnett SF, 2009)If regulations are done because of an error connected to the transmission grid, balancing requirements within the hour, or if special regulations are made because of capacity constraints, then Statnett is responsible for payment. (Statnett SF 2012b)

3.2.4. The option market for regulating reserves

Statnett is obligated to have at least 1200 MW capacity in bids in RKM at all times. They have, in addition decided to have 800 MW extra, that is in total 2000 MW (Statnett SF 2012b). To ensure that sufficient capacity is bid into RKM, an option market has been created, called the Regulating Power Option Market (RKOM). This market is used between fall and spring. There are only option-products for up-regulating capacity in the market today. This is because there has, up until now, not been a need for options to ensure down-regulating capacity in RKM. Prices in RKOM are set to at the marginal accepted bid. (Statnett SF 2012e)

RKOM consists of a seasonal and a week-based market. The timeline displayed in Figure 17 shows when bidding and delivery is done:

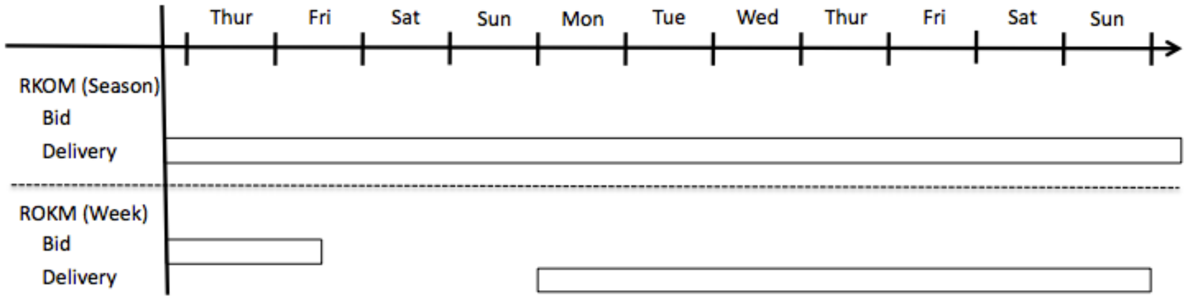

Figure 17: Timeline for trade in RKOM. Own figure based upon (Statnett SF 2012e)

Each year the seasonal market is operated for the period that Statnett needs, usually in the period between weeks 45 to 16. The bids in the seasonal market are made for the entire season, but the time interval of usage per day is only in the hours between 05:00 and 24:00. (Statnett SF 2012e)

The week-based market is run from week to week, if there is a need. Trade closes Fridays at 12:00 and provides bids for the following week. The bids are divided into night (00:00 - 00:05) and day (05:00 – 24:00) for each day of the week. (Statnett SF 2012e)

3.2.5. Bilateral agreements for manual reserve capacity

In addition to ensuring sufficient bids for manual reserves through RKOM, Statnett also enters into additional long-term bilateral contracts with producers, binding them to deliver bids in RKM. The contracts are usually a result of a two-way deal, where Statnett has assisted financially in upgrading production capacity at the producer's plants and the producers have agreed to provide manual reserve capacity. (Statnett SF 2013)

3.3. Alternatives to using reserves

The pre-planned obligations of producers and consumers for production and consumption of electricity follow from the contracts entered into in ELSPOT, ELBAS as well as bilateral contracts. This determines the pre-planned energy balance. Reserves must be used to handle energy imbalances, if they occur. The market system may to some extent give incentives that reduce the need of reserves, for example by charging participants for deviations between real delivery/production and the contract obligations. Unfortunately, it is impossible to eliminate all system imbalances. An important question is, however, whether market system conditions or market design can be altered to further improve frequency quality, and reduce the need of balancing services? We must first define the main challenges that cause a falling frequency quality, in order to answer this question.

4. Challenges of keeping a stable frequency

Decreasing frequency quality has been a growing concern for Statnett the last ten years. This chapter identifies three main challenges where we believe improved market design can contribute to an enhanced frequency quality of the system. Firstly, the system is especially vulnerable at times of large and rapid load changes, in particular occurring in the morning and in the evening (Statnett SF 2012b). Secondly, scarcity of sufficient rotating reserves seems to be an increasing and upcoming problem, this especially occurs in the spring and summer, when the electricity system is often run as a “light system” (Statnett SF 2012b). Thirdly, increased future wind power in the system also represents a threat to future levels of frequency(Nilssen, et al. 2010) (Brooker 2012). These challenges are further explained and discussed below, pointing to possible solutions of market design that can contribute to improved frequency quality.

4.1. Rapid load changes

Rapid load changes can cause severe problems for the system balance, as it can be difficult to adjust production at the same rate. The two periods with the largest load changes are in the morning and in the evening, mainly for two reasons:

- Consumption increases in the morning and decreases in the evening.
- The interconnectors often ramp from import to export in the morning, and from export to import in the evening.

The two load changes have the same “direction”, i.e. with an increase in load in the morning, and a decrease in total load in the evening. Thus, both enforce the load change. This is in contrast to countries interconnected with Norway. Here ramping has an absorbing effect on the load changes from consumption, thereby making energy balancing easier.

The problem can easily be identified by looking at Figure 18. Here are frequency deviations displayed in minutes for a year, shown for what part of the day they occur. The graph gives us a clear image of the stipulated problem. A significant share of frequency deviations occurs in the morning and evening and the frequency deviation throughout the day are around the hourly shifts as the pattern in the figure indicates (It can be difficult to recognize from the figure but the spikes that occur each hour are around the hourly shifts). (Statnett SF 2012b)

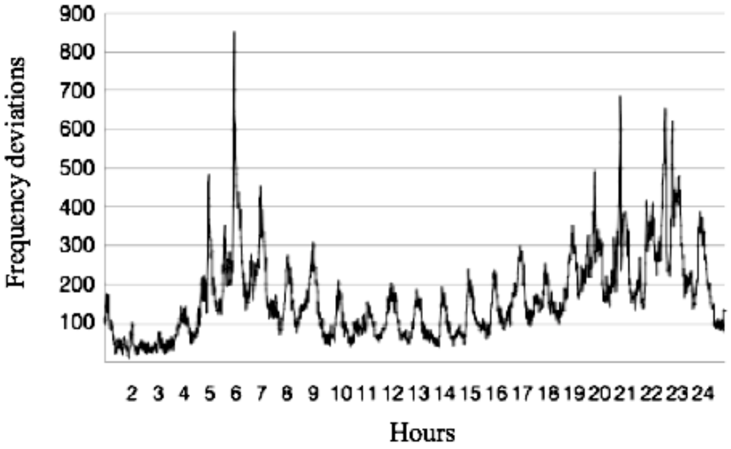

Figure 18: Frequency deviations over one day. (Statnett SF 2012b)

Rapid load changes cause frequency deviations because the system is not optimally designed to handle them. Hence, the load changes must be handled by reserves when they should have been handled by the systems design. The frequency deviations occur most frequently around the hourly shift. This is mainly because the contracts defined in the spot market and the intraday markets are hourly contracts. Thus the market is cleared by 60-minute units, implying planned changes around the hour. In contrast, however, the actual load changes continuous. (Statnett SF 2012b) This implies that the imbalances that occur between the implied production by contracts on one hand and actual consumption on the other, can be large when the load changes are rapid.

Chapter 5 discusses this problem introducing two interlinked solutions:

- Redefining contracts in the markets for planned traded to cover shorter delivery periods may contribute to better align production with consumption.
- Changing the ramping rules of interconnectors may ease and absorb consequences of load changes on the interconnectors.

Both these suggested changes in market design are envisaged to make the system better able to handle rapid load changes than within the current system.

In addition, measures to promote a more flexible demand may also offer opportunities for a better balance of supply and demand, thus also contributing to a more stable frequency and less demand for reserves. This is the topic of chapter 7.

4.2. Light system operation

In order to be able to deliver down-regulating reserve capacity in RKM and rotating reserves in the markets for FCR and FRR, the flexible power plants must be actively producing electricity. However, there might occur situations where the production mix in the system consists of little flexible production. This is characterized as a "light" system operation. Increased instances of light system operation becomes a problem because the system thus is less robust to handle energy imbalances. The result is decreasing frequency quality. (Statnett SF 2012b)

Light system operation can occur in the spring after snow melting starts and in the summer. It happens most often in the night, when demand is low and when there can be cross border import. Both supply and demand factors in the markets for planning cause light system operation, as displayed in Figure 19.

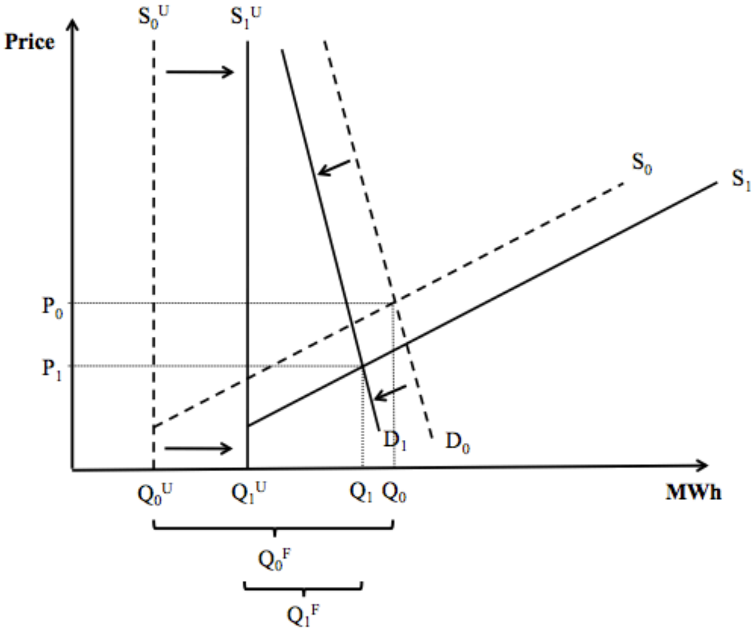

Figure 19: Demand and supply shifts lead to light system operation. Own figure.

- Consumption falls in the spring and summer, given an inwards shift in the demand curve from D_0 to D_1.
- The unregulated producers supply curve shifts outwards from S_0^U to S_1^U, given higher water inflow to their pathways. The curve is inelastic because the producers are unregulated and their production will not be affected by price. The aggregated supply curve shifts from S_0 to S_1.

- Prices fall from P_0 to P_1.
- Total production falls from Q_0 to Q_1. Since unregulated production is increased from Q_0^U to Q_1^U, flexible production will decrease production from Q_0^F to Q_1^F.
- The outcome is light system operation with a lower level of rotating reserve capacity and lower down-regulating capacity for manual reserves.

Wind power production and cross border trading capacity are both expected to increase in the future. By doing so is the unregulated supply curve shifted out. This will further increase the challenge of light system operations in the spring and summer. (Statnett SF 2012a)

Light system operation is a threat to frequency quality because the system becomes less robust to handle energy imbalances. One measure to ease this problem, seen from an economic perspective would be to increase the available reserve capacity. Chapter 6.3.4. presents the solution of introducing down-regulating capacity options in RKOM for the spring and summer. The measures in 5.1 and 5.2 will also have a positive effect for the situation of light system operation. This is because more reserve capacity will be made available by implementing the suggested changes in market design.

4.3. Unpredictable wind power

Wind power producers can only to a limited extent control their actions since wind power is both unregulated as well as highly unpredictable. This causes a great threat to frequency quality in three ways: (Statnett SF 2012a) (Statnett SF 2012b)

- Wind power production is dependent upon wind, which cannot be forecasted accurately. Thus, bids from wind power in the markets for planning are only rough estimates of what production will be. The difference between traded and actual production quantities thus creates imbalances that must be handled.
- Wind power will increase balancing problems under light system operation. They will lead to lower levels of flexible production, and at the same time to more system imbalances.
- Wind power production will seize reserve capacity to handle deviations between actual production and contracted supply in markets for planned traded, as well as to handle real-time imbalances. For a given reserve capacity, there will thus be relatively less capacity to handle energy imbalances caused by other factors, making the system less robust.

Increasing wind production may thus also contribute to a falling frequency quality if not dealt with in a proper manner. Chapter 6 discusses possible solutions to reduce imbalances caused by the deviation between actual and contracted delivery that are caused by forecasting error form wind power. More reserve capacity will then be available to handle other sources of frequency deviations. We discuss various solutions to handle wind power, including:

- Providing a more efficient intraday market with trading closer to the operating moment.
- Introducing wind power brokers.
- Introducing shorter trading units in the markets for planned trade
- Introducing down-regulating options in RKOM.

As mentioned above, also the measures discussed in relation to rapid load changes and light system operation in chapter 5, will ease the handling of increased wind. This also applies to increased flexibility of demand, as discussed in chapter 7. Flexible demand can open for new solutions in the energy system in the future and it can contribute to providing a better frequency quality by addressing all of the three challenges that this thesis stipulates.

5. Market design: Trading units and ramping rules

Statnett (2012b) highlights that frequency deviations often occur during times of large changes in load, and thus often around hourly shifts. Some of the main reasons for this are related to consumption and ramping as discussed in chapter 4. The key question of this chapter will be how the market design can improve in order to handle the challenges. Here we discuss two solutions: i) the size of trading units in the two markets for planned trade, and ii) the ramping rules on the interconnectors. In this respect, note that the term structural imbalances refers to imbalances that occur due to limitations of market design. (Statnett SF 2012a)

5.1. Trading units in the markets for planned trade

An optimal market design would imply that supply and demand could be cleared continuously based on all relevant information at all time. However, this is not possible in real life, given the constraints of physical laws as well as constraints related to provide viable markets for trading electricity. The market design partly represents ways to handle the physics of the system and adjust the market to the systems needs. The choice of a 60-minute based trading unit the spot- and intraday market is one of these constraints.

5.1.1. 60-minute trading units

In the two markets for planned trade, ELSPOT and ELBAS, electricity is traded in units covering an hour, i.e. 60-minutes. This implies that prices, quantities and balance settlements are done for each hour as a whole. The settlements thus do not address any movements or load changes within the hour, which of course are continuous. This implies that there can be significant structural imbalances within one hour, even if the market is in balance over the 60-minute period. Figure 20 is used for the purpose of showing how the market clearing quantities will deviate from the actual consumption, given today’s market design. (Statnett SF 2012a)

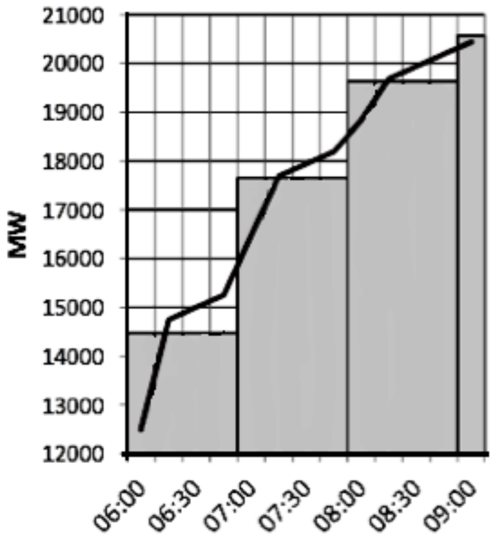

Figure 20: Market cleared consumption for 60-minute units and actual consumption. The figure is constructed for illustrational purposes but based on actual data. (Statnett SF 2012a)

The figure is constructed by Statnett (2012a) as a theoretical example and shows a market cleared in 60-minute trading units (the columns) and actual consumption (the line). The difference between the two is structural imbalance, created because the market is not cleared on continuous basis. The imbalances has to be eliminated in order to at all times ensure the right energy balance in the system. Statnett organizes this in two ways:

- By moving production with up to 15 minutes from what's determined in the production plans of the producers. This is, however, not necessary an economically optimal solution because Statnett does not have sufficient information to move production in a cost efficient way.
- By using reserves when imbalances occur. This implies that less reserve capacity will be available to handle imbalances caused by other factors. The result is the need of more reserves, or alternatively a less robust system, which will contribute to decreased frequency quality.

5.1.2. 15 minute trading units

As an alternative to trade and settle by 60-minute trading units in the markets, trade and settlement could alternatively be based on 15-minute units. The main advantage of using shorter units can be seen by looking at Figure 21. This figure is based upon the same theoretical example as Figure 20, and the same data is used. The difference is that, in this example is, the market cleared in 15-minute units. The result is that market clearing quantities follows the actual consumption much closer. Therefore the structural imbalances are decreased, contributing an improved frequency quality. This is partly due to less imbalances, and partly because less reserve capacity is used to handle structural. Using shorter trading units thus also reduces frequency deviations around hourly shifts.

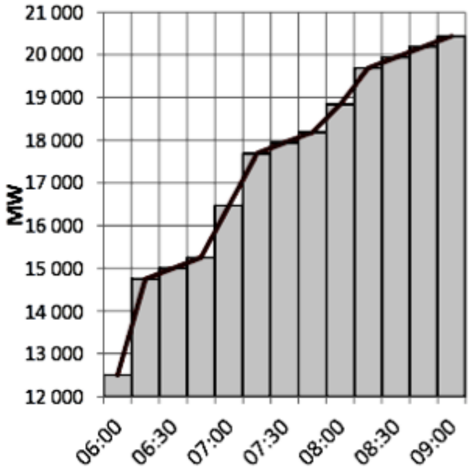

Figure 21: Market cleared consumption for 15-minute units and actual consumption. (Statnett SF 2012a)

Statnett uses the enrolled production plans today and moves production manually with up to 15 minutes in order to try to eliminate the structural imbalances caused by 60-minute trading units. By organizing trade and settlement by 15 minute units, the market will take over some of this balancing work and do it automatically and in a cost efficient way.

5.1.3. Additional advantages from implementing 15-minute trading units

Frequency quality will be improved by changing the trading units in the markets for planning because structural imbalances will be decreased. However, the change in market design also holds three other desired advantages:

- 15-minute trading units represents a step towards a more real time market solution, where the market is cleared more often. This will give more correct prices within the hour, since trade can be made on a more accurate level. (Statnett SF 2012a)
- Compared to the alternative of 60-minute trading units, a 15-minute based trading market reduces structural imbalances. This is in effect probably done better than the current alternative where Statnett exercises production movements manually. This is based on the assumption that Statnett does not have all required information to move production in an economically efficient way. (Statnett SF 2012a)

- 15-minute units will enable us to redefine the current ramping rules and apply continuous ramping. This will imply important advantages, both from an economic perspective and from the perspective of improving frequency quality. (Statnett SF 2012a) The subject will be discussed further in chapter 5.2.

Lastly, an interesting question is why we have focused on 15-minute trading units in particular. In principle, building on the arguments above, even shorter trading units, such as 10-, 5- or even one-minute trading units could represent a more efficient market solution. Likewise, a further question is why not try 45-, 30- or 20-minute units before we scale all the way down to 15? The questions are legitimate. Though they are not covered in this thesis, they should be addressed. Our discussion reflects principle arguments for reducing the trading unit, arguments that apply to all trading units less than an hour. For example, the discussion highlights the important aspect of how the implementation of shorter trading units such as 15-minutes significantly reduce the structural imbalances in the market.

5.1.4. Challenges when implementing 15-minute trading units

There are however several challenges connected to changing the trading and settlement units in the system:

Firstly is the political -and law interconnection with Europe. Norway and the Nordic synchronous system are closely interlinked with the rest of Europe through the EU, EEA and the organization ENTSO-E, which is a joint organization for European TSOs. The EU has the intention of a common European law for the power system, including rules of market design. (European Commission 2012) This implies that the EU most probably must decide upon 15-minute trading units in order for the Nordic power market to implement the design. Statnett can, through lobbying activities, try to make the EU adapt the market solution. They do however have limited actual power to change market design. (Statnett SF 2012a)

Secondly, changes in the market design of the day-ahead and the intraday markets also affect the design of the markets for ancillary services. (Nilssen, et al. 2010) If trading units are reduced to 15-minutes, this also has to be done in the day-based market for FCR and in RKM. It will not be practical to only have the possibility to trade in these ancillary service markets on hourly basis, if one already has made varying obligations within that hour in the markets for planning. RKM in addition uses the spot market price as information input.

Thirdly, there will be a need for better measuring devices in the power transmission system if 15-minute trading units were to be implemented. This would imply a major one-time investment. (Statnett SF 2012a)

5.2. Ramping rules

Ramping of the interconnectors occurs when the load on the cables is changed. This is most often done when the cables are turned either from export to import, or from import to export. Ramping often involves large load changes for the energy system since the interconnectors have high transmission capacities. Statnett has imposed ramping rules, which limits ramping to a specific speed and time period. This is in order to protect the power system, ensuring that it is able to accommodate these large changes in load. To a large extent the rules reflect the current market design. However, if trading and settlement units of the system were shortened for example from 60 to 15 minutes, this would give Statnett the opportunity to change current ramping rules. This can help improve frequency quality and have desired economic effects.

5.2.1. Current ramping rules

The ramping restrictions we have today have two important limitations (Statnett SF 2012b):

- Ramping can only be carried out in the twenty minute period of ten minutes before the hourly shift to ten minutes past the hourly shift.
- Maximal ramping speed is 30 MW/min.

Figure 22 shows a simplistic example of structural imbalances due to ramping, given the current market design. Contracted obligations of production discretely change from hour to hour. Focusing only on the need of ramping, the change of load on the cable (ramping) occurs continually within the twenty minute period around the hourly shift. The difference between these is the structural imbalance due to ramping. Structural imbalances occur because the interconnector starts to ramp ten minutes before hour shift, but the production changes in accordance with the market. In Statnett SF 2012a we calculated the maximal imbalance size to 300 MW per cable for the current ramping restrictions.[5] (Statnett SF 2012a)

---

[5] The calculation was done by the author of this thesis as part of Statnett SF 2012a. See Appendix I. for calculation, assumptions and method.

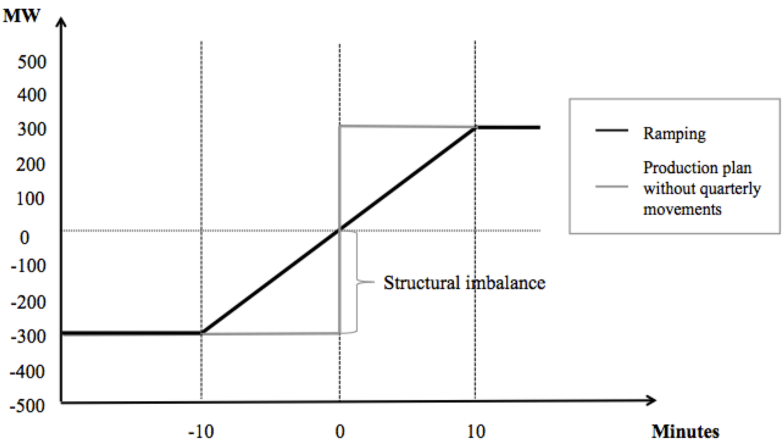

Figure 22: Structural imbalances with 60-minute trading units and current ramping restrictions. (Statnett SF 2012a)

5.2.2. Continuous ramping

Continuous ramping implies that ramping is done as a continually ongoing process within the whole hour, i.e. not limited to 20 minutes for each hour. This can contribute to decreasing structural imbalances, if implemented alongside with 15-minute trading units in the markets for planned trade. Figure 23 shows a simplistic example, similar to the one in Figure 22, using 15-minute trading units and a continuous ramping speed of 20 MW/min. The maximal structural imbalance is reduced to 150 MW looking at the same time period as above.[6] It is possible because the market is cleared for one quarter at the time and therefore is able to handle load changes from ramping in a better way. (Statnett SF 2012a)

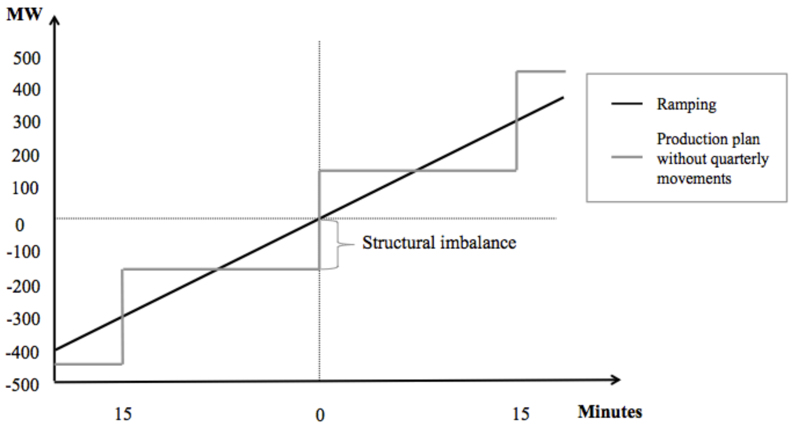

Figure 23: Structural imbalances with 15-minute trading units and continuous ramping. (Statnett SF 2012a)

---

[6] The calculation is done by the author of this thesis as part of Statnett SF 2012a. See Appendix I.

The structural imbalance also depends upon the chosen ramping speed. Table 2[7] shows the structural imbalances of this example using 15-minute trading units and continuous ramping, calculated for different ramping speeds. We see that these solutions offer lower structural imbalances for all speeds than what is possible with today's market design. The example has illustrated the principal effects of continuous ramping, reduced trading units, and different ramping speeds. Note however that further analysis is necessary to find an optimal solution. As for now can we only conclude that continuous ramping will provide better frequency quality, by making the load changes from ramping easier to handle. (Statnett SF 2012a)

Structural impalances given a quarterly based market with continuous ramping	
Ramping speed	Strucutral impalance
30 MW/min	225 MW
20 MW/min	150 MW
15 MW/min	112,5 MW
10 MW/min	75 MW

Table 2: Structural imbalances for different ramping speeds. (Statnett SF 2012a)

5.2.3. Additional advantages from implementing continuous ramping

Continuous ramping, even at lower speeds than 30 MW/min, provides higher total ramping over the hour, thus in effect increasing the transmission capacity available. As such, the economic gains from implementing continuous ramping can be large. Using the ramping rate of 20 MW/min as an example, Figure 24[8] shows how the capacity of an interconnector better can be utilized with continuous ramping, compared to today's ramping (Statnett SF 2012a). We can see that this solution offers more available capacity since the whole hour can be utilized for ramping and not only 20 minutes.

---

[7] The calculation was done by the author of this thesis as part of Statnett SF 2012a. See Appendix I.

[8] The figure was made by the author of this thesis as part of Statnett SF 2012a. See Appendix II.

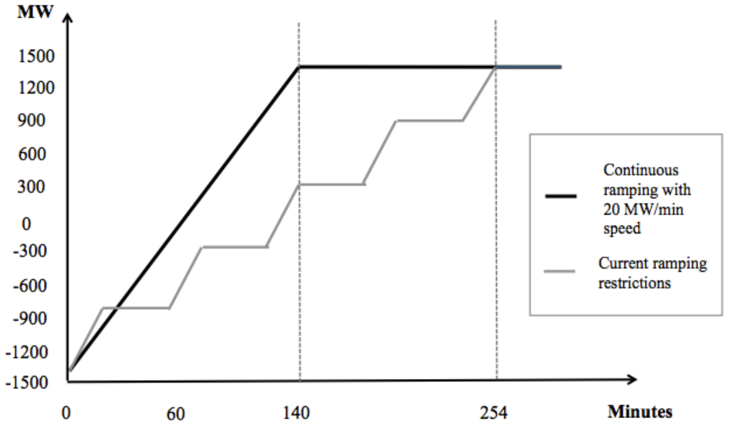

Figure 24: Ramping of an interconnector using continuous ramping speed of 20 MW/min and today's ramping rules. (Statnett SF 2012a)

Table 3[9] displays changes in capacity utilizations, using the current market solution and ramping restrictions as a reference. Continuous ramping can give significant increases in capacity usage, even for low ramping speeds. (Statnett SF 2012a) To estimate the specific economic gains from increased interconnector capacity, however, further research is required.

Continuous ramping	**Change in used capacity, given todays solution as a referance**	
	Percentage	MW
30 MW/min	78,21 %	2133
20 MW/min	58,25 %	1589
15 MW/min	38,29 %	1044
10 MW/min	-1,32 %	-45

Table 3: Increased capacity by using continuous ramping, compared with the current ramping restrictions. (Statnett SF 2012a)

5.2.4 Challenges with implementing continuous ramping

There are two major challenges connected to implementing continuous ramping.

- As already pointed out it will not be desirable to implement continuous ramping if the trading units in the markets for planned trade are not shortened. Hereby arises the same challenges as discussed earlier with respect to the development in Europe. (Statnett SF 2012a)
- An interconnector has two landing points and is therefore dependent on the coordination of the two power systems. As an example, it will not be possible for

---

[9] The calculation is done by the author of this thesis as part of Statnett SF 2012a. See Appendix III.

Statnett to implement continuous ramping on the interconnector between Norway and the Netherlands if TenneT[10] does not agree. This might imply that the use of continuous ramping depend upon whether also countries connected to Norway introduce shorter trading units in their markets for planned trade. (Statnett SF 2012a)

---

[10] Tennet is a Dutch TSO, and part owner of NorNed, which is the interconnector between Norway and the Netherlands.

6. Handling wind power production

Wind power producers will increasingly enter the energy system the next few years. Being highly unregulated and a less predictable production source than hydropower, increased wind power poses new challenges for frequency quality. We will look into alternative adjustments of market design that may secure a sufficient frequency quality. To understand the underlying challenges of wind power predictions, section 6.1 starts by discussing aspects of forecasting. The chapter proceeds by arguing that in addition to the use of reserves, additional measures are needed to handle the variations and unpredictability of wind power. Before discussing possible market design solutions that enable a better handling of wind power unpredictability in section 6.3, section 6.2 discusses the solution of how they handle wind power in Germany. This is a country that has invested heavily in wind power the last years.

6.1. Why is wind power production a threat to frequency quality?

Wind power causes system imbalances because the actual production often will deviate from the market commitments given by the traded contracts. According to Lars Fogt Andersen at energinet.dk (the Danish TSO) actual wind power production can often deviate from spot market bids by 30-40% (Karas 2009). These deviations in principle increase the imbalances that must be handled by reserves. We will shortly discuss the challenges of forecasting wind power, as well as the additional strain on reserves that increased wind power creates.

6.1.1. Forecasting wind power

The problem with production forecasts for wind is not connected to the total amount of wind power within one day, but rather at what time wind fronts reach the wind turbines (Karas 2009). This creates problems because producers need to make bids in the markets for planned trade, for all the 60-minute trading units of the delivery day. Thus, forecasting uncertainty leads to deviations between planned and actual production. There are three interesting aspects of wind power forecasting:

- Compared to the forecasts of individual wind parks, aggregated forecasts for wind power can decrease forecast error through the diversity and geographical spread of the wind parks. (Nilssen, et al. 2010) This underlines the importance of understanding the greater picture of wind power production.

- High wind speeds can give rapid load changes in the system, because wind turbines have safety limits for excessive wind speeds. (Nilssen, et al. 2010) The result can be that large wind parks may go from maximal to zero production in a short period of time, thus causing large system imbalances.
- Forecasting error decreases over time as the moment of production closes in. This can be seen in Figure 25. (Nilssen, et al. 2010) Forecasts improves with 2-3% of installed capacity from when the spot market closes and up until the operating moment. This provides interesting features for the trade of wind power production.

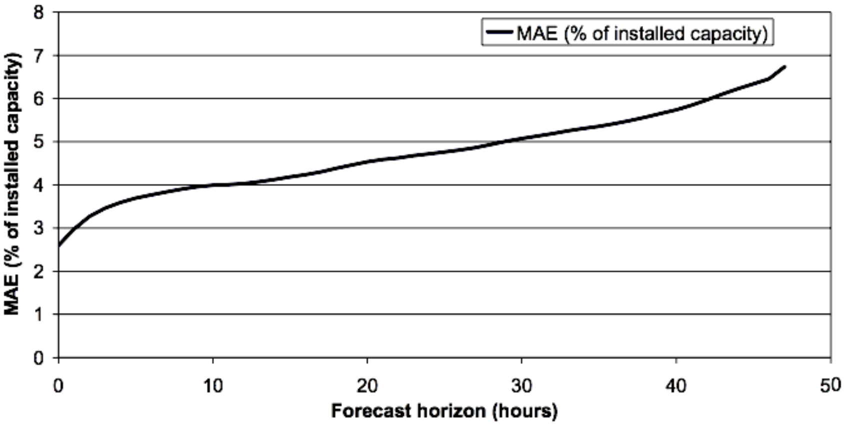

Figure 25: Mean absolute error as % of installed capacity in 2010 for Denmark West (DK1) of the short range forecast. (Nilssen, et al. 2010)

6.1.2. Increased demand for ancillary services

By handling the imbalances created by wind power through the current balancing systems, the system consequently uses reserves to handle frequency deviations caused by wind power production. However, there are two disadvantages of mainly relying on the use of reserves for this purpose:

- Imbalances caused by wind power will increase the use of reserves, thereby utilizing a large part of the available reserve capacity. This implies that less capacity will be available to handle imbalances caused by other factors. The result may be a less robust system, which may contribute to decreased frequency quality.
- Wind power production will also increase the cost of using reserves. Firstly, the increased demand for reserves give higher prices for reserves, given that the markets are cleared using marginal price. Secondly, for a given demand for electricity, wind power production implies a decrease in flexible hydropower production, also in

situations with light system operation. In turn, this will increase the prices for rotating reserves in these periods.

These two disadvantages indicate that we should try to seek additional solutions to handle the balancing problems of wind power production.

6.2. Wind power responsibility

It can be interesting to look at models for handling wind power production in other countries, since the wind power industry in Norway is quite new. Germany is one of the countries in the world that has invested the most in new renewable power production in the recent years, with a total of 6.4% of the nation's electricity produced by wind power in 2010(Federal Minister for the Environment, Nature Conservation and Nuclear Safety 2011).

In Norway wind power producers are responsible for their bids in ELSPOT and ELBAS, as well as for the energy imbalances that occur. Germany, however, has chosen a different model. Here the TSOs[11] are responsible for handling wind power. The TSOs are obligated, by the Renewable Energy Sources (RES) Act of August 1, 2004, to accept and use all production from wind power, and compensate the wind producers for the power they supply accordingly. The payments are predetermined and predictable feed-in tariffs.(Germany Trade and Invest 2013) The wind power producers do not have any market obligations and do not need to make wind forecasts or market bids. Forecasts and production plans becomes the TSOs responsibility even though they do not own or operate the wind turbines. (TransnetBW GmbH 2013)

Alleged arguments for using the German model of handling wind power are:

- The model can increase frequency quality by gathering all responsibility of wind power handling with the TSOs. They will have the opportunity to make production plans on an aggregated basis. By using aggregated forecasts can the TSOs decrease the forecast error as indicated by the research findings of Nilssen, et al. (2010)
- TSOs may have greater opportunities to make investments in good forecasts. Small wind power producers might not have the same investment opportunity, given capital and knowledge constraints. The TSOs can in this way ensure themselves against inaccurate forecasts that create imbalances that must be handled.

---

[11] Germany has four TSOs: TransnetBW (the former EnBW Transportnetze), 50Hertz Transmission, Am-prion and TenneT.

- The TSOs can forecast wind power production right up until the operating moment and make adjustments continuously according to forecast changes, also taking advantage of the decreasing forecasting error over time (Nilssen, et al (2010)).

However, two disadvantages may also be asserted as to this German model of handling wind power:

- The model may not be optimal form an economic perspective. Important economic incentives and information regarding a significant share of total production will be omitted from the market, thereby contributing to the possibility of a non-optimal market clearing.
- Feed-in tariffs provide high and stable prices for producers who have marginal costs close to zero, also affecting the optimality of the resulting market clearing prices.

Davidson (2012) says that the German approach is an example of a scheme where the considerations of physics and political subsidy financing seemingly has been stressed to a larger extent than market efficiency, implicitly undermining the energy market. Based on this, our tentative conclusion is that the German approach to balancing wind power does not seem to be an optimal solution. In stead we will consider other market design adjustments within the Norwegian approach.

6.3. Possible market solutions for handling wind power

We will consider four market solutions that might contribute to a better handling of wind power imbalances, thereby also better ensuring a sufficient frequency quality.

i. Increased trade in the intraday market.
ii. Introduction of brokers for wind power trade
iii. Shorter time units in the markets for planned trade.
iv. Introduce down-regulating options in the option market for manual reserves.

6.3.1. Increased trade in the intraday market

The intraday market is the market where Norwegian market participants can trade up until two hours before operating hour. It thus can be used to alter obligations made in the spot market. The spot market is cleared 12 to 36 hours prior to the operating moment. This implies that a lot of new information occurs between the time of spot market clearing and the time of production. From Nilssen, et al. (2010) have we seen that forecasting closer to the operating moment can reduce forecast error for wind power. Trade in the intraday market can thus contribute to balancing wind power production. Wind power producers can, by trading in the intraday market, act proactive to eliminate forecasting error, as forecasts become more accurate. This will be a more desired solution than Statnett using reserves to act upon imbalances when they occur. By trading in the intraday market can both the need for reserve usage be decreased and the frequency quality improved. There are, however, several problems:

The intraday market today is not liquid, and only holds very limited amounts of trade by Norwegian actors. There are mainly two reasons for this. Firstly, Norwegian energy production today is predictable and easy to control, so trade in the intraday market is seldom needed (Statnett SF 2012a). We might expect this to change, as more unpredictable energy production will enter the system. Secondly is there no market maker in the Norwegian part of the intraday market (Nord Pool Spot 2013f). A market maker is a company that commits to provide both buy and sell orders. As of the end of 2011 was there three market markers in ELBAS, however none of them were responsible for providing bids in Norway.

The gate closure in the intraday market is two hours before operating hour for Norwegian participants**.** However, in 2015 Statnett will decrease gate closure from two to one hour before operating hour. This may increase domestic trade in the intraday market for two reasons:

- Information improves significantly between two and one hour before operating hour. (Nilssen, et al. 2010) This gives the market participants more accurate information to trade upon.
- Approximately 40% of trade in ELBAS occurs in the last hour of trade before the market closes (Statnett SF 2012a). This trade is by non-Norwegian actors since the Norwegian actors are excluded from the market in this period. Allowing them to trade in the last hour will give them access to important market bids.

On this basis we assume that a later gate closure will benefit the efficiency and liquidity of the intraday market. As the TSO is dependent upon time for load planning after the market is closed, however, a later gate closure adds further challenges for the TSO. (Statnett SF 2012a) This is also an issue in the discussions of possible gate closure even closer to the time of delivery. In this respect, it might be that future technological development can decrease the need for planning time.

Bids by wind power producers in the intraday market will be highly affected by the marginal costs of imbalances. This is the cost that Statnett imposes on the producers for not being in balance, through the balance settlements. The balance settlements can therefore be seen as important economic incentives for wind power producers to trade in the intraday market. Note that in principle the other participants in the intraday market will be either flexible hydropower producers or other wind power producers:

- Wind power can trade with other wind power in the intraday market.(Nilssen, et al. 2010)(Statnett SF 2012a) (Mauritzen 2012).
- Flexible hydropower producers do not trade in the intraday market today, mainly because their production is highly predictable and easy to regulate. An important question, however, is whether these hydropower producers will increase their trade in the intraday market when more wind power is introduced in the system. Basically, this will depend on the prices, and the marginal costs of the hydropower producers. Firstly, hydropower producers have an optimal production curve, and a deviation from this would imply efficiency losses. In addition hydropower production has marginal costs of production, including water value. Their compensation for trading in the intraday market must therefore exceed their total marginal cost of changing production. Future trade by hydropower producers thus depend upon the prices in this market, and thus implicitly also upon the balancing costs which motivate wind power trade in this market. From a system perspective, trade in the intraday market is more efficient if the marginal costs of the flexible hydropower producer are lower than the costs of handling imbalances in the balancing market.

These aspects provide the rationale for trade in the intraday market. Further gains in trade may also potentially follow from investments in the transmission grid to the extent it enables trade between wind power producers at different geographical locations with forecast errors that don’t correlate. (Nilssen, et al. 2010).

6.3.2. Rational market participants or wind power brokers?

Rational market participants represent important premises to achieve efficient markets. It might, however, be debated whether all wind power producers can be expected to act professional in the intraday market. Let us therefore categorize the wind power producers in two categories:

- Large power producing companies that have invested in wind power.
- Small-scale wind power producers.

The large power producing companies, like Statkraft and Agder Energi, have good knowledge of the market and can be expected to act as rational profit maximizing companies. It is therefore only a matter of incentives to make them participate in the intraday market to balance their wind power. However, small-scale wind power producers might not have the same professionalism. Even if we assume that they are profit seeking, they might lack the capital or knowledge necessary. There are, however, two reasons why it will be important to get small-scale wind power producers involved in the intraday market:

- We can expect that their spot market bids will not be highly accurate. Thus, they can potentially eliminate large imbalances by trading in the intraday market.
- Wind power trade by wind power producers with opposite implied imbalances implies potential lower costs in offsetting anticipated imbalances. In addition, small-scale producers may be important to provide liquidity in the market.

An implication is that a study of the decision making by small-scale producers could provide important information regarding their market involvement, also advising Statnett and NVE of possible measures to increase market participation of this group. For the reasons discussed above, this may in turn indirectly result in an improved frequency quality.

Small-scale wind power producers might thus to some extent lack knowledge, capital or time to trade in the markets for electricity. One solution to this problem can be to encourage brokers that act on behalf of small-scale producers in the spot and intraday market. These brokers can specialize in trade of wind power production and trade on an aggregated level. This provides two main advantages:

- The brokers can invest in good wind forecasting tools achieving economics of scale since they act on behalf of several producers.
- The brokers bids in ELSPOT and ELBAS can to some extent be aggregated for producers in the same area. As Nilssen, et al. (2010) presented will this give the opportunity to decrease forecast error.

6.3.3. Shorter trading units in the markets for planned trade

Reducing the trading units to 15 minutes in the markets for planned trade was discussed in chapter 5. This can provide two desired effects for handling wind power production. Firstly, we argued that by introducing 15-minute trading units less resources and reserves are used on structural imbalances from hydropower production and ramping. A consequence is that for a given capacity of reserves, more reserves will become available for wind power. Secondly will 15-minute trading units provide wind power producers with the opportunity to trade in the intraday market more often and closer into the operating moment. (Nilssen, et al. 2010)

6.3.4. Down-regulating options in RKOM

Light system operation, partly due to the introduction of more wind power, implies that the system stands less robust to handle frequency deviations. This is because in times of more wind power production, less flexible hydropower facilities are operating. Flexible hydropower producers, however, must produce in order to be able to deliver down-regulating capacity and rotating reserves. More specifically, this implies that increased wind production may imply even more shortage of down-regulating capacity in the spring and summer than the case is today. A future challenge will then be to ensure sufficient down-regulating capacity in the market for manual reserves

The available capacity in the RKM market depends upon the bids from producers. Today, in the strained winter months, the RKOM market has been implemented to provide sufficient up-regulating capacity. This is done by the trading of up-regulating capacity options. Increased wind power production however may imply a scarcity of down-regulating capacity in times of large wind power production.

A proposed solution to provide sufficient down-regulating capacity in RKM will then be to introduce options for down-regulating capacity in RKOM, making this market operational in the spring and summer when the problem of light system operation is most crucial. This will both provide down-regulating capacity for manual reserves and at the same time offer rotating reserve capacity since the flexible producers must have running plants to offer down-regulating manual reserves. In this way can the system become more robust to handle light system operation in a future energy system with more wind power production.

7. Flexible consumption

In addressing the frequency quality of the system, we have addressed issues of production as well as cross-border trading. Implicitly, we have assumed that consumption is unregulated. However, we will briefly in this chapter also point out the potential of flexible consumption in maintaining the quality of frequency.

7.1. Advantages of flexible consumption

Consumption has historically been assumed as unregulated. This is partly because the largest share of consumers are small-scale and do not trade directly in the organized markets, nor are directly affected by the balancing markets. However, Smart Grid solutions and flexible demand are foreseen to be a vital part of the future energy system, thus being the subject of research and testing at a current basis.(Statnett SF 2011c)

Flexible demand can offer important advantages for the energy balance by providing a more even load pattern within the day:

- It can decrease rapid load changes in the morning and evening and thereby frequency deviations that occur in these periods.
- It can contribute to the supply of reserve capacity in peak demand periods by offering up-regulating reserves in RKM.
- It can contribute to the supply of reserve capacity during light system operation by offering down-regulating reserves in RKM.
- It can contribute to less congestion in the transmission grid.

We will discuss flexible demand separately for industrial and small-scale consumers, as they are different in their market involvement and flexibility potential.

7.1.1. Industrial flexible demand

Industrial consumers have a stable and predictable demand. However, they can, given their size, be important contributors to providing a better energy balance. IPA Consulting, Econnect Ltd and Martin Energy (2006) indicate that flexible demand from industrial consumers is one of the most important technical developments for the power system in Great Britain for the future. They highlight that flexible demand can contribute to fill the increasing demand for manual reserves resulting from a shift from thermal to wind production.

There can be two ways to organize flexible demand from industrial consumers:

- Consumers can make manual reserve bids directly. Some Norwegian actors do this today in peak demand hours. However, most of them can only supply one or two hours at a time. (Statnett SF 2012b)
- The most common way, however, is that an agent makes agreements with several industrial consumers and bids on their behalf in the market for manual reserve on an aggregated level (Statnett SF 2011c). The agreements can be customized to the companies needs.

An important question, however, is whether there are incentives for the industrial consumers to supply manual reserves. Their marginal costs are related to the costs of changing their own production plans, or of using alternative back-up power sources. The ability to supply this flexibility may also require specific investments. If sufficient compensation is only available for some periods of a year, this can lead to the actors not contributing to the market at all, in particular when income is needed to cover these investments. However, the prices for reserves are expected to increase in the future (Statnett SF 2012a) (Pöyry management consulting 2011). This might be enough to make more large-scale consumers participate in the market. Thus the supply of reserve capacity by these consumers are highly dependent upon the economic incentives provided by the system.

7.1.2. Small-scale consumers and smart grids

Small-scale consumers have a volatile load pattern over the day and are in principle highly inflexible and unregulated. However, this can be expected to change with the introduction of smart grids. Smart grids can be defined in several ways, since the concept does not originate from one specific technology (Statnett SF 2011c). NVE (2011) uses the following definition:

> *"A Smart Grid is an electric power network that utilizes two-way communication and control-technologies to cost efficiently integrate the behaviour and actions of all users connected to it – in order to ensure an economically efficient and sustainable power system with low losses and high levels of quality, security of supply and safety."*

This definition holds promising aspects for the future energy system. However, there are key economic mechanisms that need to be designed properly in order to extract all potential of this technology.

The main idea of flexible consumption is to make the demand curve more elastic, thereby making consumer actions more affected by prices. By doing so, a more elastic demand may result in a more even consumption pattern within the day. However, this implies that adequate information is channeled to the consumers. Here we will only briefly note two major ways that that flexible demand can been organized for small-scale consumers:

- Small-scale consumers can adjust their consumption to real prices individually, manually or automatically. For example can hot water tanks be disconnected for a number of hours or the washing machine can be run in the night instead of the day. This may contribute to shaving peak loads, also making the consumption pattern less volatile. However, in this case the consumers will not operate as reserve capacity, only as price sensitive consumers.
- Statnett (2011c) indicates that flexible consumption will be most efficient if done by aggregators with the possibility to disconnecting consumers. The consumers are compensated both for their supply of capacity and for actual disconnections. In this case, the aggregated actions of consumers can be used as reserve capacity in the market for manual reserves.

It is important to note that the two stipulated arrangements do not exclude each other. Both can be used, and they will both contribute with desired effects for the energy balance.

Smart grid solutions are still in a testing and research phase, but it is expected to become a part of the future energy system (Statnett SF 2011c). It is important that Statnett studies the possibilities that the technology enables. They need to be ready when the technology is sufficiently developed, being able to provide the right economic incentives and necessary real time information, also considering e.g. the effect of different network tariff billing, also with respect to time or load differentiation of the tariffs.

8. Conclusion

Frequency deviations are indicators of frequency quality, which determines the security of power supply in the system. The quality in the Nordic synchronous system has decreased the past ten years. In this paper we have identified three challenges for providing a sufficient frequency quality in the future. The three challenges have been addressed so that possible solutions based on economic incentives, could be presented:

- Rapid load changes cause structural imbalances and frequency deviations, mainly around hour shifts. This challenge can be addressed by implementing shorter trading units in the markets for planned trade and continuous ramping on the interconnectors.
- Light system operation makes the system less robust to handle frequency deviations. Down-regulating options for manual reserves can increase bids in RKM and thereby provide more available capacity.
- Wind power production is unregulated and hard to forecast. This can be addressed by increasing trade in the intraday market, introducing brokers for wind power, implementing shorter trading units in the markets for planning and implementing down-regulating options for manual reserves.
- Flexible demand can in addition contribute to increased frequency quality by providing manual reserves and a more even load pattern.

It is important to note that the solutions purposed will not alone eliminate the challenges of energy imbalances. Economic, technical and political factors will influence the frequency quality and must all be researched in great detail.

References

Brooker, C. (2012, September 22). *Germany's wind power chaos should be a warning to the UK.* The Telegraph. Retrieved February 16, 2013, from: http://www.telegraph.co.uk/comment/9559656/Germanys-wind-power-chaos-should-be-a-warning-to-the-UK.html

Bye, T. (2003). *On the Price and Volume Effects from Green Certificates in the Energy Market.* Statistics Norway (SSB). Retrieved February 2, 2013, from: http://www.ssb.no/a/publikasjoner/pdf/DP/dp351.pdf

Davidson, O. G. (2012, November 12). *German Law Gave Ordinary Citizens a Stake in Switch to Clean Energy.* InsideClimate News. Retrieved February 16, 2013, from: http://insideclimatenews.org/news/20121114/germany-energiewende-clean-energy-economy-renewables-tariff-FiT-solar-wind-biomass-nuclear-utilities-cooperatives?page=3

European Commission (2012). *Internal Energy Market.* Summaries of EU legislation (europa.eu). The European Commission. Retrieved February 25, 2013 from: http://europa.eu/legislation_summaries/energy/internal_energy_market/index_en.htm

Federal Minister for the Environment, Nature Conservation and Nuclear Safety. (2011). *Renewable Energy Sources in Figures National and International Development.* Federal Minister for the Environment, Nature Conservation and Nuclear Safety. Retrieved March 06, 2013, from: http://www.erneuerbare-energien.de/fileadmin/ee-import/files/english/pdf/application/pdf/broschuere_ee_zahlen_en_bf.pdf

Germany Trade and Invest. (2013, March). *Germany's Wind enerGy industry.* Germany Trade and Invest. Retrieved March 14, 2013, from: http://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Fact-sheets/Energy-environmental/fact-sheet-wind-energy-in-germany.pdf

Hope, E. (2011, February). *Vindkraft og vannkraft.* Magma, p. 57-65. Retrieved from: http://www.magma.no/vindkraft-og-vannkraft

IPA Consulting, Econnect Ltd & Martin Energy. (2006). *Reducing the Cost of System Intermittence Using Demand Side Control Measures.* IPA Consulting, Econnect Ltd & Martin Energy. Retrieved March 11, 2013, from http://www.flexitricity.com/file/56721004-01%20DTI%20Demand%20Side%20Flexibility%20DTI%20format.pdf

Karas, M.-A. (2009). *Balancing the power system.* Green thinking in Denmark, p. 14-15. energinet.dk. Retrieved March 16, 2013, from: http://energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Klimaogmiljo/Wind%20power%20magazine.pdf

Mauritzen, J. (2012). *Now or Later? Trading wind power closer to real-time and how poorly designed subsidies lead to higher balancing costs.* NHH Norwegian School of Economics, Department of Business Economics.

Nilssen, G., Uusitalo, J., Olesen, O., Mortensen, P., & Sigelfeldt, P.-I. (2010, August 31). *Impact of increased amounts of renewable energy on nordic power system operation.* ENTSO-E (European Network of Transmission System Operators for Electricity). Retrieved February 22, 2013, from: http://www.stateofgreen.com/Cache/db/db157fbd-4d3b-4350-b3d1-f0e87347d17b.pdf

Nord Pool Spot. (2013a, January 24). *Market data.* Nord Pool Spot. Retrieved January 24, 2013, from: http://www.nordpoolspot.com/Market-data1/Power-system-data/Consumption1/Consumption/ALL/Hourly1/

Nord Pool Spot. (2013b, January). *EUROPE'S LEADING POWER MARKETS.* Nord Pool Spot. Retrieved January 27, 2013, from: http://www.nordpoolspot.com/Global/Download%20Center/Annual-report/Nord-Pool-Spot_Europes-leading-power-markets_Jan2013.pdf

Nord Pool Spot. (2013c). *About us.* Nord Pool Spot. Retrieved February 08, 2013, from: http://nordpoolspot.com/About-us/

Nord Pool Spot. (2013d, February 08). *Ukemarkedet.* Nord Pool Spot. Retrieved February 08, 2013, from: http://www.statnett.no/no/Kraftsystemet/Markedsinformasjon/Frekvensstyrte-reserver/Ukesrapport/

Nord Pool Spot. (2013e, April 28). *Prices in ELSPOT.* Nord Pool Spot. Retrieved April 28, 2013, from: http://www.nordpoolspot.com/Market-data1/Elspot/Area-Prices/ALL1/Hourly/

Nord Pool Spot. (2013f). *Market makers ELBAS.* Nord Pool Spot. Retrieved May 17, 2013, from : http://www.nordpoolspot.com/Global/Download%20Center/Elbas/Market-makers-Elbas.pdf

NVE (Norwegian Water Resources and Energy Directorate). (2011, September). *Smart Grid-What is it and what is it not.* NVE. Retrieved March 11, 2013, from: http://www.dnv.com/binaries/dnv_smart%20grid%20pos%20paper_tcm4-470614.pdf

Olje- og energidepartemenet. (2012a, March 05). *NOU 2012:9 - Energiutredningen – verdiskaping, forsyningssikkerhet og miljø.* Olje- og energidepartementet. Retrieved January 24, 2013, from: http://www.regjeringen.no/nb/dep/oed/dok/NOU-er/2012/nou-2012-9/4.html?id=675435

Olje- og energidepartementet. (2012b). *Elsertifikatordningen*. (O. Berthelsen, Editor). Olje- og energidepartementet. Retrieved January 24, 2013, from: http://www.regjeringen.no/nb/dep/oed/tema/fornybar-energi/hva-er-gronne-sertifikater.html?id=517462

Olje- og energidepartementet. (2012c, March 02). *Meld. St. 14 (2011–2012). - Vi bygger Norge – om utbygging av strømnettet.* Olje- og energidepartementet. Retrieved April 15, 2013, from: http://www.regjeringen.no/nb/dep/oed/dok/regpubl/stmeld/2011-2012/meld-st-14-20112012/2/4/2.html?id=673826

Olje- og energidepartementet. (1998, July 03). *NOU 1998: 11 Energi- og kraftbalansen mot 2020.* Olje- og energidepartementet. Retrieved January 27, 2013, from: http://www.regjeringen.no/nb/dep/oed/dok/NOU-er/1998/NOU-1998-11.html?id=141308

Pöyry management consulting. (2011, March). *The challenges of intermittency in North West European power markets.* Pöyry management consulting. Retrieved April 20, 2013, from: http://www.poyry.com/sites/default/files/imce/files/intermittency_-_march_2011_-_energy.pdf

Rud, L. (2012, January 31). *LECTURE 5: THE ELECTRICITY SPOT MARKET AND REGULATING POWER MARKETS – DESIGN FEATURES OF THE NORDIC SOLUTION.*

Statnett SF. (2013). *Bilaterale avtaler.* Statnett SF. Retrieved January 13, 2013, from: http://www.statnett.no/no/Kraftsystemet/Markedsinformasjon/Regulerkraftopsjoner-RKOM/Bilaterale-avtaler/

Statnett SF. (2012a). *KUBE 2012 - Systemdrift 2020.* Statnett SF. Retrieved January 10, 2013, from:
http://www.statnett.no/Documents/Jobb_og_karriere/Studenter/KUBE%202012.pdf

Statnett SF. (2012b, April). *System og Markedsutvilingsplan (SMUP).* Statnett SF. Retrieved January 15, 2013, from:
http://issuu.com/statnett/docs/statnett_smup

Statnett SF. (2012c, September 09). *Statnetts Praktisering av Systemansvaret.* Statnett SF. Retrieved February 06, 2013, from:
http://www.statnett.no/Documents/Kraftsystemet/Systemansvaret/FoS%20for%20konsesjonærer/Statnett_FoS_NETT_1210.pdf

Statnett SF. (2012d, July). *Vilkår - anmelding, håndtering av bud og prissetting i sekundærreservemarkedet til Statnett.* Statnett SF. Retrieved February 07, 2013, from: http://www.statnett.no/Documents/Kraftsystemet/Markedsinformasjon/Sekundærreserver/LFC%20Vilkår%20for%20markedRevTilImplementering.pdf

Statnett SF. (2012e, October 01). *VILKÅR for tilbud, aksept og bruk av regulerkraftopsjoner i produksjon / forbruk.* Statnett SF. Retrieved February 07, 2013, from: http://www.statnett.no/Documents/Kraftsystemet/Systemansvaret/RKOM%20VILKÅR_%20sept%202012-endelig.pdf

Statnett SF. (2011a). *Nettutviklingsplan 2011.* Statnett SF. Retrieved January 15, 2013, from: http://www.statnett.no/Documents/Kraftsystemet/Nettutviklingsplaner/Nettutviklingsplan%202011.pdf

Statnett SF. (2011b, April 28). *VILKÅR for tilbud, aksept, rapportering og avregning i Marked for primærreserver.* Statnett SF. Retrieved February 07, 2013 from: http://www.statnett.no/Documents/Kraftsystemet/Markedsinformasjon/Vilkår%20for%20marked%20for%20frekvensstyrte%20reserver%2028-04-2011.pdf

Statnett SF. (2011c, August 12). *KUBE 2011 - Smart Grid og Statnett.* Statnett SF. Retrieved March 11, 2013, from:

http://www.statnett.no/Documents/Jobb_og_karriere/Studenter/SmartGrid%20og%20Statnett.pdf

Statnett SF. (2010, December 22). *Frekvensstyrte reserver.* Statnett SF. Retrieved February 07, 2013, from: http://www.statnett.no/no/Kraftsystemet/Markedsinformasjon/Frekvensstyrte-reserver/

Statnett SF. (2009, September, 28). *VILKÅR for anmelding, håndtering av bud og prissetting i regulerkraftmarkedet (RKM).* Statnett SF. Retrieved Februart 07, 2013, from: http://www.statnett.no/no/Kraftsystemet/Markedsinformasjon/Regulerkraft-RKM/Vilkar/

TechTerms.com. (2011, December 27). *Frequency*. TechTerms.com Retrieved January 18, 2013, from: http://www.techterms.com/definition/frequency

THEMA, Pöyry. (2010). *Challenges for the Nordic Power – How to handle the renewable electricity surplus.* THEMA Consulting Group & Pöyry Management Consulting (Norway) AS. Retrieved April 04, 2013, from: http://www.econ.no/stream_file.asp?iEntityId=4757

TransnetBW GmbH. (2013). *Wind Infeed*. TransnetBW GmbH. Retrieved March 21, 2013, from: http://www.transnetbw.com/key-figures/renewable-energies-res/wind-infeed/

Appendix

I. Calculations of structural imbalances from ramping:

The calculations of structural imbalances are based on the following:

*time of ramping without load changes * ramping speed*

Structural imbalance from ramping with the current ramping restrictions:

*10 minutes * 30 MW/min = 300 MW*

Structural imbalance by using continuous ramping and 15 minute trading blocks:

*(15 minutes / 2) *30 MW/min = 225 MW*

*(15 minutes / 2) *20 MW/min = 150 MW*

*(15 minutes / 2) *15 MW/min = 112,5 MW*

*(15 minutes / 2) *10 MW/min = 75 MW*

The reason why the time period of ramping can be divided by two is that the market is cleared in 15 minute units and continuous ramping is used. The market can therefore be cleared in better adapted steps to follow ramping, as displayed in Figure 23.

II. Calculations and assumptions behind Figure 24:

Assumptions for the calculations:

- The figure is made in excel where one unit is equivalent to one minute.
- The cable has a capacity of 1400 MW. This implies that total ramping to turn the cable from export to import (or the other way) must be 2800 MW.
- Current ramping rules restricts ramping to ten minutes before and after hourly shifts at a speed of 30 MW/min. This gives a total ramping capacity of 600 MW per hour.
- The continuous ramping is done at a speed of 20 MW/min. This provides a total ramping over one hour of 1200 MW.
- Ramping of the cables starts at the same time. This will not necessarily be the case in reality and is done for simplifying purpose. One important effect is that the numbers presented are case specific and cannot be utilized in a general matter.

III. Calculations and assumptions behind Table 3:

- The calculations are based on the same assumptions as for Figure 24, however the continuous ramping speed is changed so that calculations can be made for different speeds.
- The calculations are done as follows:
  - Excel is used to make the two graphs of interest (continuous ramping and current ramping restrictions) at the different continuous ramping speeds of interest.
  - Capacity utilized is calculated per minute and is MW of utilized capacity of the cable. Absolute value is used, meaning that both import and export is positive capacity use of the cable. The cable will therefore start with a capacity usage of 1400 MW and end at 1400 MW, with the total change of 2800 MW. Thus when the cable is turned "half way" the capacity usage is 0 MW.
  - The difference in utilized capacity between the two solutions can be calculated as percentage. Calculations are done as follows:

    (Total capacity utilized by continuous ramping – Total capacity utilized by current ramping) / Total capacity utilized by current ramping
  - The total utilized capacity is measured from when both solutions start ramping until the last is finished.
  - The figure under is taken from Statnett (2012a) and illustrates current ramping restrictions compared to continuous ramping at 20 MW/min. The continuous ramping is done in 140 minutes (2800 MW / (20 MW/min)). Current ramping restrictions will utilize 264 minutes (4 hours with 600 MW/hour and 13,3 minutes at the speed of 30 MW/min).
- The numbers presented are case specific given the assumptions made. They can therefore not be utilized in a general matter.

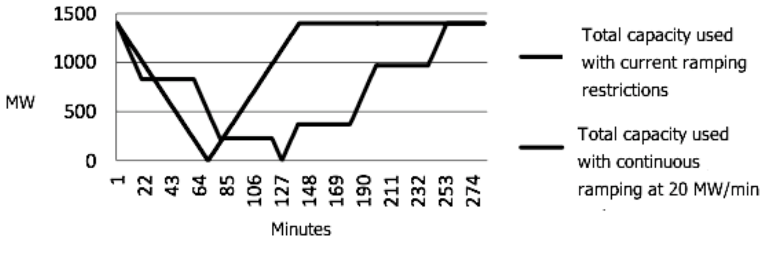

Figure 26: (Statnett SF 2012a)