The market for regulating power in Denmark and possible profitability for Norwegian hydroelectricity producers

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Master Thesis 30 credits 2013

Preface

This thesis represents the end of five years as a student at Trondheim Business School and Norwegian University for Life Sciences in Ås. During the last two years in Ås, I have had the opportunity to make good use of my degree in finance from Trondheim while majoring in Energy Economics.

I want to thank the people who have helped me finish this thesis. My two mentors here at the university, Eirik Romstad and Olvar Bergland have been invaluable. Also, my father Inge Stølen, and my fellow student Cecile Wold have been great help, both for moral support and technical advice.

May 2013

Ingvild Stølen

Abstract

The EU has decided upon a common goal that 20% of its energy should come from renewable power sources within the year 2020. Producing this energy is not considered difficult by itself, but the resources for production often are stochastic in nature, such as winds and solar power. Balancing the production to demand represents a challenge, as it is necessary for energy production and consumption to balance at all times.

Norway's extensive hydro power resources are a possible source for supplying regulating power. The focus of this thesis is to find out more about what happens to the demand for regulating power as the share of wind power increases in a system, represented by Denmark, and if such an increase in demand represents an opportunity for profit for Norwegian hydropower producers.

Data on upwards and downwards regulation, and wind power production has been collected and analysed using Newey-West regressions. The analysis on demanded quantities was based on hourly data from the period of January 2006 to December 2012, while the analyses on prices are based on data from the two years 2011 and 2012. The results are inconclusive, and do not solely support the hypothesis of increased share of wind power leading to increased demand for regulating power. The share of wind power in the Danish power system does to a very little degree explain the demand for regulating power. The analysis on prices points towards regulating power prices declining when introducing wind power. One might from this conclude that the expectations towards future profitability in flexible electricity might be somewhat unrealistic.

Sammendrag

EU har vedtatt et felles mål for sine medlemsnasjoner, om at 20% av elektrisk energy skal genereres fra fornybare kilder innen år 2020. Å produsere denne elektrisiteten er ikke vanskelig i seg selv, men innsatsfaktorene i fornybar elektrisitetsproduksjon er ofte uforutsigbare, som sol og vind. Å få produksjon til å sammenfalle med etterspørselen i tid er derfor en utfordring, i og med at produksjon og forbruk av strøm må balansere til en hver tid.

Norges rike tilgang på vannkraft er en mulig kilde til raskt regulerbar kraft som kan bidra til balansen i systemet. Fokuset i denne oppgaven er å finne ut mer om hva som skjer i et system, her representert av Danmark, når andelen uforutsigbare strømkilder øker. I tillegg undersøkes det om slike endringer kan by på en mulighet til fortjeneste for norske vannkraftprodusenter.

Data på opp og nedregulering samt på vindkraftproduksjon i Danmark har blitt analysert med Newey-West regresjoner. Analysen på etterspurt kvantum er basert på timesdata fra januar 2006 til desember 2012, mens analysene på priser er basert på data fra 2011 og 2012. Modellene som ble estimert på etterspørsel er ikke egnet til praktisk bruk, på grunn av meget lav forklaringsgrad. Resultatene gir ikke klare svar, og de støtter ikke hypotesen om at økt andel vindkraft i et system øker etterspørselen etter regulerkraft. Analysene som er gjort på pris peker mot at økt andel vind i et system kan ha negativ innvirkning på regulerkraftprisene. En kan derfor tenke seg at forventingene rundt framtidig fortjenestemuligheter i regulerkraftmarkedet er noe overvurdert.

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Legend

AC – Alternating Current

BRP – Balance Responsible Party

Dk1 – Nord Pool Price area Western Denmark

Dk2 – Nord pool price area Eastern Denmark

HVDC – High Voltage Direct Current

MW – Mega Watt

No2 – Nord Pool price area Southern Norway

SK 1 -4 – Skagerrak interconnectors 1 through 4

TSO – Transmission System Operator

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Introduction

Several Norwegian electricity producers and politicians have argued in favour of Norway becoming "the green battery of Europe". For such a vision to become reality, major investments need to be undertaken in interconnector capacity between Norway and continental Europe, and some investments may even be needed in Norwegian electricity generating capacity.

Through a detailed analysis on the nature of electricity production and the impacts of increased wind power capacity in Denmark, I seek to shed insights on the wisdom of the "green battery" vision.

1.1 Background

Electricity is an especially interesting commodity because it cannot be stored in large quantities with today's technology. The production and consumption must hence be equal at all times. Society today largely depends upon electricity in many ways. Therefore, a reliable supply of electricity is a priority for Nordic authorities. There are many methods for producing electricity, and most of the technologies are not able to adjust output on short notice. Because of this, a combination of different technologies is considered to be the best overall solution for an effective and reliable energy system.

The Nordic countries electricity markets are neatly integrated by interconnectors between the countries themselves and Europe. The demand profile is quite similar in the Northern European countries, larger demand in the winter than in the summer, and with typical daily peak demands in the morning and afternoon hours. On the supply side we find that there are large differences between the countries, as there are a wide range of different production technologies being used. In Norway, almost all of the electricity comes from hydroelectric plants. In Sweden a mix of hydropower and nuclear supplies the electricity, while in Denmark fossil fuels and wind are the main generators of power (Bye, et al. 2010).

In recent years Denmark has expanded its wind production capacity drastically, and is planning for further expansion (Ea Energianalyse 2007). Historically, Denmark has produced its electricity in coal powered plants, but as climate changes and carbon emissions are becoming increasingly important issues, the Danish authorities seek to close down coal powered plants. EU's renewable energy target requires all countries to increase their share of renewable energy produced to 20% of total production by 2020. In addition to the EU renewable energy target, the Danish government has set an additional and quite ambitious target of 50% renewable production within 2025 (Klima og Energiministeriet 2010). This increases the need for green energy both for Denmark and its neighbouring countries.

In 1985 a resolution of the Danish Parliament banned nuclear power plants. Hence, this climate gas emission free technology is not an option. Denmark does not have the topography and size of catchment areas necessary to make use of hydropower, but the country is flat and quite windy. Therefore wind power is a viable technology for producing renewable and emission free electricity. Integrating wind power in the energy system is a challenge, because the turbines only produce when the wind blows, independent of demand. Alternative technologies for supplying power in the hours with no wind, as well as methods for getting rid of power when the wind is at full strength, is necessary in order to balance the system. This is where Norwegian and Swedish hydropower can be helpful. Hydropower with dams can be regulated quite easily, and the cost of increasing or decreasing production in the short run is low.

Wind power is not only growing in Denmark. Connected neighbouring countries like Germany and the Netherlands also plan to install considerable amounts of wind turbines in the coming years (CBS - Statistics Netherlands 2013). Other renewable energy technologies are also becoming increasingly popular, such as photovoltaic, centralized heat pump systems, and direct solar heating. Replacing the predictable coal powered plants with more unpredictable renewable sources represents a need for change in the energy system, and a more integrated system with bigger markets and more players seem to be on its way. More interconnectors between countries are under construction, and other connection infrastructure investments are in the planning stage (ForschungsVerbund Erneuerbare Energien 2011).

1.2 Problem statement and research hypothesis

The demand and supply for power in the Nordic area, Estonia and Latvia is determined every day, hour by hour at the Nord Pool spot exchange. The market participants all enter their quantity and price offered to Nord Pool, and the price is set for each hour on the based on the planned supply and demand. If the grid capacity between price areas is unable to carry the load required, a difference in prices between the areas will occur. An increase in the transmission capacity will even out prices and encourage a flow of energy from low price areas to high price areas. If the market does not clear, or if the players have failed to predict the correct amount of electricity produced or consumed, reserve/balancing power is needed.

As more wind power is introduced in the power transmission system, the demand for regulating power generally increases (Bye, et al. 2010). Today, the regulating power market trades a volume of 2-3% of the total amount of electricity produced (F. Førsund 2011). Power markets were previously regulated locally, but with the growth of a joint Nordic market for electricity a common Nordic market for regulating power has been established. Until now, regulating power in Denmark has been generated by fossil fuel where short term adjustments in production are costly. Fossil fuel powered electricity generation is also a technology there is political ambition to shut down over time. However, the amount of imports and exports are limited by the capacity reserved for regulating power on the interconnectors. Regulating power normally has a higher price than power in the spot market, and building new interconnector capacity will expand the export market for Norwegian hydropower. The Norwegian transmission system operator (TSO), Statnett, and the Danish TSO, Energinet.dk are building a new interconnector between the south of Norway and West Denmark called Skagerrak 4. This subsea interconnector runs parallel to the older interconnectors Skagerrak 1 – 3 and will be completed by the end of 2014 (Statnett 2009).

Wind power normally decreases the spot price, as it has a marginal cost close to zero, but its effect on the price of regulating power might be the opposite, due to the stochastic nature of its production, and the difficulty in making good prognosis for wind. A larger fraction of wind power is considered to increase the value of hydropower (Førsund and Hjalmarsson 2010). The spot market price has several times been zero or negative for Danish power, due to overproduction and the high costs of downwards regulation of thermic power production (F. Førsund 2011). The Danish government has stated that 50% of energy production shall be from renewable technologies, and most of this will have to be produced in wind turbines. This represents a major challenge for Energinet.dk, and an opportunity for Norwegian hydropower producers to increase the value of their product.

In light of these major changes in the energy system for Norway's trade partners, it seems interesting to make an attempt to analyse the demand in the regulating power market as the share of power produced by wind increases. The main objective of this thesis is to make an attempt to assess the future demand for regulating power in Denmark with increased amount of wind power installed.

My research hypotheses are therefore as follows:

- The demand for regulating power in Denmark will increase as the share of renewable power production grows and thermic power plants shut down.
- Norwegian hydropower producers can profit from this development by offering regulating power on the Skagerrak interconnectors.

1.3 Structure of the thesis

The thesis is divided into three chapters. This chapter produces a brief background, statement of the problem and structure of the thesis. The second chapter explains how the Nordic energy markets are designed, how prices for the different types of energy delivered are determined and how the different kinds of balancing and regulating power are acquired in Denmark. It also explains Denmark's strategy for obtaining the necessary regulating power in the future and technologies alternative to hydropower imports for balancing the system. In the third chapter I present the econometric models to be used in my analysis and chapter four presents the data used. Chapter five displays the findings. Chapter six discusses the future demand in the regulating market and possible profitability for Norwegian hydropower in the market. Chapter seven concludes.

2. The Northern Europe power markets

Most of the electric power in Northern Europe is traded at the Nord Pool Spot market, and by *over the counter bilateral contracts* cleared at the Nord Pool clearing house. Elspot covers the Finland, Norway, Sweden, Denmark, Latvia, and Estonia. In addition to this, financial contracts for future deliveries with maturity up to five years ahead are available at Nasdaq OMX Commodities. The players at Elspot predict how much they are willing and able to buy/sell at different prices and submit their bids for each hour of the coming day in a double sided auction, 12 hours prior to the day of delivery. Nord Pool then decides the spot price and volumes after collecting all bids by calculating aggregated curves for supply and demand. As this happens 12 – 36 hours prior to delivery, there are many ways that the calculated volumes might deviate from actual demand and supply in the delivery hour. Players who realize they have miscalculated after their bidding at Nord Pool can buy or sell at the intraday market Elbas until one hour prior to delivery. Elbas covers the Nordic region, Estonia and Germany. 358 different players are trading at the Elspot market and 118 players are trading at Elbas.

There are many possible reasons for a mismatch between predicted and actual power supply and demand. A plant or a power line might fall out, or the demand might suddenly change. Wind is also quite difficult to predict, so the actual production can differ from the prognosis. These mismatches can occur suddenly and within the operating hour, also after the Elbas trade has closed for the hour. These imbalances are dealt with in the balancing power system, where the Transmission System Operators trade in upwards and downwards power delivered on short notices.

2.1.1. What determines supply in the Nord Pool system area

The supply and demand for power in the intraday market Nord Pool Spot decides the system price for electricity, and the constraints in transmission between the price areas decide the deviation from the system price in each area. On the supply side many factors are relevant, because of the diversity in technologies used to produce electricity. In the Nord Pool system area, gas powered plants, waste incinerators, nuclear reactors, coal boilers, hydropower plants with and without reservoirs, photo voltaic (solar), combined heat and power plants and wind turbines are all being used to produce the power that is being delivered to the grid. Some of the technologies are intermittent producers with a marginal cost close to zero, and has to sell whatever power they can at the time it is produced. This goes for solar, wind and hydro without reservoir technologies. Through the input from these technologies wind, rain, temperature and clouds impact the supply of power. Nuclear power reactors also have low marginal costs. Because of the large production capacity of many of the reactors, these often cause large disturbances in the system price if an outage occurs unexpected, or if maintenance takes longer than planned for. Coal and gas fired plants have marginal costs related to the cost of fuel, the level of operation, start/stop costs and the price of carbon credits. As these are commodities traded on international markets, economy wide events influence the prices.

In the Nord Pool Spot market the supply offered is ranked from the lowest price to the highest. The technologies with the highest marginal cost will normally only be activated when demand is high, or the lower marginal cost technologies become unavailable for some reason. Because of the many and different factors that affect the supply of electricity, it is one of the most volatile commodities available.

2.1.2. What determines the demand in the Nord Pool system area

The consumers in the Nord Pool system area are as diverse as the population. In some countries, electricity is mostly used for light. In other areas electricity covers a large part of the energy consumption, and is being used for heat, transport, industrial production and light. Therefore, conditions dictated by nature also affect the demand side of the electricity market. The need for lights is bigger during the dark winter times in the North; temperatures affect the need for heating and so on. In the short run, the household's demand for electricity is quite inelastic due to the necessity of the commodity, but in the longer run consumers finds substitutes such as heating oil, kerosene lamps, sunlight water heating and small home generators if the prices of electricity stay high for longer periods of time.

2.2. Exchange between the Norwegian and the Danish energy system.

The Norwegian and the Danish energy systems are connected by the Skagerrak-interconnectors. There are three interconnectors at the moment. The first ones, Skagerrak 1 and 2 were finished in 1976/77. These were the longest and deepest subsea connection in the world at the time. With the completion of Skagerrak 3 in 1993, the capacity was doubled from 500MW to 1000MW. The interconnectors are owned by Statnett and Energinet.dk (Statkraft 1991).

A new interconnector, Skagerrak 4, is being built parallel to Skagerrak 1-3. It will be put to use in 2014 and will further increase capacity by another 700MW (Statnett 2009).

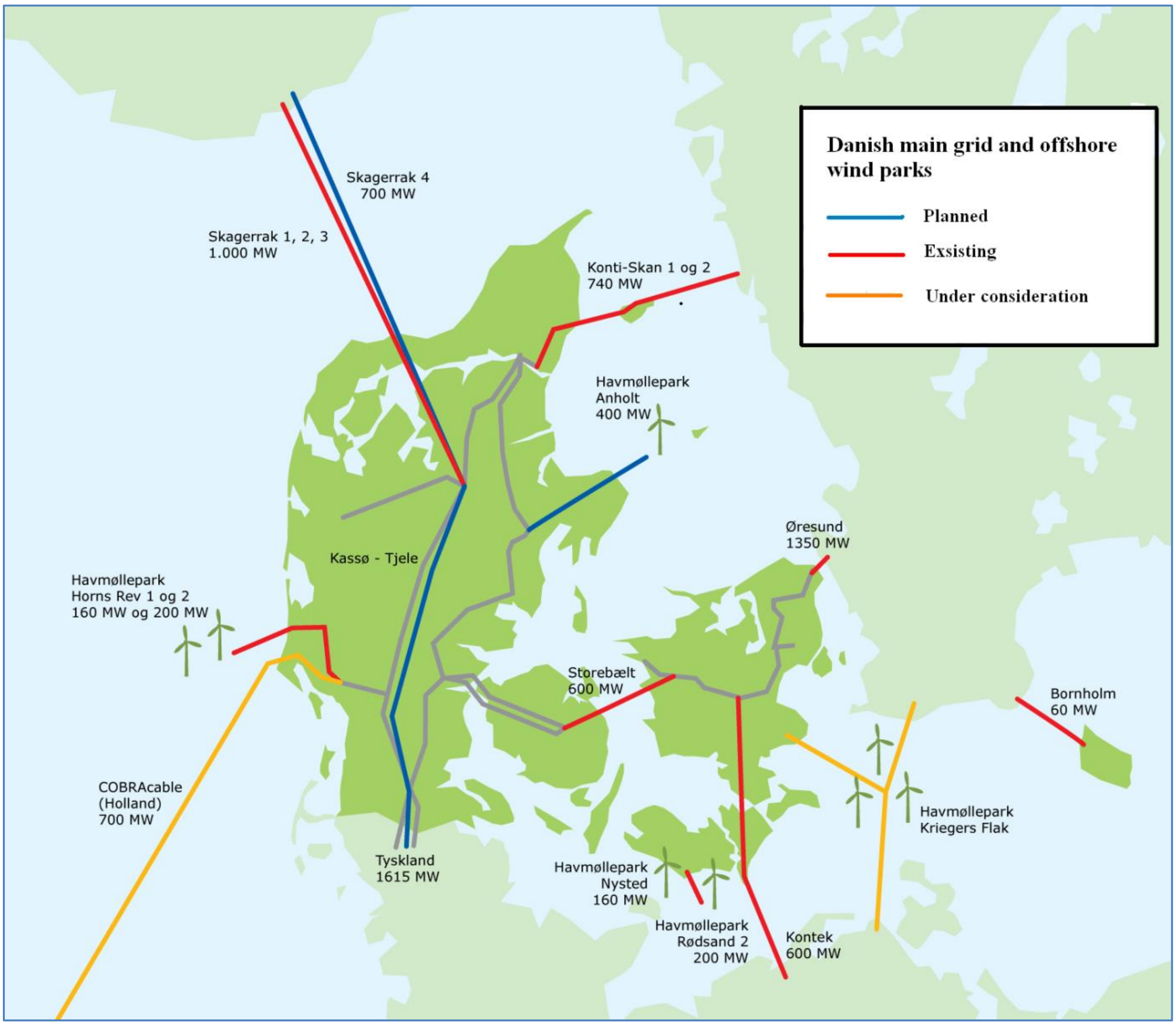

Figure 2.1: Danish Interconnectors (Energistyrelsen.dk 2010)

Skagerrak 4 is said to be an important condition necessary in order for the planned growth in Danish wind power to be viable. Without sufficient and reliable transmission capacity one might get into a situation where Denmark would have to keep coal powered plants running in order to maintain balance in the grid, leaving emissions unchanged despite considerable amounts of wind power produced (Statnett 2009).

Reports suggest that the daily profile of exchange of power between Norway and Denmark is a result of the demand for regulating power in Denmark, and that the level of exchange is determined by the amount of wind and the stock of water stored in Norway (Nord Pool Consulting 2010). The Norwegian and the Danish energy systems differ:

- The Norwegian system is energy limited: it can allocate the power to the time it is most needed, but in dry years storing enough water in the lakes to provide for the entire winter might be a problem. Consuming the potentially produced energy in wet years can also be a problem which might lead to spilled water and lost production.
- The Danish system on the other hand is a capacity limited system. The production is adequate to provide the energy needed, but distributing it amongst demand in different time periods is a problem. With the increased capacity of exchange built the later years, Norway is heading in the direction of a capacity limited system (Wangsten, Doorman and Grinden 2000).

On a normal day, the Danish prices fluctuates a lot more than the Norwegian prices, because of the large share of slowly regulated thermic power. Typically, one will have what is called a “devil’s head” -curve, with prices peaking in the morning and afternoon because of demand spikes when people wake up and get ready for work, and when they get home and start to cook etc. Because of the high cost of adjusting the short term production in a thermic plant, these normally run all hours of the day. This leads to low prices nighttime when demand is low. With increased wind generation capacity, this pattern is expected to become less prominent, because of the stochastic nature of wind power production. The Danish combined heat and power plants produce less electricity and heat during the summer and the wind production is also lower in summertime than in winter.

The demand pattern is similar in Norway, but because of the flexibility in supply due to the hydropower system, the prices more stay stable over the day. Wind power production is extremely volatile. For the period January 2011- February 2013, the standard deviation in wind production is 670,19 MWh/h, 79% of average production. The wind production in the period has a minimum of 0,7 MWh/h and a maximum of 2926,1MWh/h.

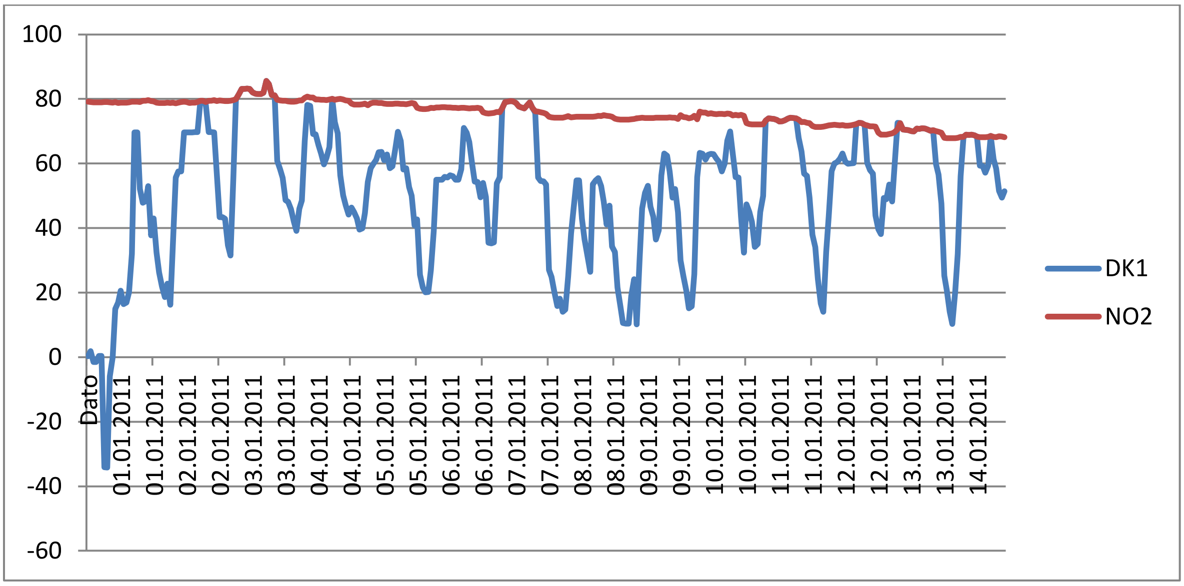

Figure 1.2: Elspot prices January 2011, Hourly data €/MWh

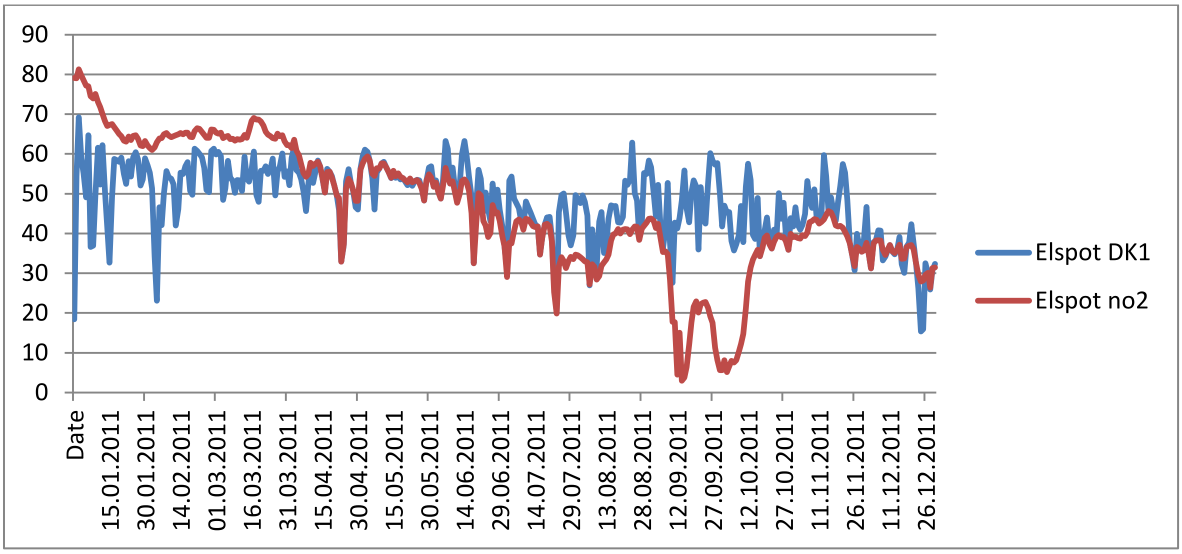

Figure 2.3: Elspot prices 2011, daily averages, €/MWh

For the period 01.01.2011 – 20.02.2013 the standard deviation in elspot prices are higher for NO2 than DK1. In wintertime the standard deviation is higher for DK1 than NO2 (16,62/15,93), and in summer the opposite occurs (12,23/13,95). On average, the Danish price is significantly higher than the Norwegian (+4, 28€), but there are seasonal variations here as well. In wintertime, the Norwegian price averages 0, 57€ more than the Danish, but in the summertime the Danish average spot price is 6, 71€ more than the Norwegian for the sample period. This deviation in prices suggests profitability in exchange capacity. See Appendix 1 for volatilities.

2.2.1. Danish power supply: the past, the present and the future

The Danes have been eager in developing wind power since the early history of wind to electricity technology. Government funded projects testing increasingly large wind turbines over the years have contributed to increasing the effectiveness of the technology, and todays average wind turbine has an installed effect of 2.5 – 3 MW, a dramatic increase from the 200kW turbines first installed in the late seventies. For example, in 1990, wind power supplied 1, 9 % of the total Danish energy consumption. The fast development led to a rapid increase, and by 2011 wind power had increased its share to 28% of total consumption (Energinet.dk 2013). In addition to more effective turbines on land, large offshore wind farms have been built and activated. In 1991 the world's first offshore wind park was opened in Denmark, Vindeby 1, with an installed effect of 4,9MW. The good wind conditions of the open seas have encouraged the building of large new wind parks across the Danish shores, despite the high costs of building and maintaining such installations. Theoretically, Denmark could cover its entire demand for electricity from offshore wind power plants (Energinet.dk 2012). Today, 505,6 MW of offshore wind power is installed and operating, and another 1402 MW is planned or under construction (Offshore Center Danmark 2013).

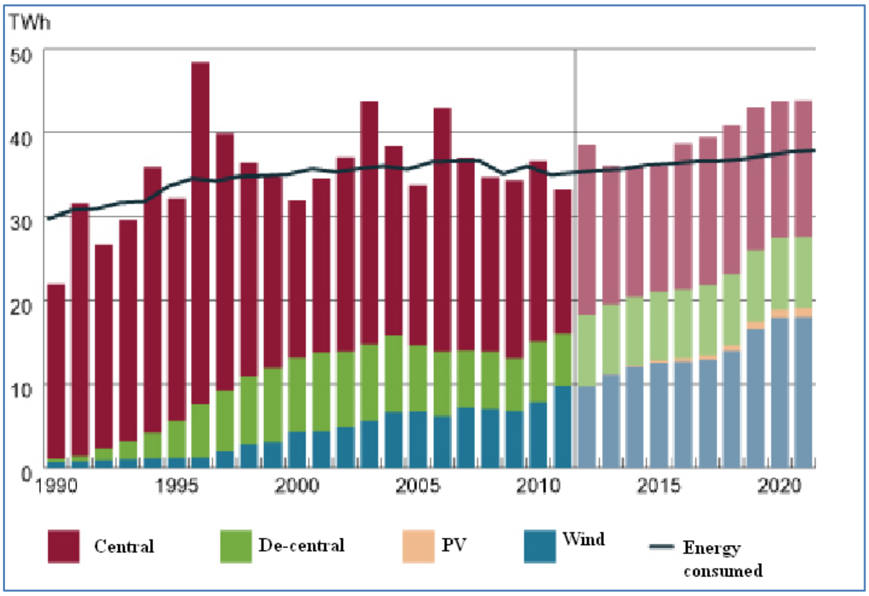

Figure 2.2: Energy production in Denmark with forecast (Energinet.dk 2013)

Danish electricity production is divided between central plants, de-central plants and wind turbines. The central plants are mainly coal- or gas fired but has an increasing share of biomass as alternative fuel. Most de-central plants are gas-fired, but some of them are also fired by waste, biomass, biogas and oil. Since the 1980's there has been an increasing share of de-centralized power production. These plants are mostly combined heat and power plants (CHP), and they supply both district heating and electric power. The extensive use of district heating has strongly contributed to Denmark being one of the world's most energy effective nations. From 1980 to 2010, energy consumption in Denmark has stayed nearly the same, despite en economic growth of 79% (Klima og Energiministeriet 2010).

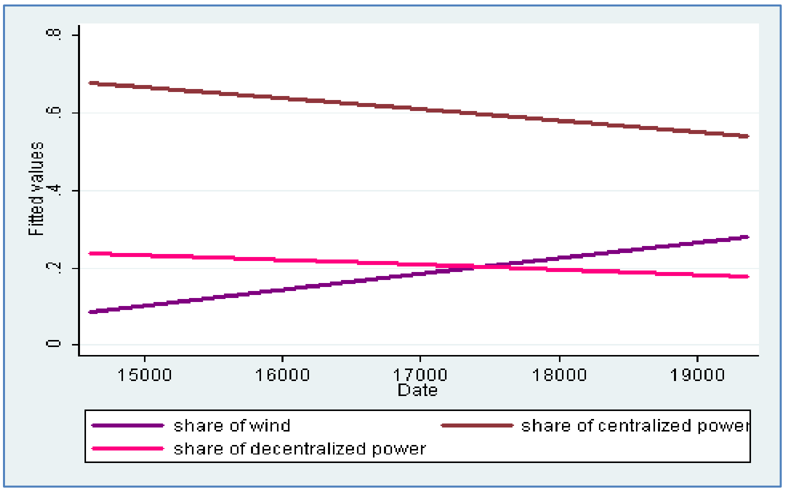

Figure 2.3: fitted lines to hourly production of power from different sources in Denmark in the period 03.01.2000 24.12.2012.

The graph shows fitted lines to the share of power from the different sources fed into the grid in the period 03.01.2000-24.12.2012. More power comes from wind and less from thermic sources.

The Danish government has stated that Denmark shall be one of the three countries in the world who increases their share of renewable energy the most within 2020. In 2007 the Danish government publicized the report "A visionary Danish Energy policy – 2025" where a 50% share of energy supply being from wind power by 2025 is a proposition. In the long run the goal is for Denmark to be completely independent from fossil fuels, but this goal has no specific time limit for the time being (Klima og Energiministeriet 2010).

2.2.2. The Norwegian power system

In Norway, most of the power is produced in hydropower plants. In 2011 95% of the electricity produced came from hydropower plants, 4% came from thermic plants and 1% came from wind turbines. Not all of the hydropower produced is easy to regulate, a share of the hydropower produced in Norway comes from run of the river plants. The levels of production in these plants are decided by nature, as in the case of wind power. Typically, they produce a lot in spring, when snow in the mountains is melting, and in autumn when there is a lot of rain. Still, the reservoir hydropower plants in Norway have the capacity to store 84,6TWh of power, 67% of the average annual production (SSB 2013). This reservoir capacity has been used to even out the seasonal fluctuations, but due to the ability of very fast regulation it is also useful as regulating power. Estimates show that as much as 40% of the wind power produced in Denmark is stored in Norwegian water reservoirs (Mauritzen 2012).

The demand is high in winter in Norway, as the winters are cold, and Norwegians rely on electricity for heating. Historically, the reservoirs have served to satisfy this demand, as the natural flow is low in the wintertime when precipitation comes in the form of snow. Because of the regulating properties of the Norwegian hydropower, prices fluctuate less across the hours of the day than what is normal in a thermic power system, but there is high volatility across seasons.

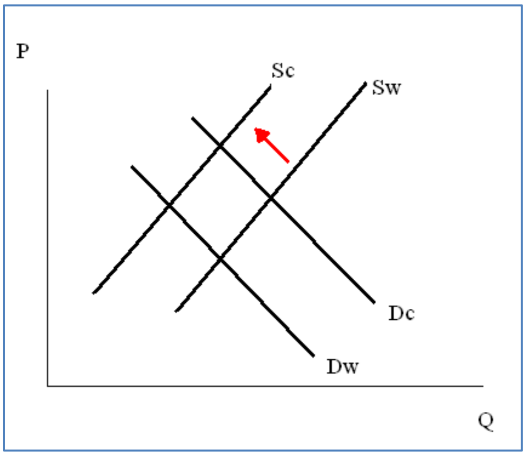

Figure 2.6: How the supply side shifts in a system with limited storage capacity and inflow. In cold years, the demand is not the sole thing driving the prices up. The increased scarcity of water as it is used during the winter also shifts the supply side, and contributes to increased volatility across seasons.

Supplying enough electricity has been a challenge in particularly cold and dry years, and in such times the Norwegian power system can benefit greatly from being linked to the Danish, where wind turbines produce more in the winter than in summer. In the years ahead, researchers predict a warmer climate with more rain due to climate changes (Seljon, et al. 2010). This represents a decline in the demand for heating and an increase in potential production.

2.2.3. The Danish balancing power system

In order to keep the frequency on the grid at 50Hz, there needs to be balance between power consumed and power produced at all times. Failing to keep production and consumption in balance will result in power outages and possibly expensive damages to the grid. To ensure balance the transmission system operator (TSO), in Denmark Energinet.dk, need to continuously monitor the power being transported in the grid, and adjust it accordingly.

Frequency controlled reserves

The reserves are automatically responding to deviations from 50Hz in the grid. Energinet.dk purchases these reserves on a daily basis, and capacity for regulating up or down is treated separately. There are five daily auctions that open after the spot market closes, and the players enter their bids to energinet.dk for the coming hours. All the bidders whose offer has been accepted receive the price of the highest accepted bid. According to the Nordic agreement (Nordisk systemavtale), Energinet.dk can get up to one third of the required frequency controlled reserves from non-local providers, which today means Norway, Sweden, Germany and exchange between the two price areas Eastern and Western Denmark.

Frequency controlled reserves in the future

In the next two years Energinet.dk is planning for bigger markets within the synchronized areas west and east Denmark. 3-10 years into the future, the plan is to establish common markets for frequency controlled reserves across the borders of these areas. In the short run the expansion of the markets is directed towards Sweden and Germany. This is due to technical limitations.

The subsea cables over to Norway and between west and east Denmark are high voltage DC-connections (HVDC), and in order to run frequency controlled reserves over these lines one would have to reserve a fraction of the available capacity for this purpose. For AC-connections on the other hand, the connections are continuously running a lower flow than the maximum capacity due to security limitations. This makes it possible to activate frequency controlled reserves across the borders on short notice without keeping an additional part of the capacity on stand-by. In the long run Energinet.dk' plans are a common north-European market for these reserves (Energinet.dk 2011).

Secondary reserves (load frequency control, LFC)

Today, secondary reserves are being used only in western Denmark. Its purpose is to soften the primary reserve requirement, and balance the frequency back at 50Hz when unexpected imbalances and outages occur. The LFC is effective within a max of 30 seconds after activated, and will stay active for as short as possible, and a maximum of 15 minutes before the manually activated reserve takes over. The demand for LFC is decided by Energinet.dk, and a purchase of the necessary available capacity is done by a monthly auction. The suppliers bill Energinet.dk a fixed price per MWh after activating the reserves, in addition to the pay as bid price offered for keeping the reserves available.

Statnett and Energinet.dk has agreed upon the exchange of +/- 100 MWh across Skagerrak 4 when it is completed and for the following 5 years. The agreement implies that Energinet.dk will no longer buy LFC in Denmark. If Skagerrak 4 has an outage, the load can be distributed across Skagerrak 1-3 in order to supply the reserve needed. If such an event occurs Energinet.dk will also consider counter trading. A similar agreement is already made with one of the German TSOs. The purpose of these agreements is to reduce the overall need for activating LFC reserves through automatic equilibrium of opposite imbalances over larger areas.

Energinet.dk has been in dialog with the suppliers and concluded that there is no potential for an hourly market for LFC. In the long run, Energinet.dk wants to establish a common Nordic/German market for secondary reserves, but the large differences between the Danish and the German system in particular represent challenges.

2.2.4. Manual reserves and regulating power

The regulating power is activated when an imbalance exceeds 15 minutes and the secondary reserves can no longer be used. The manual reserves requirement in Western Denmark is similar to those in Norway and operated by what is called the N-1 criterion. This indicates that the transmission system operator must purchase sufficient manual reserves to handle the outage of a dimensioning unit in each area. A dimensioning unit might be domestic transmission lines, generation units or international interconnector lines.

The market participants enter their bids for manual reserves to Energinet.dk, which calculates the daily need and forwards the bids to the common Nordic regulating power market. Here, the Danish reserves and voluntary bids from other Nordic players are auctioned as two different products: upward regulation power and downward regulation power. The lowest bid is activated, and the player gets paid the auction price of the bid times the amount of power activated. The players must submit a minimum of 10MW reserve in order to enter the auction and they must be able to activate within 15 minutes (Tang 2008). A special feature of the regulating power market is that both producers and consumers of power can act as suppliers of regulating power. A consumer can increase (downwards regulation) or decrease its consumption (upwards regulation), in order to meet the needs of the TSO.

In Eastern Denmark, Energinet.dk has an agreement with Svenska Kraftnät which makes the parties jointly responsible for acquiring the necessary reserves to fulfill the N-1 criterion south of the internal congestion in Sweden. In addition the additional cables must have excess capacity enough to handle an outage on the Öresund interconnector. Energinet.dk has signed a 5-year agreement with national power producer Dong energy for the delivery of Eastern Denmark's reserves (The Kyndby Agreement). Dong will deliver 300 MW of fast reserves (15 minutes) and 375 MW of slow reserves (up to 2 hours) until the agreement expires in 2015.

Previously, the TSO needed to obtain enough manual reserves to be able to handle outages in Eastern and Western Denmark separately, but in 2010 the commissioning of the Great Belt Power Link, a 600MW HVDC subsea cable between Eastern and Western Denmark, changed this. After the completion of the Great Belt Power Link both parts of Denmark reduced the need for manual reserves. If there is a dimensioning fault in Western Denmark, the export to Eastern Denmark can be reduced as Eastern Denmark holds the manual reserve capacity to handle the outage. The Great Belt Power Link reduced the demand for manual reserves in

Denmark by 300MW. The total purchase of manual reserves in Denmark is 900 – 1000 MW, 675 MW in Eastern and approximately 250 MW in Western Denmark, but not all of this is being activated as regulating power.

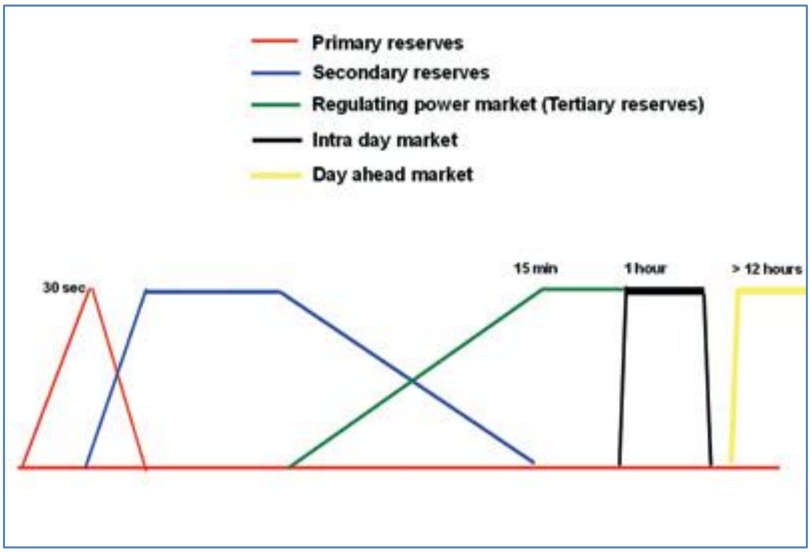

Figure 2.7: Danish Electricity markets (Andersen and Sorknæs 2011)

Future plans for manual reserves and regulating power in Denmark

Energinet.dk has stated that they will not purchase more manual reserves as a result of the wind power expansion (Energinet.dk 2011). Energinet.dk seeks to expand the Nordic regulating power market both geographically and in the range of products definitions. International markets will make it possible to share reserves over larger areas and Energine.dk points out an inclusion of Germany to the common Nordic regulating power market as advantageous. Also, making several products could make it possible for units with an activating time of more than 15 minutes to enter the common Nordic regulating power market.

2.2.5. Regulating power prices on Nord Pool and settlement

The next figure illustrates how regulating power prices are set on the Nord Pool exchange. The green rectangles represent upwards regulation orders in the market (available capacity), and the orange represent downwards regulation orders. The orders are submitted to the responsible TSO in each of the player's respective area, and from there forwarded to Nord Pool. All the submitted orders are ranked in merit order. The orders with the lowest price are activated, until the demand is satisfied (in this example, 400MW).

The offers that are activated all receive the price of the highest offer activated. Downwards regulating price is decided in the same way as for upwards regulation. A bid might sometimes be surpassed if it cannot be activated, either because of bottlenecks in the interconnectors, or because of the trade conditions between the Nordic TSOs and the N1-criterion.

All traders must settle with the TSOs, who invoice the balance responsible parties for their surplus or deficit of power purchased/produced. In an hour with upwards regulation, a producer with a production surplus will receive the elspot price from the TSO, and a producer with a deficit will be invoiced the up-regulating price. In an hour with downwards regulation a producer with a surplus will receive the downwards regulation price, and producers with too low a production will be invoiced the elspot price (Nord Pool Spot 2013).

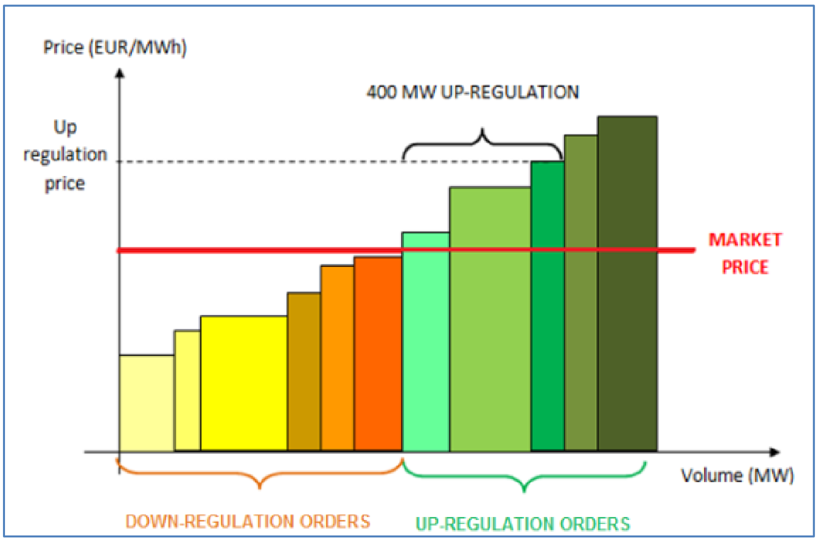

Figure 2.8: Pricing on the regulating power market (Nord Pool Spot 2013)

Balancing power prices are on average higher the faster the activation is required. Also, balancing/regulating power is less expensive in periods with high activity on the supply side. It is easier and cheaper to ramp up or down a power plant already in use, than to start up one from stand still. During low demand hours or maintenance, many power plants will be at total stand still and will therefore require a high price in order to start up production for balancing purposes. This causes daytime regulating power to have a lower price than nighttime regulating power in system with a large share of thermic production.

2.3. Market power in the regulating power market

The regulating power market is characterized by an uneven relationship between supply and demand. The nature of a regulating power supplier is that the supplier can shift its production in order to adjust to the demand, but the TSO has no such freedom. Regulating power is therefore inelastic in demand.

Despite of this, the market is functioning well, due to the large number of supplies at the Nordic Regulating Power market. In 2006 the Danish companies Energi E2, Nesa, Københavns Energis el-forretning, Frederiksberg Forsyning and Elsam merged, and formed energy market giant Dong Energy. This caused concern about the market power situation in the Danish markets, both for gas and electricity, as Dong Energy at the moment supplies about 49% of the electricity and 35% of the heat in the Danish electricity market, and are also an active player at the regulating power market. This would have caused problems in a closed market, but as the Danish suppliers compete with producers from all of the Nordic countries on the exchange, the possibilities for executing market power is expected to be limited. In 2009, the prices for regulating power were equal in the entire Nordic exchange area in 40% of the hours, which indicates significant competition between players (Det energipolitiske Udvalg 2009-10 2010).

2.4. Different strategies for supplying flexibility to the power system

2.4.1. Energinet.dk's actions for handling the increased amount of wind power

In the beginning of Denmark's wind adventure the turbines was a lot smaller than they are today, and located widespread around on private properties in the countryside. A large share of the small scale local power was used directly in the connected household, thus not being loaded in to the grid. The remaining load that is fed in to the grid is decentralized. This way of integrating wind into the power system was sufficient during the 1980's but as the wind power production grew, alternative measures were needed. As electricity from renewable sources has priority in the grid due to legislation, balancing by shutting down the wind turbines is not an option unless absolutely necessary.

2.4.2. Reducing forecast errors in wind power production

More so than temperature and rain, wind is difficult to predict. At wind speeds between 5 and 15 metres per second, one meter per second deviation from forecast will result in a 350 MW deviation from the expected load (Energinet.dk 2012). This equals the amount of energy produced in a large thermic power station.

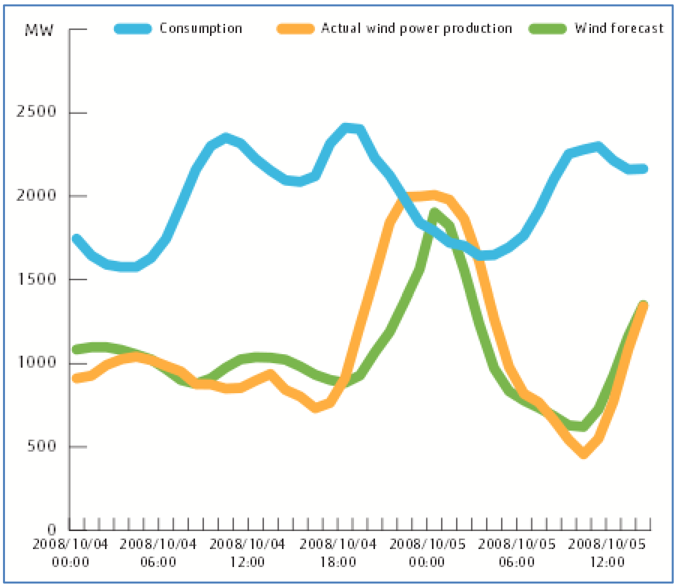

Figure 2.9: Typical load curve in winter. This day, wind hit earlier and stronger than forecasted, and production unexpectedly exceeded consumption by up to 250MW per hour. Wind production was 650MW more than forecasted at most. The curve is from West Denmark (DK1) (Energinet.dk 2012).

The prognosis being used when the traders estimate their production for the coming day is made at 0700AM the day before delivery. Thus, the oldest prognoses are made 41 hours prior to delivery. This significantly reduces reliability of the prognosis. For the first hour of the day of delivery, the average forecast error is roughly 20%, but for the last hour in the day this error has increased to 30%. This indicates that splitting the trading period into two 12 hour slots, instead of today's one day trade period would decrease the forecasting errors, and thereby the demand for regulating power, by a significant amount (Ea Energianalyse 2009). Meteorologists are continuously working to improve their methods for forecasting wind.

2.4.3. Smart grid, exploiting demand side flexibility

Smart grids are technologies that seek to make use of the consumer's flexibility. The idea is that automatic measuring devices in homes and businesses will communicate with the supplier at all times, and the consumer is billed for his real time consumption. This gives the consumer an incentive to move his power consumption to the low priced hours of the day. Fully automated versions of such systems that communicate both ways are also available. Using such systems one can program household electronics to start up when the price drops below a given level, or to shut down when the price rises. Combining smart grids with electric transportation exploits the storage capacity in electric vehicle batteries to the benefit of grid balance (Goldbach, Hansen and Næss-Schmidt 2008). There are also test projects on feeding power from car batteries back in to the grid at high demand times, so called Vehicle to Grid/V2G (Tomić og Kempton 2007) .

2.4.4. Compressed air energy storage (CAES)

This technology stores energy by compressing air with an electric motor. The compressing process also generates heat as a by-product. When it is time to use the energy, the air is released through a turbine which rotates a generator. This process (decompression) normally requires heat to be applied in order to prevent the generator from freezing. The heat exchange technology applied determines how energy effective the storage is. Up to 70-80% of the stored energy can be reused. The plants normally store in night/day intervals, compressing air during night and releasing during day. Cavities in rock are used as storage vessels, either abandoned mines or cavities created for the purpose by dissolving minerals for extraction. CAES technology is not considered viable in the Danish market today, but this might change if the TSO experiences increased costs for ancillary services in the future (Salgi and Lund 2009).

2.4.5. New generation Combined heat and power (CHP)

This is a technology well suited for the Danish power system, with a large amount of CHP plants already integrated. New CHP plants usually have a heat storage unit, and can use this to store energy. This means that the plant can offer downwards regulation by shutting down the power generating part of the plant, while the heat is still running. CHP plants can also offer upwards regulation in hours when not all of the power has been sold at the Elspot market (Andersen and Sorknæs 2011). This is particularly useful due to the daily production profile of the wind turbines. In the wintertime there often are strong winds during the night, when the Danes are sleeping and have little use for energy. In 2008 Denmark passed an energy act reducing the taxes on electricity used for heating in CHP-plants in such a way that it is profitable for the owners to produce heat from surplus wind generated electricity (Energinet.dk 2012). The CHP technology can run on waste, biogas and other biofuels, and is therefore a viable addition to Danish all-renewable goal. Even if waste and biofuels are considered to be renewable sources, they are not exempted from buying carbon emission credits, and these are added to the technologies marginal cost. Is therefore reasonable to assume it would be optimal to use as much use electricity from renewable and emission free sources as possible in these plants.

2.4.6. Downwards regulation by shutting down wind turbines

Before 2009, the price floor on Nord Pool elspot was zero. This gave the wind turbine owners no incentive to shut down production, even when there was large surplus of power in the system. Before 2009, this was handled by Energinet.dk by ordering the turbine owners to shut down in cases with risk of overload, and offer a financial compensation for the megawatts not produced during the shutdown (Energinet.dk 2012). With the growing share of wind power in Denmark, this solution was not viable in the long run. In December 2009, a negative pricing floor was introduced on Nord Pool spot, at -200€. This provides an incentive for wind power producers to seize production in times of extreme energy surplus.

2.4.7. Mixing photovoltaic and wind generation

To balance the seasonal variations the mix between solar powered generation (PV), and wind might be effective. In Europe, the wind is stronger in winter than in summer, and the maximum production in winter is about twice the minimum in the summer. The solar power generation is correlated negatively with the wind power generation. In a theoretical, all-renewable system, fluctuations between seasons in Europe could be smoothed by a mix of 45% PV and 55% wind generated power (Heide, et al. 2010). This does not help with the short term fluctuations, and with the current prices of solar panels it does not appear financially viable at the moment.

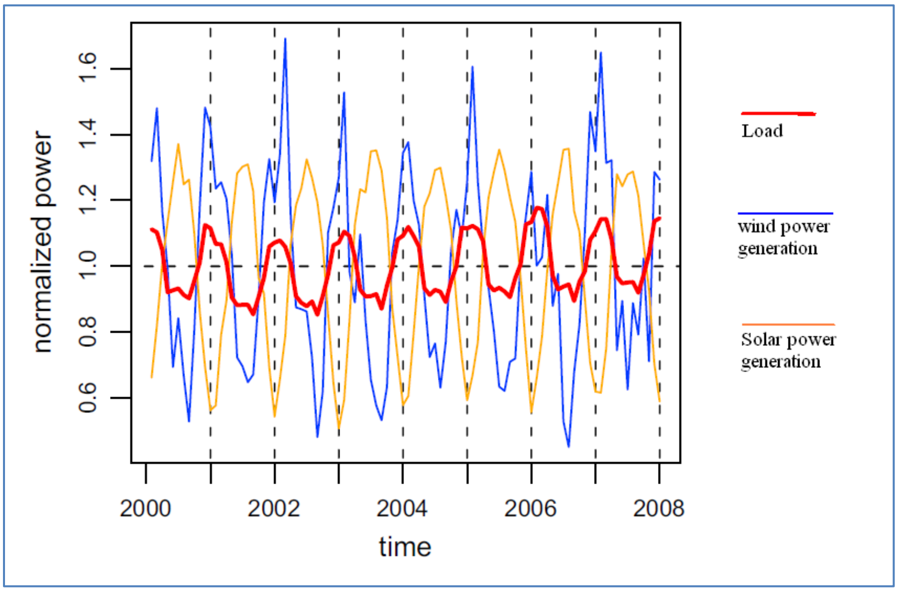

Figure 2.10: seasonal variations and load in Europe (Heide, et al. 2010)

2.4.8. Pumped storage

The “green battery”-function of hydropower plant can be increased by installing pumped storage. This requires that the plant has two dams, one upstream and one downstream of the generator. The turbine can run in reverse and take the function of a pump, and thereby place the water back in the upstream reservoir to be stored for later. Building a pumped storage plant requires significant interventions in nature, and it is therefore not expected to be commissioned any new plants of this type in southern Europe. An exemption is locations where hydropower plants are already installed, and the reservoir requirements are satisfied. Norway has several locations of this kind, and is one of few countries with potential for new pumped storage (Bjørndalen and Bakken, Europas behov for fleksibilitet 2011). Upgrading existing plants to facilitate storage, or building new pumped storage is capital intensive, and one uses more energy than one generates by doing this. 15-30% of the energy is lost in the process. It is therefore necessary to have a significant difference in prices over time for this solution to be viable (F. R. Førsund 2011).

2.4.9. Geographical spread of wind turbines

Research finds that geographic dispersion of wind turbines and volatility in wind power production is negatively correlated (Østergaard 2008). Locating wind parks in different parts of the country is a part of the Danish strategy for reducing the volatility in the wind power output. For this strategy to be successful, one needs good transmission grid within Denmark, especially between the east and west coast where large offshore wind parks with significant installed effect is located. Transmission to Germany, which is also planning to expand their wind power production in the coming years, is also assumed to lower the total volatility. However, this will not decrease the need for regulating capacity, as there will be periods of no wind in either end of the country.

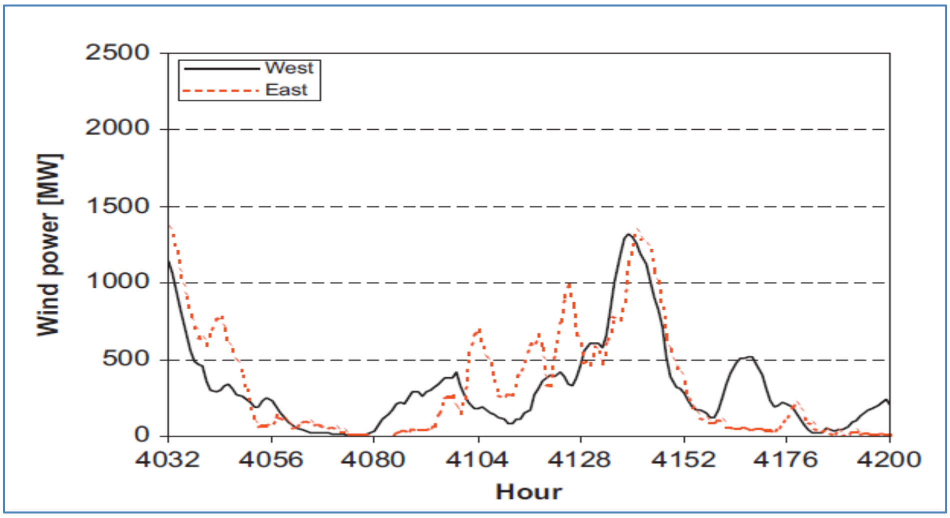

Figure 2.11: wind power production in a summer week 2005, hourly data. East time series have been scaled for illustrative purposes (Østergaard 2008).

2.5. Profitability of regulating power

2.5.1. How the elspot price works on the regulating power price

The value of hydropower is determined by the alternative use of the power, as it has close to zero marginal cost. The value of saving the water for a time period with higher prices determines the price. This allocation of production over time also brings down the prices in the high-demand period, and creates a social surplus. The power generator has a choice between selling its power at the regulating market or to the day-ahead power market. For thermal producers, technical restrictions apply. The start-up costs might be high, and the efficiency loss of not running at optimal production is relevant to the pricing. Hydropower is subjected to less of these restrictions, but there are still issues with how fast they are allowed to ramp up and down production, maxi/min water level in rivers, technical constrains et cetera.

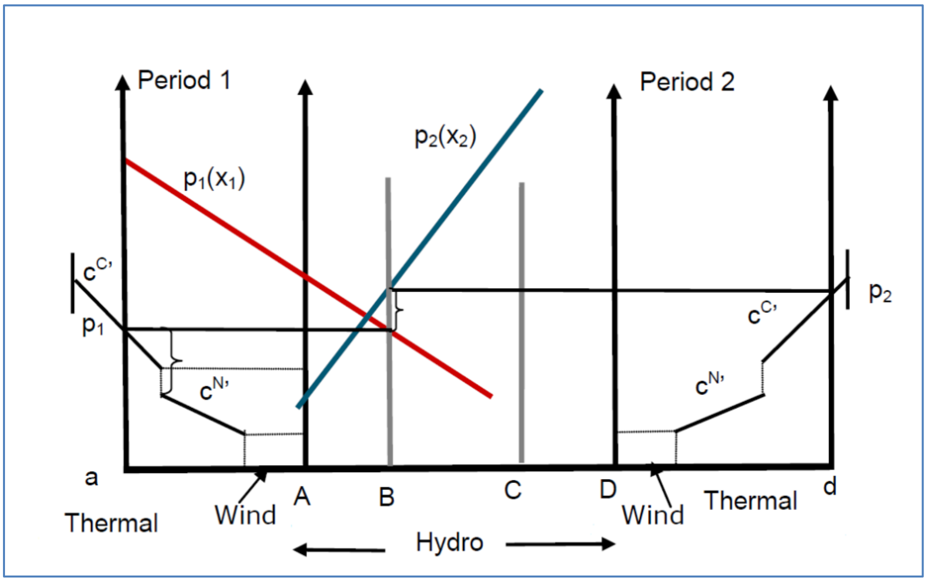

Figure 2.12: How wind power affects the system price

The figure above describes how wind power affects the price in a system with both hydro, thermic and wind power, like the Danish system with imports from Norway. The distance BC represents the available storage capacity for the hydro producer. The lines Cc and Cn represent the marginal cost for nuclear and coal power. The hydro producer allocates all production possible to period 2, obtaining a higher price for the product than possible in period 1 **(**Førsund and Hjalmarsson 2010**)**.

More so, the cost of producing regulating power by hydro production depends on the expected regulating prices and energy prices in the future. If the spot price is lower than the regulating price, the producer has no incentive to produce regulating power. If the price for regulating power is higher than the one in the spot market, the producer would only want to offer regulating power. If the usual arbitrage conditions apply, and there is no execution of market power, the regulating power price should be equal to the cost of the marginal supplier in the spot market. The regulating power price will therefore be correlated with the spot market price (Førsund and Hjalmarsson 2010).

2.5.2. Intermittent power sources impact on the elspot price

Adding wind to a system has impact on the spot price it two ways:

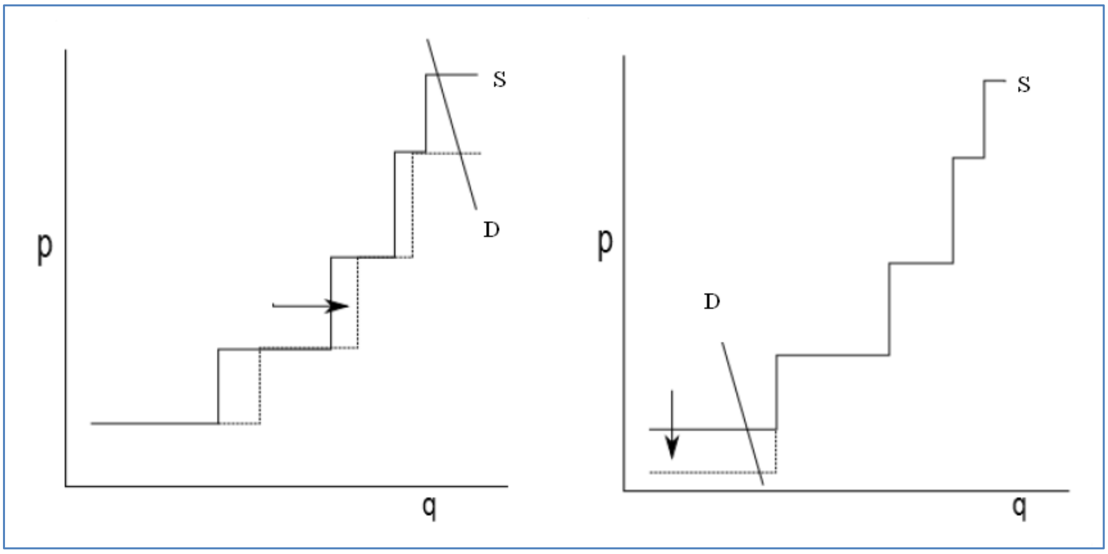

Figure 2.13: the different effects of wind power production on the spot price (Mauritzen 2012)

The first panel shows the supply effect. The wind power adds to the total supply of electricity offered, and shifts the entire supply curve to the right. Because the wind power has a marginal cost close to zero, it adds to the base load power which is activated first on the spot market. This implies reduced priced in the supply curve as a whole, but the peak load end of the curve is steeper than the base load side, and so the price effect will probably be more pronounced at peak load times. The second panel illustrates the cost effect. In low demand times, wind power can outbid other sources for base load power because of its low marginal cost, and in this way lead to lower prices in the system. Empirical studies as well as theoretical models imply that these effects are real and that the supply effect is dominant (Mauritzen 2011).

3 Empirical model

3.1. Model for wind production and quantity of regulating power

In the previous chapter I showed that theoretically, the demand for regulating power in Denmark should increase in the following years, and that this demand possibly can be met by exchange of hydropower over the Skagerrak connections. In order to empirically estimate if these theoretical assumptions hold for the Danish regulating power market, some modelling needs to be done.

Which factors decide the supply and the demand for regulating power? There is a need for regulating power when the expected demand or supply of power deviates from the actual production and consumption. In other words someone has to be wrong about their production or consumption prognosis in order for there to be a demand for regulating power. What causes wrong prognosis? Consumption can be predicted quite accurately. The traders usually do a good job taking normal fluctuations throughout the day and week into account, as well as specific events like halftime in a national soccer match or earth hour. Power plants failure and outages on the power lines will also contribute to the demand for regulating power, but as there is no way to predict these kinds of events, and hence there is no obvious way to fit these in to an econometric model. Also, both consumption and production depend on temperature, precipitation and wind. Temperature and precipitation can both be predicted quite accurately within the 36hr window of the Nord Pool market, but wind is less predictable. It is therefore difficult to find good variables to explain the volume of regulating power demanded, but theory implicates that an increased share of wind power will increase the demand for regulating power due to the stochastic nature of wind production. When production is high, many technologies are running. This adds more factors that might be wrongly predicted. Also, in times of unusually high production, wind turbine owners might have an incentive to shut down production temporarily because of negative prices of the spot market. A term for total production is therefore added. I will test this hypothesis using the following regression:

$$Q_t = \alpha + \beta_1 W_t + \beta_2 P_t + \mu$$

Where Q is the quantity, W is the volume of wind power, P is production of power in the area, and μ is the error term. The following equations are used in the analysis:

$$\widehat{Q_{1t}} = \hat{\alpha} + \widehat{\beta_1} W_t + \widehat{\beta_2} P_t + \mu \qquad (1)$$

$$\widehat{Q_{2t}} = \widehat{\alpha_2} + \widehat{\beta_3} W_{st} + \widehat{\beta_4} P_t + \varepsilon \qquad (2)$$

Here, W represents the amount of wind produced each hour, and W_s represents the share of power produced coming from wind turbines.

3.2. A model for identifying price drivers for regulating power

In order to test if the second research hypothesis holds, it is useful to determine what influences the price of regulating power. The price of regulating power depend on the marginal cost of production. For hydropower, the marginal cost of production is close to zero, but there is an alternative cost related to keeping capacity reserved for regulating purposes. This suggests that the price of upwards regulating power should exceed the spot price in order for the hydropower producers to offer their product on this market rather than selling in the spot market. If the price of regulating power exceeds the marginal cost of production in a gas powered plant, or if the capacity of hydropower offered is insufficient, gas power plants will also offer their production on the regulating power market. Hence, the price of natural gas might be a relevant factor in the price determination of upwards regulation. Pure oil fired plants are also used for regulating purposes and peak load supply. Oil prices are therefore added to the regression. If the market for regulating power in Denmark represents an opportunity for Norwegian producers to profit, the prices need to exceed the spot prices, and the option of using gas powered plants needs to have a higher cost than the alternative cost of producing by hydropower. The minimum price for regulating power is the spot price in the area for delivery, and the maximum price is DKK 37500/MWh (approx. 5000 €/MWh). The volume of upwards regulating power activated is relevant and necessary to add in order to avoid omitted variables bias (V_{reg}). There also needs to be sufficient capacity of transfer between the price areas. In order to see if capacity constraint is an issue, and thereby be able to say something about the profitability of new capacity, a term for transmission capacity or congestion on the Skagerrak connection is added (X_{Sk}). A lagged term of the price is also included to isolate the effect from previous price.

$$P_{t\,up} = \alpha + L.P_{up} + P_{t\,coal} + P_{t\,ng} + P_{t\,oil} + P_{t\,spot} + X_{t\,Sk} + V_{t\,reg} + W_t + \mu$$

The price of downwards regulation is determined in large part by the spot price. The suppliers of downwards regulation offer to shut down their production in exchange for the downwards regulating price, or they buy excess production from the transmission system operator (TSO) at the downwards regulating price. If the input factors for producing power are priced high, this represents an incentive to supply downwards regulation. The maximum price for regulating power is the spot price in the area of delivery.

$$P_{down} = \alpha + L.P_{down} + P_{coal} + P_{ng} + P_{oil} + P_{spot} + V_{reg} + W + X_{Sk} + \mu$$

Transmission capacity is likely to have an effect on the regulating power prices. If prices on average are lower in Norway than in Denmark, this suggests that there are profits to be made from export from north to south. But, as the transmission capacity increases, the Danish prices are likely to decrease as a result.

4 Data

The data used are collected from several different sources. The data on quantities and prices in the spot market is collected from Nord Pool, as is the data on imports and exports. The data on hourly wind, central and de-central production in Denmark comes from Energinet.dk. These are highly reliable sources, and one can assume that the data is of good quality. For regulating power the observations start in December 2005, but prices for downwards regulation are only available from January 1. 2011. The analysis period will therefore be from December 2005 - December 2012. Upwards regulation was purchased in West Denmark in 38% of the hours in the period, and downwards regulation in 33% of the hours. A list of the data used is found in Appendix 2.

4.1. Nord Pool Spot prices

	No2	Dk1
Average	41.77	42.86
Standard deviation	19.27	18.05
Variance	371.26	325.93
Min	1.45	-200.00
Max	1400.10	943.04
Observations	61320.00	61320.00

Table 4.1: Statistical summary of the hourly elspot prices. No2 and Dk1 represent the price areas of southern Norway and Western Denmark.

The prices are recorded hourly. All prices are given in Euros. The average in Norway is higher than the average in Denmark, and the difference is statistically significant on a 1% level of confidence. The high standard deviation and the dramatic gap between maximum and minimum values are typical for the electricity market. The minimum value in Denmark is equal to the pricing floor at Nord Pool Spot, which indicates the value probably would be even lower if allowed.

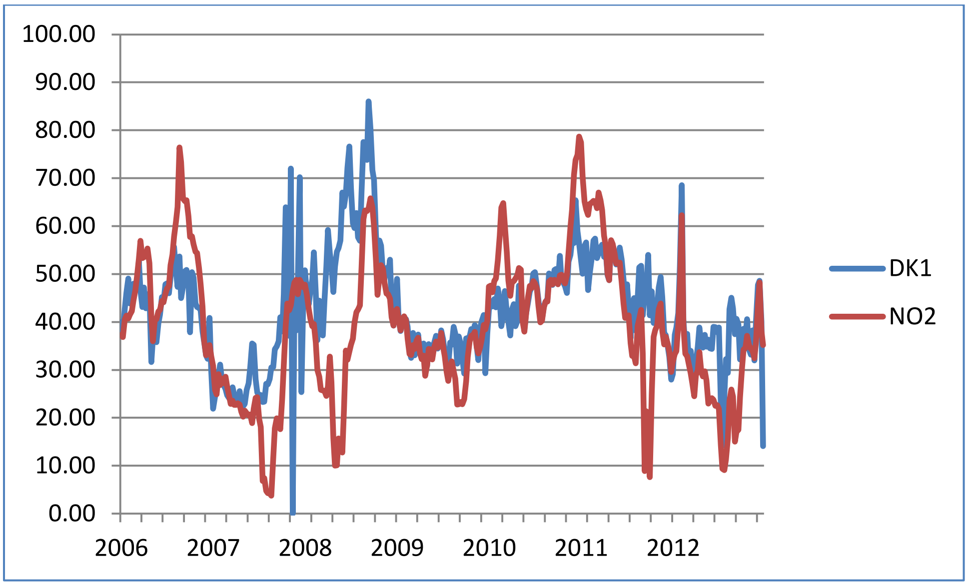

Figure 4.1: Spot prices in Euros in the period 2005-2012, weekly averages.

The graph illustrates the large variation between the two time series, and the volatility in the electricity market. Because of the weekly resolution, the most dramatic price drops in the DK1 is not visible, but extreme variations like the one of winter 2007/08 stands out. 2006 was a dry year, and the Norwegian prices rose high above those in Denmark during fall this year. October 2008 was the oil price peak, and the prices in Denmark were affected. In February 2012 two of the largest nuclear reactors in Sweden failed, and combined with low temperatures this resulted in a high spike in both time series. It is evident that many different factors set of fluctuations in the electricity market. The two time series has positive correlation (0.48).

4.2. Difference in regulating power prices

	Up no2-dk1	Down no2-dk1
Average	-6.40	-2.80
Standard deviation	21.40	16.28
Min	-593.83	-106.45
Max	234.17	281.48
Number of obs.	18526.00	18526.00

Table 4.2: Statistical summary of the difference in hourly regulating power prices in the period 01.01.2011-20.02.2013

The table above shows the summary statistics of the differences in prices between the southern Norway and west Denmark. On average, the prices in Denmark are higher than those in Norway for the hours that data are available. The averages are tested and found to be different from zero on a 1% level of confidence.

4.3. Coal, oil and natural gas prices

The price data for natural gas is collected from the Russian exchange, and represent monthly averages (€/1000m³). The coal prices (€/1000kg) are collected from the Australian exchange because of difficulty obtaining data from European sources. The oil price (€/barrel) used is for light Texas intermediate (WTI), as this is a common benchmark for oil prices. All of the prices have been converted from original currency to Euros, in order to simplify interpretation of the results.

Variable	Obs	Mean	Std. Dev	min	max
Natural Gas	70056	251.12	70.82	134.86	460.46
Coal	70056	66.84	22.34	34.00	123.72
Oil	70056	57.88	12.90	21.66	92.73

Table 4.3: Statistical summary of the Natural gas, coal and oil prices

Correlation coefficients				
	Natural Gas	Coal	Oil	Elspot dk1
Natural Gas	1.00			
Coal	0.45	1.00		
Oil	0.14	0.71	1.00	
Elspot dk1	0.11	0.34	0.24	1.00
Elspot no2	-0.02	0.18	0.03	0.47

Table 4.4: Correlation coefficients between fossil fuel and elspot variables.

Natural gas is the commodity most relevant to this analysis, as it directly impacts the marginal cost of regulating power produced in Denmark, but coal prices are also interesting, as they are price drivers for the base load production and thus affects regulating power prices. Natural gas is known to be one of the most volatile commodities in the world, and as it is commonly used for direct heating as well as for peak load electricity, its prices tend to correlate with temperature. Coal is easier to store, and used mainly for base load production, and therefore also less volatile. We can see that in this period, the standard deviation for coal is quite high. This is likely to be a result of the significant shock during the 2008 financial crisis. Oil prices are largely influenced by macroeconomic relations, and therefore moves about with coal. As expected, the correlation of the fossil fuels and the Danish spot price is stronger than the correlation with Norwegian spot price. There are no hourly prices available for these commodities, and so, a daily resolution is used.

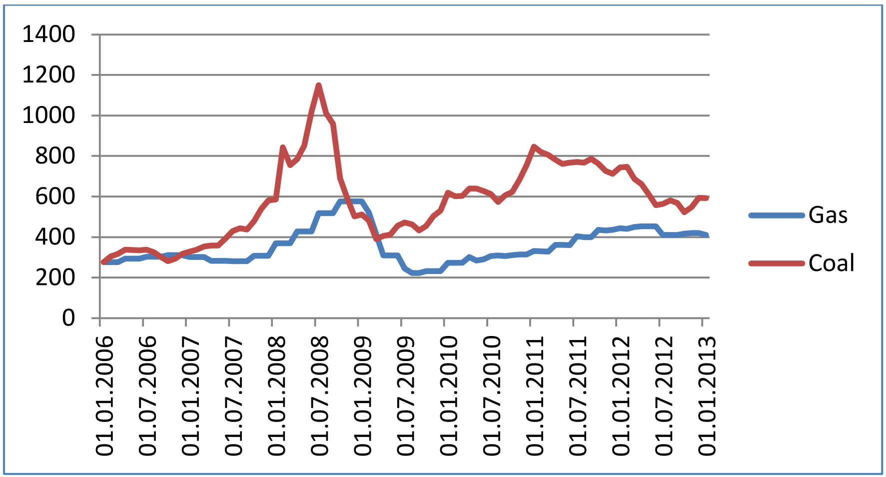

Figure 4.2: Price development in Oil and Natural gas in the period.

During the period analysed, both coal and gas prices has been subjected to shocks in the economy. Coal was hit hard by the credit crunch and the following reduction in industrial activity. There is positive correlation between the return on two in the period (0,12). All three data sets are integrated order one (non-stationary, but stationary in first differences).

4.5. Testing the data and the estimators

In order to determine if the obtained estimators are likely to be the results of coincidences or not, the will be tested using t-values. In the regressions with multiple explanatory variables an F-test is used to determine whether the variables are jointly significant or not.

As the data used is time series data, these are likely to have problems with serial correlation in the residuals. If serial correlation is present, this might interfere with and obscure the results of t and F-tests, and make them unreliable. One will therefore need to determine if serial correlation is present, and if so correct for this problem before running the regression. As the dataset consist of hourly observations over 12 years, the number of observations is high enough to rely on asymptotics. This way one can obtain consistent and unbiased coefficient estimators and standard deviations. Using Newey-West standard errors will correct for auto correlation and heteroscedasticity, as they will converge asymptotically to the correct standard errors (Woolridge 2009). However, a Newey-West regression in Stata does not result in any R^2-values. Because Newey-West estimation only corrects the standard errors, R^2-values are obtained using a normal OLS-command.

In order to make conclusions about the different variables relationship to each other, it is necessary to assume that their relationship is somewhat stable over time. Stationarity implies that the joint probability distribution stays the same over the entire period of observations. All of the data were tested for stationarity using a Dickey-Fuller test, and all of the variables are stationary, except those for coal and natural gas, see appendix 3.

In addition to checking for stationarity, it is also necessary that the data that is weakly dependent. Weak dependence implies that as the observations grow further apart, the connection between them converges towards zero. If one can conclude that the time series data to be used is weakly dependent, one can apply the large sample properties to the results obtained from the regressions. We can assume weak dependence because of the scope of time and the high number of observations. There is no reason to believe that the price of on a given date has any impact on the price of electricity 3 months after.

5 Analysis and results

5.1. The impact of wind power on the demand for regulating power

When calculating the results from equation 1 and 2 in order to establish the relationship between the volume of wind power produced and the demand for regulating power, the following results appear:

5.1.1. Downwards regulation

Table 5.1: Results of regressions with Newey-West standard errors for the period January 2006 to December 2012, made in Stata.

Western Denmark							
Q Dk1	Coef.	Std. Err.		Q Dk1	Coef.	Std. Err.	
share wind dk1	-164.677	9.282	***	MWh wind dk1	-0.055	0.004	***
share wind dk2	122.129	9.639	***	MWh wind dk2	0.068	0.008	***
Production dk1	-0.017	0.001	***	Production dk1	-0.009	0.001	***
_cons	25.968	2.849	***	_cons	6.186	2.515	***
Eastern Denmark							
Q Dk2	Coef.	Std. Err.		Q Dk2	Coef.	Std. Err.	
share wind dk1	-5.086	1.691	***	MWh wind dk1	-0.001	0.001	**
share wind dk2	-0.698	1.918		MWh wind dk2	-0.003	0.002	*
Production dk2	0.000	0.000		Production dk2	0.000	0.000	
_cons	-2.920	0.424	***	_cons	-3.795	0.374	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level							

The regression is done with two different explanatory variables, both representing the amount of electricity generated by wind in the system. The first one, takes values between zero and one, and represents the relative share power in the system generated by wind turbines for each operating hour. The second one, is the amount of wind power generated in the operating hour expressed in MWh/h. Dk1 represents the Western Denmark price area, and Dk2 represents the Eastern Denmark price area.

The regressions for Western Denmark have R^2-values of 0.093 and 0.094. The regressions for Eastern Denmark have R2-values of 0.004 and 0.006. Both the regressions for Western Denmark failed the Ramsey-reset test for misspecification, and their coefficients are most likely biased and inconsistent (see Appendix 5).

The poor statistical fit of the estimated equations suggest parameter estimates should not be given too much weight. As this is the only model estimated for downward regulation, I still choose to comment on the individual parameter estimates.

In this dataset, downwards regulation is registered as negative value. Hence one would expect the coefficients for downwards regulation to be negative. The coefficient estimates for wind in Western Denmark are negative and significant. This is interpreted as an increase in the amount of wind power in the system increases the volume of regulating power needed. It seems like strong winds are correlated with the need for downwards regulation. Also, the model explains about 9,4% of the total demand, and can be said to have some explanatory power.

The positive sign of the coefficients for Dk2 on demand in Western Denmark is interesting. The share and amount of wind produced and in Eastern Denmark is not significant for the areas volume of regulating power demanded in the period. This may be due to the low wind production in the area, especially in the first half of the period. The models for Eastern Denmark also have very little explanatory power. When there is need to downwards regulate in Dk2, this can be done by reducing exports from Dk1 to Dk2, after the Great Belt Power Link was opened. This policy change might have biased the results.

5.1.2. Upwards regulation

Table 5.1 Results of regression with Newey West standard errors for the period January 2006 to December 2012, made in Stata.

Western Denmark							
Q Dk1	Coef.	Std. Err.		Q Dk1	Coef.	Std. Err.	
share wind dk1	13.223	8.823		MWh wind dk1	-0.045	0.003	***
share wind dk2	-101.433	7.941	***	MWh wind dk2	0.041	0.009	***
Production dk1	0.005	0.001	***	Production dk1	0.014	0.001	***
_cons	57.591	2.810	***	_cons	34.014	2.519	***
Eastern Denmark							
Q Dk2	Coef.	Std. Err.		Q Dk2	Coef.	Std. Err.	
share wind dk1	0.088	2.799		MWh wind dk1	-0.002	0.001	**
share wind dk2	-12.510	2.284	***	MWh wind dk2	-0.005	0.003	*
Production dk2	0.001	0.001		Production dk2	0.002	0.001	***
_cons	11.127	0.866	***	_cons	8.684	0.768	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level							

The R^2-values for Western Denmark are 0.036 and 0.038, and for Eastern Denmark they are 0.006 and 0.004. F-tests show joint significance of the variables for all of the regressions. The regression on Western Denmark with production quanta variables failed the Ramsey-reset test for misspecification, and the coefficients are most likely biased and inconsistent. Despite the lack of explanatory power I will comment on the results, as this is the only model available.

For upwards regulation, the sign of the wind coefficients are expected to be positive. For Eastern Denmark, the statistically significant coefficients have negative signs, except for the very small coefficient for production, in the regression on production values. For Western Denmark, all coefficients for wind power, except the one for production in Eastern Denmark are negative. It seems from these calculations that the amount and share of wind power produced has a negative effect on the demand for upwards regulating power. These results do not support the research hypothesis.

5.1.3. Policy changes in the analysed time period

The first of December 2009, Nord Pool Spot introduced a negative pricing floor. This is expected to decrease the demand for regulating power, as this has given the wind turbine owners an incentive to shut down the turbines when the production exceeds the demand drastically. Another structural change that has influenced the demand for regulating power is the opening of the Great Belt Power Link (Storebælt HVDC), between East and West Denmark in 2010. As previously mentioned, this connection reduced the need for regulating reserves in Western Denmark by 300MW, which is a significant amount (33% of the manual reserves purchased in Denmark).

A split regression of before and after negative prices were introduced and the Great Belt Power Link opened gives the following results:

Downwards regulation

Table 5.2 Results of regressions with Newey-West standard errors for the different time periods, made in Stata.

Before negative prices: Jan 01. 2006 - Dec 01. 2009							
Western Denmark	**R2: 0.17**			Eastern Denmark	**R2: 0.009**		
Q-Dk1 Down	Coef.	Std. Err.		Q-Dk2 Down	Coef.	Std. Err.	
share wind dk2	173.065	19.617	***	share wind dk2	-8.166	4.583	
share wind dk1	-278.862	15.493	***	share wind dk1	-5.074	3.110	
Production dk1	-0.026	0.002	***	Production dk2	0.000	0.000	
_cons	55.279	4.686	***	_cons	-2.403	0.551	***
After negative prices, before TGBPL: Dec 01. 2009-Aug 20.2010							
Western Denmark	**R2: 0.081**			Eastern Denmark	**R2: 0.01**		
Q-Dk1 Down	Coef.	Std. Err.		Q-Dk2 Down	Coef.	Std. Err.	
share wind dk2	44.058	14.256	***	share wind dk2	-3.128	4.367	
share wind dk1	-93.688	14.122	***	share wind dk1	-1.174	4.051	
Production dk1	-0.006	0.001	***	Production dk2	-0.003	0.001	***
_cons	14.198	3.311	***	_cons	-1.135	1.226	
After TGBPL: Aug 20. 2010- Dec 31.2012							
Western Denmark	**R2: 0.012**			Eastern Denmark	**R2: 0.002**		
Q-Dk1 Down	Coef.	Std. Err.		Q-Dk2 Down	Coef.	Std. Err.	
share wind dk2^2	-31.39	7.27	***	share wind dk2	2.128	1.956	
share wind dk1^2	4667.23	1649.4	***	share wind dk1	-3.341	1.803	*
Production dk1	-0.006	0.001	***	Production dk2	-0.001	0.001	*
_cons	-8.22	2.501	***	_cons	-3.617	0.707	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level							

From the R^2-values, we can see that these models have very little explanatory power. F-tests show joint significance of the variables for all of the regressions. The regressions for Western Denmark in the first and second period failed the Ramsey reset-test for misspecification, and the coefficients are most likely biased. In the regression for the third period, quadratic terms for share of production from wind had to be added to avoid problems with wrong functional form. In lack of better alternatives, I choose to comment on the results despite the poor fit of the models.

Here, the expected sign of the coefficients on wind share is negative. When dividing the data set, none of the coefficients for wind is significant above a 10% level in Eastern Denmark. In the case of Western Denmark, the coefficients on wind power are decreasing in absolute value over the time periods. The introduction of negative prices might have had an effect on the impact of the wind turbines on the market for regulating power. The difference in the coefficients for the different time periods were tested against each other with weighted standard error t-tests [1]and all found to be statistically different from zero on a 1% level of confidence. During the analysis period, there has been installed a considerable amount of new capacity. The production coefficient estimators for Western Denmark are declining from the first period to the second period. Because of the quadratic terms, the coefficients for the third period are somewhat more difficult to interpret, but the convex form of the Dk1 wind coefficient suggest the relationship between Dk1 wind and the volume of regulating power is negative until a certain point, before changing sign. The policy changes seem to have worked as planned, reducing the need for regulating power in relation to the share of wind power. The last period is the most relevant on order to get some insight in what to expect from the future, and the result is similar to the previous, an increase in the share of wind power leads to an increased demand for downwards regulating power in Western Denmark, and the coefficients for wind are not significant on a 5% level of confidence for Eastern Denmark.

[1] T- values obtained by the formula: $t = \frac{\beta_a - \beta_b}{w\ S.E}$, where w S.E is given by $w\ S.E = \sqrt{(Var_a N_a) + (Var_b/N_b}$

Upwards regulation

Table 5.3 Results of regressions with Newey-West standard errors for the different time periods, made in Stata.

Before negative prices: Jan 01. 2006 - Dec 01. 2009							
Western Denmark	R2: 0.035			Eastern Denmark	R2: 0.009		
Q-Dk1 Up	Coef.	Std. Err.		Q-Dk2 Up	Coef.	Std. Err.	
share wind dk2	72.826	22.121	***	share wind dk2	-6.473	3.506	*
share wind dk1	-156.116	14.973	***	share wind dk1	-7.542	2.527	***
Production dk1	0.006	0.002	***	Production dk2	0.002	0.001	***
_cons	70.737	4.491	***	_cons	6.531	0.807	***
After negative prices, before TGBPL: Dec 01. 2009-Aug 20.2010							
Western Denmark	R2: 0.01			Eastern Denmark	R2: 0.022		
Q-Dk1 Up	Coef.	Std. Err.		Q-Dk2 Up	Coef.	Std. Err.	
share wind dk2	32.326	21.194		share wind dk2	-5.192	7.428	
share wind dk1	-55.613	15.636	***	share wind dk1	-10.220	7.740	
Production dk1	-0.001	0.002		Production dk2	0.005	0.002	***
_cons	45.046	5.881	***	_cons	5.418	2.577	**
After TGBPL: Aug 20. 2010- Dec 31.2012							
Western Denmark	R2: 0.025			Eastern Denmark	R2: 0.017		
Q-Dk1 Up	Coef.	Std. Err.		Q-Dk2 Up	Coef.	Std. Err.	
share wind dk2	-0.164	7.973		share wind dk2	-41.11	4.97	***
share wind dk1	-48.459	7.402	***	share wind dk1^2	-5701.6	1132	***
Production dk1	0.005	0.001	***	Production dk2	0.004	0.001	***
_cons	34.619	3.067	***	_cons	30.91	2,96	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level							

These models have very little explanatory power, with R2-values ranging from 0.01-0.035. F-tests rejected the null hypothesis of no joint significance of the coefficients on a 1% level of significance for all of the regressions. The regression for Eastern Denmark in the first period failed the Ramsey reset-test for misspecification, and the coefficients are most likely biased. For the last period regression on Eastern Denmark, a quadratic term on share of production from wind had to be added to avoid problems with wrong functional form.

Here, the expected signs for the wind coefficients are positive. Again, the results have negative signs, indicating that increased wind reduces the demand for upwards regulating power. One explanation for this seemingly odd result might be that there is biasedness in forecast errors; they more often predict higher amounts of wind than actually occurs, than lower. However, one might suspect the wind power variables no longer are uncorrelated with the error term after negative prices were introduced, as the producers now has an incentive to seize production when demand is low compared to supply of slow regulated base load. This effect will probably be reflected in the production variable. Also, the very low goodness of fit measure (R^2) indicates that the effects estimated in the model have little practical value.

5.2. What influences the prices for regulating power

5.2.1. Upwards regulation Western Denmark

Table 5.5: Results of regression with Newey-West standard errors, made in Stata.

Price upwards regulation Dk1	Coef.	NW Std. Err.	
Lagged price of upwards regulation	0.61	0.03	***
Exponential term of spot price Dk1	1.12E-37	0.00	*
Spot price Southern Norway	0.17	0.02	***
Wti Oil price	-0.08	0.02	***
Price natural gas	-0.02	0.01	**
Share of el. Production from wind, Dk1	-8.52	1.00	***
Share of el. Production from wind, Dk2	0.91	1.20	
Volume of upwards regulation Dk1	0.05	0.01	***
Volume of upwards regulation Dk2	0.09	0.01	***
Export capacity from Dk1 to No2	0.00	0.00	
Export capacity from No2 to Dk1	0.00	0.00	
Planned export from No2 to Dk1	0.00	0.00	***
Volume of reserves purchased Dk1	-0.01	0.00	***
_cons	27.92	3.61	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level			

The R^2-value for this regression is 0.693, and the F-test shows joint significance of the coefficients. The model has problems with misspecification, and can therefore not be trusted to be consistent and unbiased. It is correctly specified when testing at a 10% level of confidence, but fails at a 5% level (see Appendix 5 for misspecification testing).

Here, one would expect to find a positive relationship between the share of wind production and price for upwards regulation if increased wind power does increase the demand for regulating power. The model estimates show that the share of wind production in the system in the hour of upwards regulation has a negative effect on the price for Western Denmark. This might be explained by the fact that many peak load plants are likely to stand by in periods with a high share of wind, and are able to offer low price upwards regulation. Also, the price effect of low marginal cost wind on the system price might influence the regulating power price. The coefficient for Eastern Denmark has a positive sign, but is not statistically significant. The price of coal is omitted from this model because it caused problems with misspecification. When visually inspected, the term for spot price in Western Denmark seems to have more of an exponential relationship than a linear one to the upwards regulating price (see Appendix 4). The relationship between the regulating power price and the spot prices both in Southern Norway and in Western Denmark are positive and significant, as expected.

5.2.2. Upwards regulation in Eastern Denmark

Table 5.6 Results of regression with Newey-West standard errors, made in Stata.

Price upwards regulation dk2	Coef.	NW Std. Err.	
Lagged price of upward regulation	0.567	0.035	***
Exponential term of spot price Dk2	3.1E-37	9.9E-38	***
Spot price Southern Norway	0.139	0.026	***
Volume of upwards regulation Dk2	0.206	0.028	***
Price natural gas	0.016	0.008	**
Wti Oil Price	-0.157	0.032	***
Coal Price	0.162	0.027	***
Dummy for congestion on SK 1-3	3.355	0.412	***
Volume of upwards regulation Dk1	0.018	0.007	***
Share of el. Production from wind, Dk2	0.041	1.341	
Share of el. Production from wind, Dk1	-10.182	1.244	***
_cons	6.233	3.394	
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level			

The R^2-value for this regression is 0.649, and the F-test shows joint significance of the coefficients. This model does not show misspecification problems when tested, and is therefore more trustworthy than the model for Western Denmark.

As in the Western Denmark price analysis, the coefficients on share of production from wind are negative for Western Denmark and insignificant for Eastern Denmark. In this model, a dummy for congestion on the Norway-Denmark interconnector was added instead of the export capacity, as it is easier to interpret and fitted to the model without causing misspecification problems. The congestion term is positive and significant, indicating profitability in exports from Norway to Denmark. The volume of upwards regulation has the expected positive sign, both for Eastern and Western Denmark.

5.2.3. Downwards regulation in Western Denmark

Table 5.7 Results of regression with Newey-West standard errors, made in Stata.

Downwards regulating price Dk1	Coef.	NW Std. Err.	
Lagged term for regulating price	0.741	0.022	***
Volume of downwards regulation, Dk1	0.034	0.003	***
Volume of downwards regulation, Dk2	0.004	0.001	***
Exponential term of spot price Dk1	3E-37	4E-38	***
Price natural Gas	-0.029	0.004	***
Price Coal	0.041	0.010	***
Wti oil price	0.021	0.014	
Dummy for congestion on SK 1-3	1.482	0.186	***
Share of el. Production from wind, Dk2	-0.539	0.777	
Share of el. Production from wind, Dk1	-8.986	0.767	***
_cons	16.879	2.517	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level			

The R^2-value for this regression is 0.786, suggesting the model explains 78.6% of the changes in price on downwards regulation. An F-test show joint significance of the coefficients.

As in the above regressions, the coefficient for wind production in Eastern Denmark is insignificant, and that for Western Denmark is negative. Here, the congestion coefficient is significant and positive. The coefficient for elspot price is positive, but hard to interpret in this case as well because of the exponential form. The use of this form was necessary to use in order to avoid functional form problems.

5.2.4. Downwards regulation in Eastern Denmark

Table 5.8 Results of regression with Newey-West standard errors, made in Stata

Price downwards regulation dk2	Coef.	Std. Err.	
L1. Down Regulation Dk2	0.514	0.032	***
Elspot DK2	0.448	0.039	***
Price Natural Gas	-0.014	0.004	***
Price Coal	-0.046	0.012	***
Price Oil	0.048	0.019	***
Congestion	-0.200	0.235	
Share of production from wind power East	-0.359	0.672	
Share of production from wind power West	-4.111	0.785	***
_cons	5.567	2.176	***
*significant on a 10% level ** significant on a 5% level *** significant on a 1% level			

The R2-value for this regression is 0.813, and the F-test shows joint significance of the coefficients. The model is correctly specified according to Ramseys reset test.

Here, the congestion term is insignificant, implying that the imports/exports of downwards regulation is insignificant in regard to the price. For the share of wind in Eastern Denmark, the coefficient is not significant, but this is not all that surprising, considering the low production in Eastern Denmark. The coefficient for wind share in Western Denmark is significant, and negative. This might again be an effect of wind power productions impact on elspot prices.

5.3. Problems with the model

The variables to use are chosen by intuitive deduction, as there seems to be little empirical research available on the regulating power market. The identification of what variables to use has therefore been somewhat problematic, and might not be correct for the purpose. Prices and volume for faster reserves is probably significant, but data is hard to access. Further, the market is quite complex, with many unobserved factors, and players with different objectives. For simplicity reasons, the prices in neighbouring areas like Sweden and Germany has been left out, but the demand here is likely to impact prices as ancillary services are traded across borders.

The volume demanded is unpredictable by nature, as the demand occurs as a result of an unexpected event. Poor explanatory power in these models is therefore not surprising.

Data available for downwards regulating prices turned out to be quite difficult to obtain, so the analysis on this is done on data from the two years 2011 and 2012 only. This period is most likely too short to conclude from the analysis.

Also, the prices of fossil fuels are all non-stationary, which might lead to spurious correlation. These prices are also for daily prices, and the use of data with different time resolution further complicates the analysis.

6 Discussion

My two research hypotheses:

- the demand for regulating power in Denmark will increase as the share of renewable power production grows and thermic power plants shut down, and
- Norwegian hydropower producers can profit from this development by offering regulating power on the Skagerrak interconnectors,

lie behind the discussion in this chapter. Please note that I choose to frame these discussions in a more open format than the stricter postulate form of the hypotheses as I find this more conducive for the discussions.

Will there be increased demand for regulating power in the Danish market?

The results of the analysis from in the previous chapter does not support the hypothesis of increased demand for upwards regulating power when there is increased wind power production. When looking at the different strategies available for balancing the power system, and the analysis result, it does not seem appropriate to assume such an effect will find place in the coming years.

It is possible that in spite of an increased share of wind in the grid, the demand for regulating power in the way it is traded today might stay the unchanged or even decrease, due to changes in the market structure. In 2001, the German intraday market changed gate closure from one hour to 15 minutes, giving the balance responsible parties more opportunities to correct for imbalances without involving the TSO. Such a development does not change the overall demand for flexibility, but the trade is taken out of the regulating power market. A development in this direction is expected (Bjørndalen, Bakken and Berg Skånlund, et al. 2011), and it would lead to a decreased demand in the regulating power market.

If there is such an increase, does it represent an opportunity to profit for Norwegian hydro producers?

For downwards regulating, the analysis does show increased demand. In some periods during the summer when Norway is importing wind power and the demand is low, there is little downwards regulation available in the Norwegian system. When demand is low, most of it is covered by the run of the river power plants. The reservoir hydropower plants are not producing and can therefore not reduce their production. Downwards regulation will in these periods have to be done by shutting down wind turbines or spilling water through run of river plants without producing (Bjørndalen, Bakken and Berg Skånlund, et al. 2011), or through the expensive downwards regulating in thermic plants. It is therefore not certain that the increase of demanded downwards regulation represents an opportunity for Norwegian hydropower producers to profit.

Independent of the demand for regulating power, there is a strategic limit as to how much of the supply the transmission system operator (TSO) feels safe buying from one source, considering the security of supply. Estimates made by EC-Group limits the potential for regulating power calculates possible exports to be about 20% of capacity for each HVDV-cable (Bjørndalen and Bakken 2011). In the case of Norway-Denmark this amounts to 340MW after Skagerrak 4 is completed. This will limit the possible exports of regulating power from Norway, and further limit the possibilities for future profitability.

The electricity prices on the spot market will decrease as different subsidising schemes for building more renewable power production units has been implemented, and a power surplus in neighbouring countries as well as in Norway might be the reality within the coming years. The increase in production is not expected to be matched by a similar increase in demand (Bjørndalen and Bakken 2011). As most of the available reservoir capacity is already in use, the renewable power being built is intermittent in most cases. So far, the immediate price reducing effect of Danish wind on Norwegian spot prices has been small. Estimation shows that a doubling of wind power production in Denmark will typically reduce the prices in southern Norway by 0.3-0.5% (Mauritzen, Dead battery? Wind power, the spot market, and hydro power interaction in the nordic electricity market 2012).The price effect is far more significant in Denmark. The transmission capacity constraints cause the price reducing effect of intermittent power sources to appear in the price area where the generation takes place. With increased transmission capacity, such as Skagerrak 4, the effect most likely will be spread over a bigger area. Because the price of regulating power is closely linked to the spot price, it is possible that the increase in production capacity might absorb some of the possible profitability in Norwegian regulating power.

In the period of the analysis, there has been an active agreement between Energinet.dk and Dong Energy for delivery of manual reserves in Eastern Denmark. The agreement expires in 2015, and because of the Great Belt Power Link, this will also affect the regulating power market in Western Denmark. When the agreement expires, Dong Energy is no longer committed to submit bids for regulating power at the market. This might lead to a more efficient market, but the effect on the prices for regulating power is uncertain.

The analysis on regulating power prices in Eastern Denmark pointed out the prices of natural gas as important for the price of regulating power. The market expects the prices to increase in the time until 2021, as the forward curve for natural gas prices show:

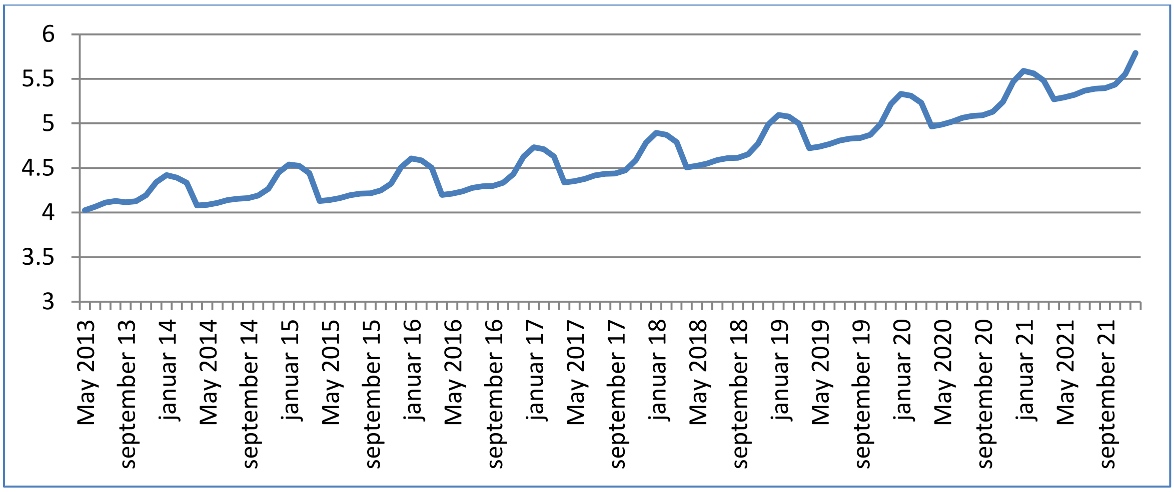

Figure 6.1: Gas forward prices from CME Group downloaded 29. March 2013. Prices are in US Dollars (Group u.d.).

This indicates growing marginal cost for gas power plants which competes for the deliveries of regulating power. Gas plants also deliver peak load power on the elspot market, and increasing gas prices might also affect regulating power prices through increased spot price. This development points in favour of increased profitability for Norwegian hydro producers, both in the regulating market, at Elbas and in the spot market.

7 Conclusion

The research hypotheses for this thesis are:

- The demand for regulating power in Denmark will increase as the share of renewable power production grows and thermic power plants shut down.
- Norwegian hydropower producers can profit from this development by offering regulating power on the Skagerrak interconnectors.

If the results of the empirical analysis are trust worthy, there is no reason to assume an increased demand for upwards regulation in the Danish market in the future, despite the rapid expansion of wind power production. This might indicate that the possibilities for Norwegian hydro producers are not mainly in the regulating power market. However, this does not mean that the flexibility of hydropower will not be profitable, as the need for flexibility stretches far beyond the regulating power market. New market designs and a larger scope of ancillary service products represent opportunities for all market participants, including hydro producers. The outlook for prices is not the most optimistic, seen from a hydro producer's point of view, and this also limits the possible profitability.

For downwards regulation the empirical analysis points towards an increased demand. The analysis might however not be reliable due to the short analysis period. If, however, there is an increased demand, there is no certainty of profitability for Norwegian hydro producers due to the price effect of new installed intermittent capacity, and the competition from numerous other regulating technologies.

All in all, it seems the regulating power market might not be the goldmine for Norwegian hydropower as the second hypothesis suggests, but there might still be profitability for Norwegian hydro power exchange in the other power markets.

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9 Appendices

Appendix 1

Volatility, data from the period 03.01.2006 – 30.12.2012

. summarize price_dk1 price_dk2 price_krs if year>2006

Variable	Obs	Mean	Std. Dev.	Min	Max
price_dk1	52584.00	42.63	18.72	-200.00	943.04
price_dk2	52584.00	45.59	30.72	-200.00	2000.00
price_krs	52584.00	37.45	15.34	0.00	210.00

. summarize price_dk1 price_dk2 price_krs if summer == 0 & year>2006

Variable	Obs	Mean	Std. Dev.	Min	Max
price_dk1	31416.00	42.39	18.71	-200.00	943.04
price_dk2	31416.00	46.77	36.47	-200.00	2000.00
price_krs	31416.00	41.51	14.00	2.23	210.00

. summarize price_dk1 price_dk2 price_krs if summer == 1 & year>2006

Variable	Obs	Mean	Std. Dev.	Min	Max
price_dk1	21168.00	42.99	18.73	-23.64	184.94
price_dk2	21168.00	43.85	19.12	-0.10	190.40
price_krs	21168.00	31.43	15.25	0.00	70.28

. summarize price_dk1 price_dk2 price_krs if daytime == 1 & year>2006

Variable	Obs	Mean	Std. Dev.	Min	Max
price_dk1	26292.00	47.87	20.10	-50.06	943.04
price_dk2	26292.00	52.02	38.88	-50.06	2000.00
price_krs	26292.00	38.74	15.56	1.15	210.00

. summarize price_dk1 price_dk2 price_krs if daytime == 0 & year>2006

Variable	Obs	Mean	Std. Dev.	Min	Max
price_dk1	26292.00	37.39	15.56	-200.00	215.09
price_dk2	26292.00	39.16	17.13	-200.00	420.85
price_krs	26292.00	36.16	15.00	0.00	169.90

Appendix 2

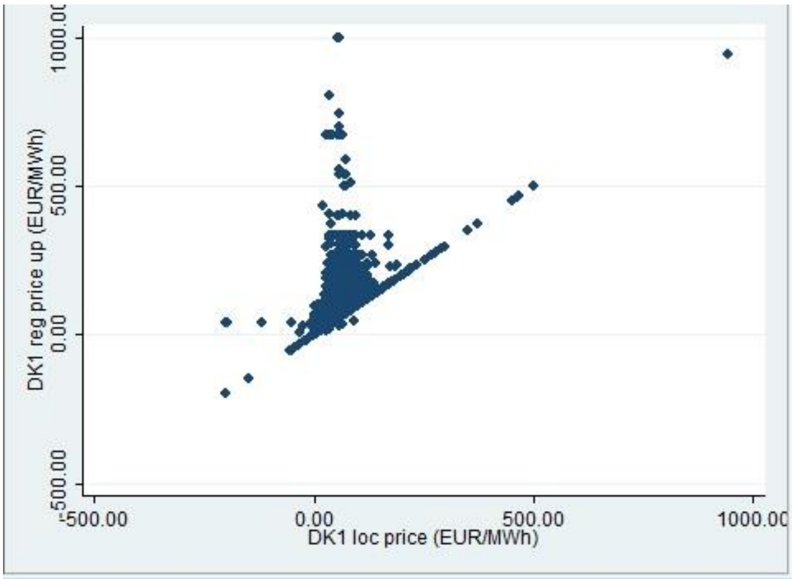
Variable	Short	Frequency	Denomination
Quantity upwards regulation Western Denmark	regv_up_Dk1	Hourly	MWh
Quantity upwards regulation Eastern Denmark	regv_up_Dk2	Hourly	MWh
Quantity downwards regulation Eastern Denmark	rev_do_dk2	Hourly	MWh
Quantity downwards regulation Western Denmark	regvv_do_dk1	Hourly	MWh
Price upwards regulation Western Denmark	regp_up_dk1	Hourly	€/MWh
Price upwards regulation Eastern Denmark	regp_up_dk2	Hourly	€/MWh
Price downwards regulation Western Denmark	np_do_dk1	Hourly	€/MWh
Price downwards regulation Eastern Denmark	np_do_dk2	Hourly	€/MWh
Price Coal	pcoal	Daily	€/1000kg
Price Natural Gas	pngas	Monthly	€/1000m^3
Price oil	wti	Daily	€/barrel
Share of production from wind, Western Denmark	wndshr_dk1	Hourly	%
Share of production from wind, Eastern Denmark	wndshr_dk2	Hourly	%
Production of wind power, Western Denmark	wpdk1	Hourly	MWh
Production of wind power, Eastern Denmark	wpdk2	Hourly	MWh
Production of electicity in Western Denmark	prod_dk1	Hourly	MWh
Production of electricity in Eastern Denmark	prod_dk2	Hourly	MWh
Spot price in Western Denmark	price_dk1	Hourly	€/MWh
Spot price in Eastern Denmark	price_dk2	Hourly	€/MWh

Appendix 3

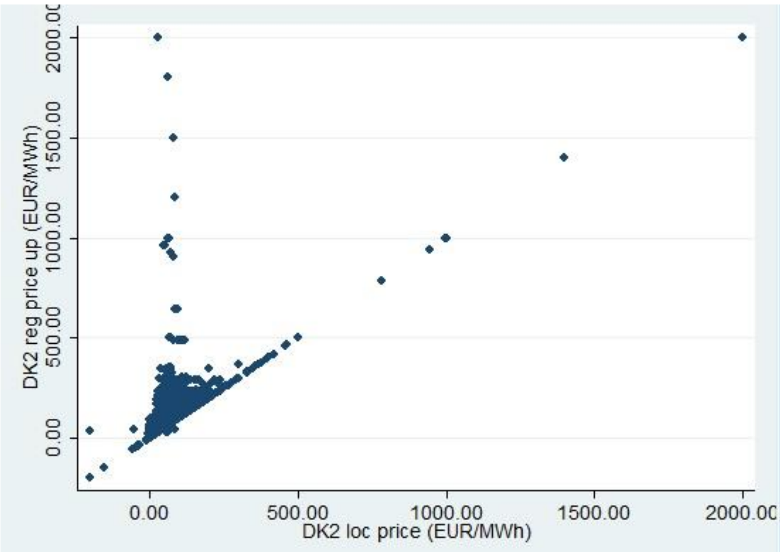
Variable	Short	Stationary	
Quantity upwards regulation Western Denmark	regv_up_Dk1	yes	***
Quantity upwards regulation Eastern Denmark	regv_up_Dk2	yes	***
Quantity downwards regulation Eastern Denmark	rev_do_dk2	yes	***
Quantity downwards regulation Western Denmark	regvv_do_dk1	yes	***
Price upwards regulation Western Denmark	regp_up_dk1	yes	***
Price upwards regulation Eastern Denmark	regp_up_dk2	yes	***
Price downwards regulation Western Denmark	np_do_dk1	yes	***
Price downwards regulation Eastern Denmark	np_do_dk2	yes	***
Price Coal	pcoal	no	
Price Natural Gas	pngas	no	
Price oil	wti	yes	*
Share of production from wind, western Denmark	wndshr_dk1	yes	***
Share of production from wind, Eastern Denmark	wndshr_dk2	yes	***
Production of wind power, Western Denmark	wpdk1	yes	***
Production of wind power, Eastern Denmark	wpdk2	yes	***
Production of electicity in Western Denmark	prod_dk1	yes	***
Production of electricity in Eastern Denmark	prod_dk2	yes	***
Spot price in Western Denmark	price_dk1	yes	***
Spot price in Eastern Denmark	price_dk2	yes	***

*significant on a 10% level ** significant on a 5% level *** significant on a 1% level

Appendix 4



Scatterplot of the spot price and the upwards regulating price in Western Denmark



Scatterplot of the spot price and the upwards regulating price in Eastern Denmark

Appendix 5

Misspecification tests for price analyses

Price model for upwards regulation Western Denmark
F(3, 17314) = 3.64
Prob > F = 0.0121

Price model for downwards regulation Western Denmark
F(3, 17291) = 2.15
Prob > F = 0.0920

Price model upwards regulation Eastern Denmark
F(3, 17291) = 2.15
Prob > F = 0.0920

Price model downwards regulation Eastern Denmark
F(3, 17503) = 1.57
Prob > F = 0.1949

Misspecification tests for volume analyses

Table 9.5.1: results of Ramsey reset tests for misspecification on the different models for upwards regulation

For the period Jan. 01.2006 - Dec 31. 2012							
Western Denmark share of wind model				Eastern Denmark share of wind model			
F	1.8	Prob > F	0.14	F	1.93	Prob > F	0.12
Western Denmark wind production model				Eastern Denmark wind production model			
F	8.92	Prob > F	0	F	2.32	Prob > F	0.73
Before negative prices: Jan 01. 2006 - Dec 01. 2009							
Western Denmark				Eastern Denmark			
F	0.37	Prob > F	0.77	F	3.78	Prob > F	0.01
After negative prices, before TGBPL: Dec 01. 2009-Aug 20.2010							
Western Denmark				Eastern Denmark			
F	1.11	Prob > F	0.34	F	1.68	Prob > F	0.169
After TGBPL: Aug 20. 2010- Dec 31.2012							
Western Denmark				Eastern Denmark			
F	1.8	Prob > F	0.14	F	0.36	Prob > F	0.07

Table 9.5.2: results of Ramsey reset tests for misspecification on the different models for downwards regulation

For the period Jan. 01.2006 - Dec 31. 2012							
Western Denmark share of wind model				Eastern Denmark share of wind model			
F	71.73	Prob > F	0	F	1.09	Prob > F	0
Western Denmark wind production model				Eastern Denmark wind production model			
F	23.23	Prob > F	0	F	2.94	Prob > F	0.032
Before negative prices: Jan 01. 2006 - Dec 01. 2009							
Western Denmark				Eastern Denmark			
F	65.19	Prob > F	0	F	0.7	Prob > F	0.55
After negative prices, before TGBPL: Dec 01. 2009-Aug 20.2010							
Western Denmark				Eastern Denmark			
F	10.12	Prob > F	0	F	1.44	Prob > F	0.23
After TGBPL: Aug 20. 2010- Dec 31.2012							
Western Denmark				Eastern Denmark			
F	7.28	Prob > F	0	F	1.88	Prob > F	0.13