Wind power and electricity markets

A study of wind power capacity, trade and prices on the Nordic electricity market.

Anders Haulin

Supervisor: Jerker Holm

Department of Economics
School of Management and Economics
Lund University
Autumn 2014

Abstract

Global wind power capacity has greatly increased in the last decades and is in certain areas constituting a significant share of generating capacity. This thesis examines wind power production data along with prices and inter-regional trade volumes on the Nordic electricity market *Nord Pool Spot* to deduce the effects of wind power on the grid. The research focused on Denmark, since it gets a very large fraction of its energy from wind power and keeps excellent energy data available for research. By computing measures of the state of the energy market and looking at the developments of these over time as well as their correlation to wind power capacity, conclusions were drawn on the role of wind power in the electricity market.

It was found that investments in wind power capacity had not experienced decreasing marginal returns but that wind power had reduced the capacity utilization of conventional Danish power plants. Wind energy was found to be sold on average at 10 % lower prices than conventional energy and Danish prices were found to have increased relative to Norwegian prices, although causation in wind power expansion could not be proven. Spot price standard deviation did not increase notably during the time span examined.

As wind power capacity increased, wind power production became an increasingly accurate predictor of electricity export and Danish trade balance did worsen, although not in a statistically significant manner. Neither transmission capacity nor profits made by operators of transmission cables increased during the period.

Subsidies were found have expanded rapidly during the 21st century and were shown to be good predictors of wind power capacity expansion, with a lag of 1-2 years. Around 20 % of Danish wind power subsidies were exported during the period studied.

The thesis concludes that the Nordic electricity market has incorporated large volumes of intermittent power capacity without any radical effects on trade or prices, plausibly due to large hydro-electric capacity, and with a likely decrease in CO_2 emissions.

Contents

Chapter 1

Introduction

> *The first lesson of economics is scarcity: there is never enough of anything to fully satisfy all those who want it. The first lesson of politics is to disregard the first lesson of economics.*
>
> – Thomas Sowell

This thesis is divided into five chapters, the motivation and relevance is provided in this introduction, along with some background knowledge about electricity markets. Chapter 1 concludes by stating the research questions guiding the work. A theoretical background about the economics concepts relevant to the work is provided in the theory chapter. The method for investigating the research questions is presented in Chapter 3 and the results of these investigations under Chapter 4. The results are discussed, put into perspective and concluded in the final chapter.

1.1 Thesis scope

This thesis aimed to study the electricity markets, looking at the effects of increasing wind power generating capacity on market properties. The work was focused on Denmark: a country that, by international standards, produces a very large portion of its electricity from wind power and keeps excellent and transparent records on the electricity market. The focus of the thesis was on wind power capacity, electricity prices, electricity trade, wind power subsidies, market mechanisms and the links between these aspects of the electricity market.

1.2 Purpose

The reason for examining the effects of increasing wind power is to better understand how the electricity market responds to increasing intermittent generating capacity. This response is interesting since electricity markets across the globe are seeing more power generated from intermittent renewables. The effects of these changes and the challenges they bring are interesting for policy-makers and market actors. The project looked at some of the implications for wind energy producers, other electricity producers, governments and market traders to investigate which players are being and will be most affected by wind power expansion. To better guide future investments it is necessary to understand how changes in the electricity market are effected by wind power expansion. Potential challenges include changing dynamics between the need for capacity and the return on this capacity; when thermal plants expected to generate enough electricity on calm days are squeezed out by low prices on windy days, the return on investments in capacity is harmed. Wind power brings supply shocks and could necessitate more trade between areas with available demand and supply to cope with quickly rising and falling production. If wind power expansion goes so far that good locations for turbines are exhausted it is possible that new turbines have to be placed in sub-optimal locations leading to poorer performance. If forecasts for wind power production are not accurate enough it is possible that the day-ahead bidding for sale and purchase of electricity that has been the predominant market for electricity in the Nordics could become less efficient: resulting in day-ahead contracts not equilibrating supply and demand. These are some of aspects of why the study of this area is interesting, the research questions guiding the project are stated in Section 1.6.

1.3 The electricity market and prices

Electricity is a unique commodity in many ways and has one property that separates it from almost all other widely traded commodities: it can not be stored. There are ways to *convert* electricity into other forms of energy that can later be easily reconverted with small loss, such as chemical energy in a re-chargeable battery or potential energy in a hydro-power dam (by pumping water up the stream). Most grids do not however have this kind of capacity on any greater scale and if demand exceeds supply, grid voltage will drop, causing a *brownout*. In analogy there are usually not any means for a grid to dispose of surplus electricity: if supply exceeds demand the voltage in the grid will start to rise, endangering the grid and equipment connected to it. Alas, electricity cannot be stored and it must always be produced in such a way that supply meets demand and any deviation from equilibrium is instantly corrected. On the demand-side, electricity use is dictated by consumer behavior and although demand management is possible (some industries may only run electricity-demanding equipment at night) it is vital for a grid to have a good level of supply-side management to meet demand at all times. Section 1.3.1 deals with the properties of different power sources.

1.3.1 Generating properties of different electricity sources

Since electricity can not be stored and consumer behavior can't be dictated, the robustness of a grid depends greatly on the flexibility of the supply side. Different energy sources can have very different properties and the flexibility aspects of major power sources are listed below.

Coal Power is an important (albeit environmentally ghastly) power source in Europe, power plants are large and cheap to run but can not regulate output well since they burn large quantities of solid fuel.

Natural Gas plants also utilize fossil fuel (but a much cleanlier one than coal) and can regulate output quickly. Gas turbines are a form of gas power plants that regulate power extremely quickly but are expensive to run, traditionally gas turbines are used to meet peak power and compensate for shortfalls in other power plants. An important portion of supply on the Danish grid is that of Combined Heating and Power Plants, *CHP*, these plants produce central heating water and electricity in parallel, from many possible fuels (natural gas, bio-gas, municipal waste etc.).

Nuclear power plants are large fixed sources, in that aspect similar to coal plants[1], but due to the complexity of their operation their output can not be regulated and shutting them down is avoided unless it is for annual (or biennial) fuel changes or in case of emergency. A commercial reactor is typically licensed for a certain number of quick stops and if this number is exceeded it must close down before its scheduled end-of-life. For an investment of several billion euros this would be disastrous and therefore nuclear power plants are never turned off in times of low demand.

Hydroelectric power is by many accounts the best possible power source: it has very low marginal costs (and often reasonable capital costs), it does not produce emissions, it can produce very high peak power and it can be regulated very quickly. The only drawback is rather obvious: it can't be built if there aren't physically and politically suitable rivers to develop.

Wind Power is the subject of this thesis and is by nature highly intermittent. Figure 1.1 shows the best and worst days for wind power production in the DK2 bidding area (Eastern Denmark), the share on best days has increased as more capacity has come online over the last decade but on the worst days wind power still does not produce more than a percent of the total. This is due to the small area on which all the wind turbines are located: this small area will often have calm conditions at all turbine sites, making the minimum wind electricity share very small and precipitating a need to keep substantial backup generating capacity available.

1.4 The Nord Pool Spot electricity market

Nord Pool Spot is an electricity market where buyers and sellers of electricity meet and place bids for electricity delivery at specified times. The market was launched in 1997, initially covering Norway and Sweden. Today (December 2014) the market covers the four Scandinavian and three Baltic countries. The market is currently divided into 15 bidding regions that may all have different spot prices reflecting the local supply, demand and transmission situation. Finland and the Baltic countries all constitute their own separate bidding regions while Denmark is divided into two bidding regions, Norway five and Sweden four: these bidding areas are defined by the need to sometimes keep different prices in different areas due to dissimilar supply and demand properties combined with limited inter-regional transmission capacity.

The Nord Pool Spot market trades electricity on different forums depending on the time-aspect of how contracts are settled and electricity delivered.

[1]The environmental aspects of nuclear power plants are, however controversial, very different from those of coal power plants.

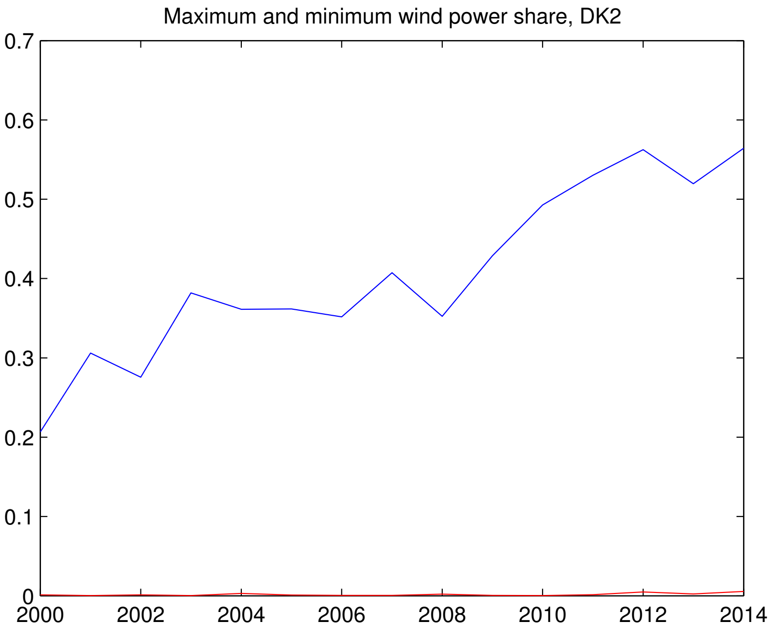

Figure 1.1: The maximum (blue) and minimum (red) daily wind power share of electricity consumption in the DK2 bidding area. Increasing wind power capacity does not improve the minimum production in a small area such as Eastern Denmark.

ELSPOT is the spot market for contracts that are settled a day in advance for every hour the following day. ELSPOT[2] is the main market for electricity selling 79 % of the consumed electricity in West Denmark during 2014.

Regulating power markets are markets for correcting the balance between predicted supply and demand from the previous day and the actual supply and demand at real time.

ELBAS is an intraday market that initially covered Sweden and Finland but since 2009 all of Norway and Denmark is also included [1]. ELBAS is open 24/7 and contracts are settled per hour as late as 60 minutes in advance of delivery.

The Nord Pool markets for Denmark is divided into two bidding areas: West Denmark (DK1) comprising Jutland and Funen with 55 % of the population and a population density of 92 inhabitants per km^2 and East Denmark (DK2) comprising the island of Zealand with 45 % of the population and a population density of 261 inhabitants per km^2 [2]. The two regions are electrically connected over the Great Belt but as can be seen in Table 1.1 the capacity of this link is no greater than the international connectors linking the grids to Germany (DK1&DK2), Sweden (DK1&DK2) and Norway (DK1 only).

[2]Nord Pool Spot is the name of the entire marketplace dealing in ELSPOT contracts as well as ELBAS and others, the word "Spot" by itself will in this thesis refer to the ELSPOT market whereas Nord Pool or Nord Pool Spot to the entire system with its many markets and features.

From	To	Capacity (MW)
Western Denmark	Norway (Kristiansand)	1632
Western Denmark	Sweden (Stockholm & Gothenburg)	280
Western Denmark	Nothern Germany	1780 / 1500
Eastern Denmark	Sweden (Malmö)	1700 / 1300
Eastern Denmark	Nothern Germany	590 / 600
Eastern Denmark	Western Denmark	600 / 590

Table 1.1: The connections from the Danish bidding areas to other bidding areas, capacities are in megawatt (MW) as of 2014-12-01 [3]. Links with two values have different capacity in different directions, shown as export / import.

1.4.1 Trade between bidding areas

The transmission links in Table 1.1 define the market regions as areas between which there is sufficiently small transmission capacity and sufficiently large difference in supply and demand characteristics to warrant separate bidding processes. The owner of a transmission link effectively holds an money-making tool that can generate profits as soon as prices at its different ends differ, this is further explained in Section 2.2.1.

1.5 The Energy mix in the Nordic region

The energy mix in a given region is, in the context of this thesis, the capacities of different types of power sources available in an area, or their respective production during a time period. As this project focuses on the Danish market it is important to know the energy mix in Denmark and its neighbors since this mix shapes the trading between the countries.

Denmark is too flat to generate any electricity from hydropower and has never operated nuclear power plants. Ever since the oil crises of the 1970s Denmark has championed wind power and is in many respects a world-leader in the field. In 2013 33.2 % of electricity consumed and 34.3 % of electricity produced came from wind power, the figures for 2014 are likely to exceed 40 %. The non-wind generating capacity in Denmark is made up mainly of CHP plants burning fossil fuels or biogas, in official statistics these are distinguished as the large ”centrale verker” and the smaller ”decentrale verker” depending on size and features.

Norway essentially produces all its electricity from hydroelectric power plants. This is a very advantageous situation and Norwegian power producers are working to become the ”battery of Europe” selling their regulating power at high prices to compensate for shortfalls abroad and importing surplus wind power from Continental Europe at low prices to save water in reservoirs [4].

Sweden has a mixed power supply coming predominantly from hydro-electric and nuclear power plants. In recent years Sweden has seen a wind power expansion similar to Denmark's but smaller in relative scale. With wind power capacity not exceeding hydro or nuclear capacity the nuclear plants can run at constant power and hydro can compensate wind generation between 0 and 100 % capacity.

Germany has mixed electricity supply with relatively small hydro-electric capacity, larger nuclear and fossil capacities and a quickly growing renewable (wind and solar PV) capacity. During recent years the *Energiwende* (energy transition) has set out to close down nuclear plants and prop up renewables, transforming the energy mix[3].

1.6 Research questions

To better specify the areas of study, a set of quantitative economic questions were posed to be investigated.

- How has wind power capacity and generation been developed in Denmark? Are there decreasing marginal returns in electricity output to investments in generating capacity?

- How has production from other electricity sources developed, is there a link to increasing wind power capacity?

The phenomenon of decreasing marginal returns (to investment, labor. etc.) is a common one in economic theory. In the case of wind power expansion it could demonstrate itself in that newer turbines could produce less energy per nominal power capacity than older ones, due to an exhaustion of suitable plant locations with good wind characteristics.

- How does increasing wind power capacity affect the level of electricity spot prices on the Danish spot market? How have price levels developed between countries and how have price differences between electricity sources developed? Have negative electricity prices become more prevalent and how are they affecting producers?

- How does increasing wind power capacity affect the fluctuations in electricity spot prices on the Danish spot market? Is there a correlation between wind power capacity and price fluctuations?

The nominal spot price levels themselves are affected by a great number of factors so a correlation specifically to wind power is hard to analyze. The price difference to neighboring areas that have not seen a similar wind power expansion is however a feasible measure of wind power effects on price levels. The fluctuations of the spot price, measured by variance or standard deviation, reflects the robustness of a grid: if large positive and negative shocks can be absorbed without large fluctuations in spot price it is not likely that these shocks will generate concrete damage on the grid through power spikes or brownouts[4]. Price variance is therefore an interesting quantity of an electric grid.

[3] And bringing with it some unwanted consequences, such as a coal resurgence. [5]

[4] A brownout is a decrease in grid voltage arising from temporarily inadequate supply.

- How has increasing wind power capacity in Denmark affected its electricity trade balance to other regions on the Nordic spot market?
- How much wind power electricity is exported and at what price? How does this compare to other electricity sources?
- How has transmission capacity developed over the time period studied? How have potential and real electricity trade profits developed?

The question of to which degree new wind power generation ended up being exported was a topic of debate in two papers [6],[7], these papers collectively provide an understanding of how to look at exports and imports on the energy market but did not draw conclusions on the time evolution of this trade. By examining transmission figures, prices and wind power production fractions on an hourly basis and studying the time evolution, this thesis will address this topic in greater detail and with a larger set of data.

- How have subsidy programs affected the pace of wind-power expansion?
- Are Danish wind power subsidies being "exported"[5] to power producers in other countries?
- How can electricity markets adapt to growing volumes of intermittent power sources being connected to the grid?
  - Does the day-ahead spot market remain efficient at clearing supply and demand? Are other markets gaining ground due to increasing intermittent electricity generating capacity?
  - Will there be need for greater transmission capacity between regions?

These questions address the need for changes in the markets for electricity as well as the physical connections between countries. By examining the volume of trade on the day-ahead *ELSPOT* market to the intraday *ELBAS* market conclusions can be drawn regarding the efficiency of the market structure, one that was set up for a majority of trade being done on the day-ahead market. The development of connection capacities between bidding areas was studied for the time period (1999-2014) and some estimates on the future need for further transmission capacity were made.

1.7 Other work in the field

There are many studies on the economics of wind power and some in particular are relevant to this thesis. A paper from Center For Politiske Studier [6], argued that wind power expansion was not beneficial for the Danish grid and that subsidies for wind power chiefly benefited Norwegian and Swedish hydro-power companies. A counter-paper from Lund, Hveplund et. al. [7] argued against these conclusions and claimed that wind power had indeed given Denmark more competitive electricity prices. Some quantitative questions were however answered in unsatisfactory ways by both papers, despite the necessary data being publicly available, inspiring some of the calculations done in this thesis.

[5] This was claimed in a report [6] from Center for Politiske Studier.

Chapter 2

Theory

2.1 The electricity market

The Nordic electricity spot market ELSPOT is in many ways an ideal *free market* with straightforward characteristics: buyers and sellers meet on the (electronic) marketplace every day to settle contracts for the following day. The peculiarity of the electricity market is as mentioned in Section 1.3 that supply must meet demand at every point in time. There are several ways to regulate the market from its day-ahead state determined by spot auctions but they tend to be more expensive than the day-ahead auction which is why forecasts on consumption and production are critical to a well-functioning market.

A typical electricity market has regular demand fluctuations from consumer and industry behavior and is also subject to more or less predictable shocks in demand (such as heat waves, cold spells or Earth Hour). *Supply shocks* are also part of the fluctuations on the grid: these can come as nuclear power plants need to shut down unexpectedly or during strong winds if a grid has large wind power capacity.

2.1.1 Supply and demand curves

Electricity demand is, as mentioned above, irregular and not fully price-conscious. Consumers are sometimes unaware of what they're paying for electricity, often they pay fixed (or slowly varying) prices and thus aren't likely to turn on and off lights depending on the spot price given moment. Many power-thirsty industries are however aware of prices and adjust their production accordingly, the combination of these demands can be exemplified by the downward-sloping demand curve in Figure 2.1

The supply side of the market is a combination of the different electricity sources and their respective marginal cost of production, Figure 2.1 shows a classic case of market equilibrium and the sources contributing to it. The Figure is fairly representative for Denmark and does not include hydroelectric power[1]. Since wind power has almost zero marginal cost of production the supply curve is virtually flat and

[1]Hydroelectric power has a more complicated supply curve than other sources due to its unbeatable combination of low marginal cost and high flexibility. It can operate both as peak power and base power depending on the features of a market. Its marginal cost can in fact be thought of as the alternative profit that can be made by saving the available water in the dam to sell it at another time, thus varying with the features of the market and the rain.

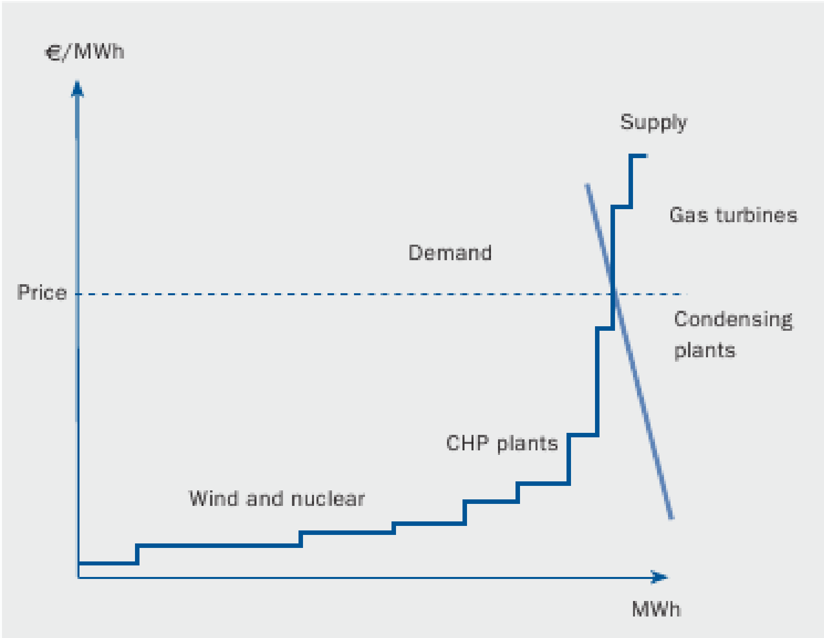

Figure 2.1: Classic case of supply and demand in a market without hydroelectric power. [8]

close to $p = 0$, albeit varying in volume depending on wind. Turbines will generate their maximum amount at any given time and the market price will be set by demand and other sources of supply. Wind power is not the only source that can have unconventional supply curves: CHP plants that are designed to generate electricity along with central heating water might not be able to generate heat without also running generators, thus giving a negative marginal electricity production cost when heating demand is high. Nuclear power plants are unable to regulate electricity output (electricity generation being part of their reactor cooling) as well as extremely expensive to stop and start. Therefore the marginal cost of production could be considered negative. There is also the possibility of producers and intermediaries involved in fixed long-term contracts where intermediaries can end up with more power than they can sell at a positive price, meaning that they must pay to get rid of it, resulting in a below-zero marginal cost of "production".

2.1.2 Negative Prices

Due to the peculiarity of the supply curves involved and the uncertainty of day-ahead predictions, the electricity market can sometimes clear at electricity prices below zero. In the intraday market producers can effectively be charged for producing more electricity than they sold on the spot market. The spot market has however also started to clear at negative prices during exceptional circumstances, such as periods or strong winds feeding wind power (which can be profitable at negative prices due to subsidies, explained in Section 2.3) coinciding with cold weather that drives up demand for heating from plants producing district heating and "bonus" electricity. Negative price floors were introduced on the ELSPOT market in 2009 [1].

2.2 Trade

2.2.1 Transmission Profits

A key feature of the market region division is of course that prices in neighboring price areas will differ according to supply and demand: electricity import or export therefore becomes logical and this can be done on transmission links instantly at a near-zero marginal cost.

The two Danish price regions studied are connected to several neighboring bidding areas, see Table 1.1. As electricity can be bought and sold at the going market price at both ends of a transmission link there is a potential for almost risk-less profit over the transmission which can be exploited by the link owner. Indeed, bar legislation or other sources of friction, the link operator can gain the entire price difference between two regions regardless of which side is more expensive at the time. If the market for transmission capacity is non-competitive these profits could be labeled as *economic rent*, the evolution of the transmission market and its relation to wind power is investigated in Section 4.3.

2.3 Subsidies

The Danish electricity market is influenced by a number of subsidies for different energy sources, these have also varied over time[2]. Subsidies are well-intentioned distortions to the supply curve, shifting the supply curve of targeted sources downward so that they can produce the same amount at lower prices. With subsidies present the marginal cost of wind power production is below zero, there are therefore incentives for turbine owners to produce even when prices are very low or negative. The supply and demand equilibrium can thus on a windy day with high central heating demand be found at prices below zero as shown in Figure 2.2. A question that was discussed in the previously mentioned papers, [6] & [7], was whether subsidies for wind power were in fact exported to power producers in other countries. The CEPOS paper claimed that they were, based on the[3] assumption that the grid functions at days of no wind so all additional wind energy must be exported and subsidies along with it. The DWEC paper claimed that since it is impossible to discern what electricity comes from where we can only argue that no wind power is exported when export is zero and that, if wind power production exceeds total consumption, the difference must be exported. In this thesis, all electrons are equal, and exports of wind power are computed by multiplying electricity exports from the Danish price regions by the production share of wind power in respective regions, this is done for every individual hour in the 21st century to ensure accuracy. By simultaneously computing the average subsidy level in the wind energy sector for every year it is possible to actually measure to what extent subsidies are exported.

[2]For a detailed list of current and historical subsidies, see [9].

[3]In my mind simplistic

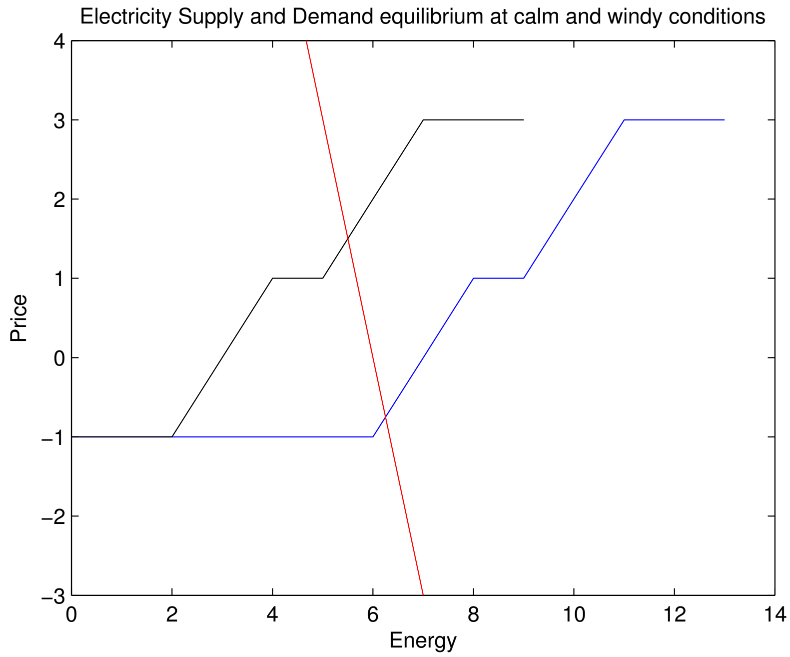

Figure 2.2: Stylized examples of normal positive, and negative price equilibrium. Red curve is the steeply downward-sloping (inelastic) demand. Blue and black curves represent the total electricity supply from several sources, wind power subsidies contribute to creating the below-zero portion of the supply curve. On windy days the wind power generation extends the sub-zero portion of supply horizontally, contributing to a negative equilibrium price.

2.4 Market efficiency

An interesting measure of the effects of wind power expansion is whether the ELSPOT market's ability to clear supply and demand is affected by wind power capacity. If the ELSPOT market would, for example, not be able to clear supply and demand as efficiently as before then electricity trade would migrate to other markets. The total market share of different NordPoolSpot markets is investigated in Section 4.5.

Chapter 3

Method

The general line of questioning guiding this project was: how does increasing intermittent electrical generating capacity affect the electricity market and how will electric grids continue to develop in the future? The research questions in Section 1.6 drove the work forward and the method used is explained in this chapter.

3.1 Choice of data

To examine effects of increasing intermittent generation this thesis focused on Denmark, arguably the country in the world most dedicated to wind power. There is ample data available on prices, production and trade in the Danish electricity market during the 21st century. During this time the Danish installed wind power capacity more than doubled, making the market as a whole a suitable candidate for an analysis on wind power's effect on electricity markets.

3.2 Acquiring data

Substantial volumes of data were required to do the relevant calculations for the research questions above. Data on Danish wind power generation stretching from 1977 to present were acquired from the Danish Energy Board *Energistyrelsen*. The data set was impressive in its scope, covering 5200 active and 2200 decommissioned wind turbines. Detailed information on dates of commission/decommission, turbine capacity and geometry, location and annual production figures were obtained this way. Data on prices in the Nordic markets was obtained through Nord Pool Spot's database stretching back to 1997. Actual wind power generation and flows from and between Danish bidding areas, as well as other Danish production and consumption data, was found at energinet.dk. Almost all data on price, flow, production and markets was obtained with hourly resolution from January 1st 2000, making the data set very large.

3.3 Breaking down data

To make sense of the vast quantities of data and produce reasonable models a few strategies were implemented for different calculations. Scripts and functions were written to compute average prices, price deviations, production, capacity utilization, trade, trade balance, transmission profits, trade by electricity source, subsidy payouts etc. Most of these were written to return data by year, month or day.

3.4 Statistical analysis

The data sets used for this thesis were extensive and a major focus was put on mining for data: visualizing trends in graphs and only making stringent covariance analysis on potential correlated sets. Measures such as exported wind power volume were computed and tested to corresponding wind power capacity for given time intervals. Simple linear model regressions were done using the MATLAB *fitlm*-function, providing models along with its error measures and significance levels.

3.5 Apparatus

Finding and using the necessary hardware and software apparatus to do this project was a small but important part of the work undertaken. Since the acquired data on electricity price, volume, flow and type was extensive and very detailed the use well functioning data management and mathematical computation software was of the utmost importance. MATLAB version R2014a was used throughout the project to process data from different sources and do the necessary computations. Albeit extensive in the volume of price data, the project did not involve any especially advanced calculations so the available 4-year old laptop proved perfectly adequate for the regressions and visualizations necessary.

Chapter 4

Results

4.1 Wind power capacity and generation

4.1.1 Capacity and production

To investigate potential links between wind power capacity and economic variables of the electricity market, wind power data from Denmark's Energistyrelsen was used. The database used lists every grid-connected wind turbine in Denmark complete with information on model, capacity, location, production and commissioning/decommissioning dates. Figure 4.1 shows how installed wind power capacity has evolved in the two bidding areas, West Denmark (DK1) and East Denmark (DK2) over the years 1977-2014. The data in Figure 4.1 is a measure of total nom-

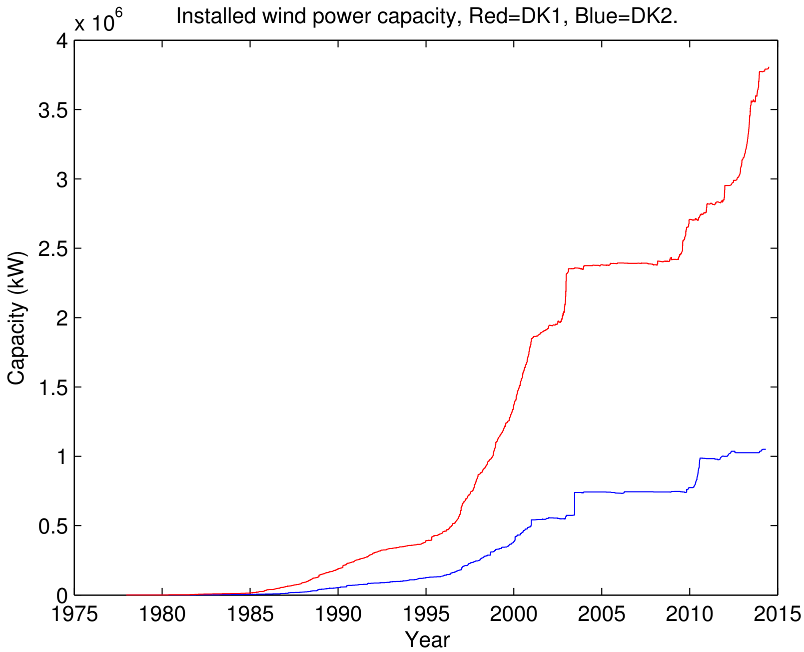

Figure 4.1: The installed wind power capacity in the two Danish bidding areas, an almost exponential rise can be observed, with a marked lull in expansion between 2005 and 2009.

inal capacity: the actual wind power production depends, naturally, on the wind and the state of the turbines. The actual wind power production was therefore also examined and its intermittency investigated.

Intermittency

Central to this thesis is that wind power is intermittent: to give a visual picture of how intermittent it is, typical production data is shown in Figure 4.2, where the production in the West Denmark bidding area is plotted for every day the first half of 2014.

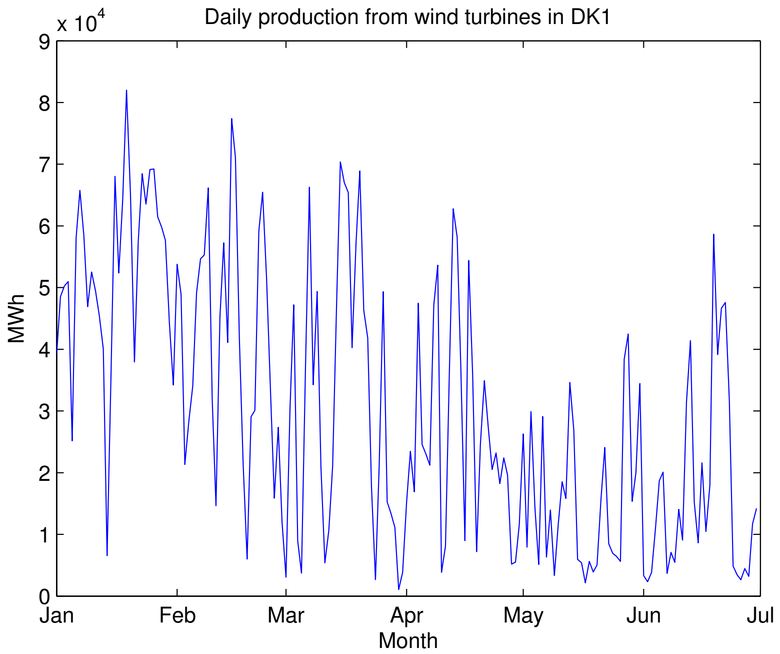

Figure 4.2: Daily wind power production in DK1 bidding area, seasonal variations are regular but daily production is extremely irregular, albeit decently predictable through weather forecasts.

The curve in Figure 4.2 shows daily production of wind power in the DK1 area. Since data with hourly resolution was available, some computations were made to illustrate the intermittency over such short time spans. Hour-by-hour differences in production can be seen in Table 4.1. The hourly production in MW varies between a maximum value determined by capacity (and maximum wind strength) and a minimum of almost zero. An interesting aspect is how quickly the production can fluctuate: the third column in Table 4.1 shows that the difference in power production from wind in DK1 can be as large as one nuclear reactor. If hourly fluctuations are very large they are likely to be harder to predict accuarately and could therefore pose challenges to the market and the grid.

Area	Max Production	Min Production	Max hourly difference
DK1	3460	0.6	855
DK2	924	0	560

Table 4.1: Hourly production figures in MW for the two Danish price areas during the first half of 2014, the hourly difference means that from one hour to another the production DK1 at most increased or decreased by 855 MW.

4.1.2 Marginal returns on capacity

To analyze whether wind power expansion exhibits decreasing marginal returns on capacity, the database on grid-connected Danish wind turbines was examined. To obtain a figure of efficiency over time, wind turbines were grouped by the year of their connection to the grid, and for any year of operation the production of a group was divided by its nominal maximum production (the nominal capacity multiplied by the number of hours in a year). Figure 4.3 shows how, during 2013, well turbines from different years did compared to their nominal installed capacity.

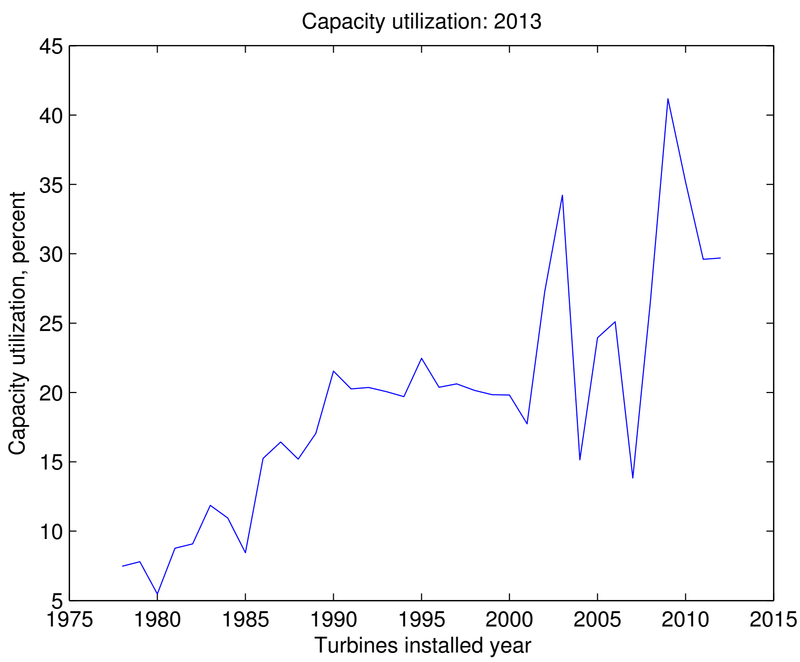

Figure 4.3: Wind capacity utilization in percent during 2013, there seems to be a trend that newer turbines live up better to their nominal capacity than old ones. This is contrary to an assumption of decreasing marginal returns on capacity investment.

It can be seen in Figure 4.3 that any potential decreasing marginal returns from saturation of suitable turbine sites is not yet large enough to counteract the efficiency-increasing improvements made over time. The low utilization for turbines built during 2004-2007 is interesting since it could be assumed that lower expansion pace should mean that turbines are only built on a few well-selected sites. No other explanation has been found than that the small sample of turbines built in this period allows for large variance.

4.1.3 Wind power effects on other power sources

The intermittent nature of wind power generation means that even if the total production of wind power increases other sources must still be available to fill the gap on calm days, see Figure 4.2. These sources, such as gas turbines and CHP plants, have certain fixed costs that must be recuperated by selling electricity. Since their marginal costs (including fuel) are in normal cases (for exceptions, see Section 2.1.2) higher than wind-power their production share will be squeezed out as wind power expands, but on calm days they must still be relied on to meet the total demand. Figure 4.4 shows the development of centralized power production in the two Danish price regions. The utilization of central producing capacity is shown in Figure 4.5, where capacity utilization has been computed as mean central production over maximum central production. It can be seen that while mean production decreases, the maximum peak production stays comparatively high and the ratio between mean production and max production decreases, making the plants less economical. The implications of this decrease in capacity utilization are discussed in Section 5.1.1.

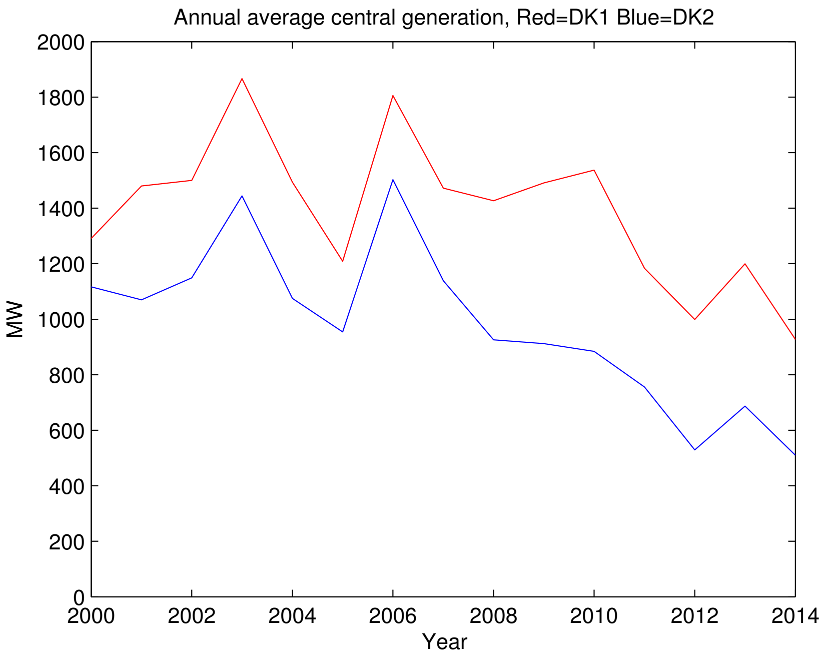

Figure 4.4: Annual averaged electricity production from central production plants.

The effect on smaller de-central production plants is smoother and decreasing during the period studied, see Figure 4.6. Testing these measures against the wind power capacity in the two regions yields the linear model seen in Table 4.2.

The correlation is significant and R^2-values are reasonable. There is however a great number of causes and variables affecting the capacity utilization (notably heating demand) and any potential link between wind power capacity and thermal capacity utilization is more complicated than a simple linear single-predictor model.

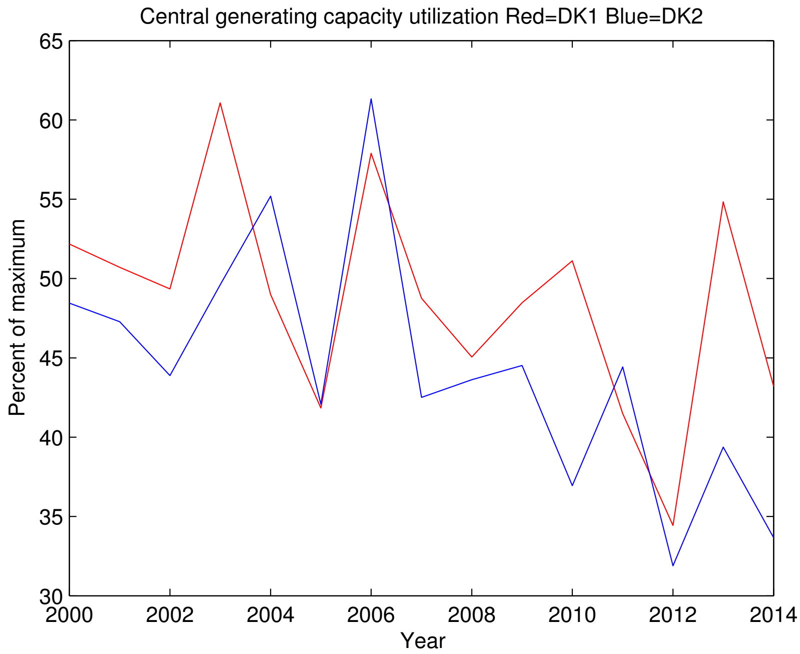

Figure 4.5: Annual averaged generating capacity utilization from central production plants.

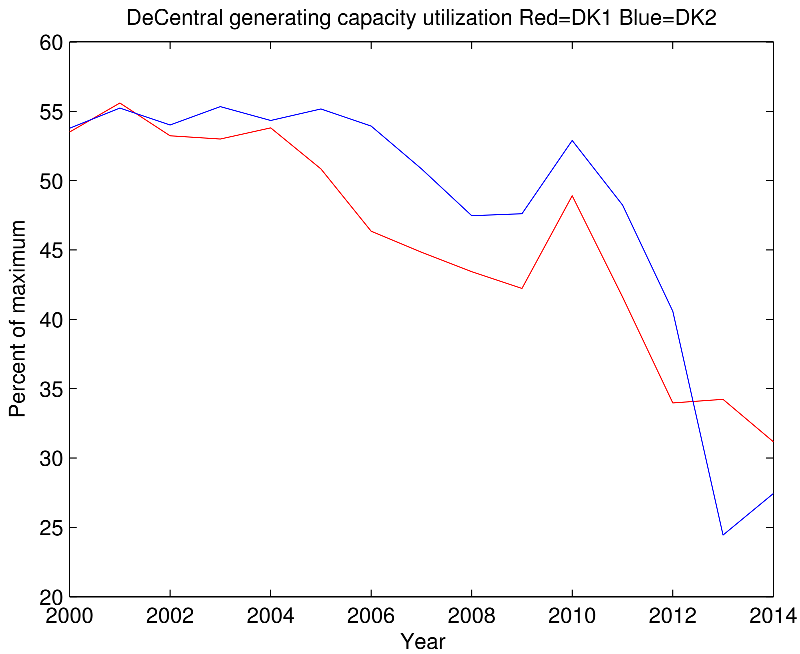

Figure 4.6: Annual averaged generating capacity utilization from de-central production plants.

Area	x1	p-value	R^2
DK1	-0.45	1.8E-5	0.768
DK1	-0.41	0.00197	0.534

Table 4.2: Fitted linear models for yearly correlation between total wind power capacity and de-centralized capacity utilization in the two regions. Wind power capacity is measured in relative terms where capacity at the end of the period is taken to be 1.

4.2 Spot prices and wind power

4.2.1 Price levels

The spot prices in the Danish regions were compared to the spot prices in neighboring regions. To extract the effect of wind power on this difference prices from Norway were chosen, since both Sweden and Germany have increased their wind power capacity along with Denmark. The price differences and their evolution over time can be seen in Figure 4.7.

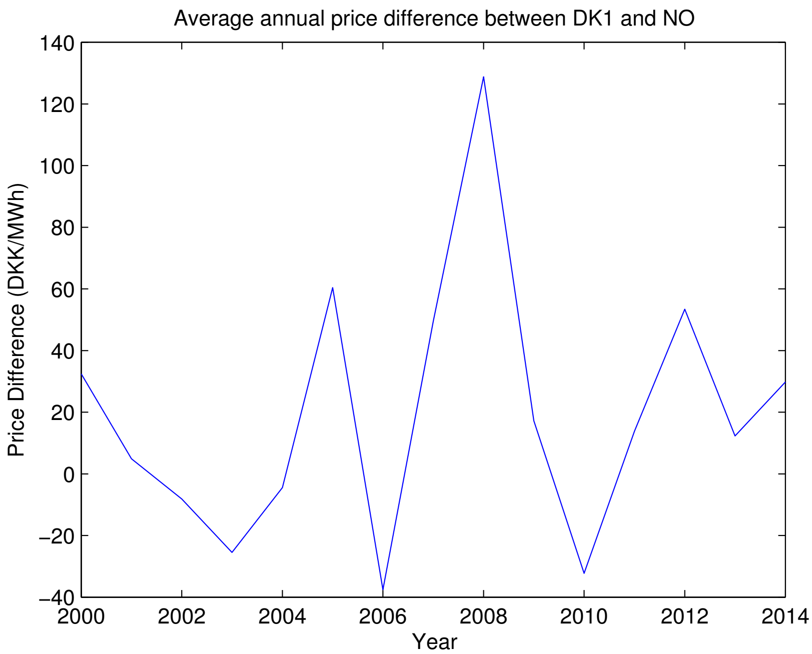

Figure 4.7: Average yearly price difference between the Danish and Norwegian bidding areas, positive values mean that electricity prices are higher in Denmark than in Norway.

The price difference in Figure 4.7 was not deemed likely to have any significant correlation to installed wind power capacity since the variance between years was much larger than the total change during the investigated period. Many other factors affect prices in the two areas: demand, fuel prices, reservoir levels, etc. Finding data for all these predictors was not judged to be within the scope of this project. On average it can however be seen that Danish prices are more expensive than Norwegian, which is to be expected given the vastly different properties of the countries' electricity supplies.

Negative Prices

Wind power is not the only factor in spot price development but certain effects, such as negative prices, are only present in the wind power intensive Danish and German markets. Table 4.3 shows the annual incidence of negative spot prices in different areas on the Nordic and German spot markets.

Area	Pre-2009	2009	2010	2011	2012	2013
DK1	0	9	11	15	33	39
DK2	0	0	5	14	31	30
DE	15	71	12	15	56	64

Table 4.3: Number of hours during which the spot price was negative in the West Denmark (DK1), East Denmark (DK2) and German (DE) bidding areas. The Swedish and Norwegian bidding areas have so far had 0 instances of negative spot price.

Even though number of hours with negative prices have increased, the total sum that producers have had to pay to get rid of electricity was still comparatively low: 65 million DKK in DK1 since 2009, 11 million of this during 2013 (total positive price sales amounted to 6.5 billion DKK during the same year).

Prices and electricity sources

The spot price level was expected to be correlated to wind power production. To examine the level of this correlation a linear effects model was created: spot price was postulated as a function of wind power production and calendar month. The calendar months were set up as dummy variables capturing some seasonal effects in demand and production from CHP plants. This correlation could use raw hourly data or daily averages or price and production. It was found that wind power production with strong significance negatively correlates with spot prices at hourly and daily resolution. This is perfectly logical when wind power capacity is large enough to affect the pricing of electricity. Without the dummy month variables the R^2 were however minuscule, discarding any false hope that a linear model with wind power production *by itself* could determine electricity spot prices. Table 4.4 shows linear single-predictor models for hourly correlation between wind production and spot price.

Year	2000-2014	2001	2004	2007	2010	2013
Coefficient	-0.029	-0.019	-0.027	-0.055	-0.031	-0.065
P-value	0	10^{-22}	10^{-151}	10^{-61}	10^{-76}	10^{-44}
R^2	0.01	0.01	0.08	0.03	0.04	0.02
Wind Capacity (MW)		1883	2379	2392	2830	3550

Table 4.4: Linear model tests for hourly spot price and wind production correlation in DK1. P-values are extremely small, which validates the very reasonable assumption that hourly spot price and wind electricity production are not uncorrelated. The yearly sets have over 8000 degrees of freedom and the longer set 130000.

Including the dummy variables for calendar month and reducing the resolution to daily averages the regression changed slightly and R^2-values improved substantially. Table 4.5 shows the regressions made with dummy variables.

Year	2000-2014	2001	2004	2007	2010	2013
Coefficient	-0.033	-0.027	-0.068	-0.055	-0.042	-0.076
P-value	10^{-39}	10^{-8}	10^{-35}	10^{-36}	10^{-51}	10^{-6}
R^2	0.01	0.162	0.426	0.429	0.535	0.124
Wind Capacity (MW)		1883	2379	2392	2830	3550

Table 4.5: Multi-variable linear model tests for spot price and wind production correlation in DK1, dummy variables for calendar month included. P-values are small, and R^2-values significantly higher than without dummies. The yearly figures now have 365 degrees of freedom and the total 5446.

Using a monthly resolution in prices and production, while removing dummies, a non-significant but *positive* correlation was found. Alas, wind power generates more power during months when prices are high than when they are low. Looking at the period 2000-2014 the coefficient for monthly correlation was 0.027 with P-value of 0.2, discarding significance. That the correlation-coefficient is larger than zero is however a good property in electricity generation and stems from seasonal variations in electricity price and wind patterns: winters usually bring high electricity prices and strong winds whereas summers tend to bring the opposite.

The difference in spot price between wind energy and other sources of electricity was computed using hourly production and price data for the two Danish bidding areas. As predictable periods[1] of high wind power production are likely to deprecate the spot price it was assumed that wind power would claim a lower spot price than controllable sources. Figure 4.8 shows the evolution of annual average production spot prices for different sources.

Figure 4.9 shows the evolution of the relative price difference between centrally produced power and wind power. The price differences were computed by taking the hourly production figures for the different sources and hourly spot prices, multiplying prices with volumes to obtain the average price when wind energy and centrally produced energy is generated. The difference has grown during the period studied but the year-to-year fluctuations do not appear to be well-correlated to changes in wind power capacity.

4.2.2 Spot price fluctuation

The relationship between spot price deviation and wind power was first examined on an annual basis. Installed capacity of wind turbines in a region for a given year was studied along with the spot price standard deviation of electricity in that region. The overall difference between the hydropower-dominated Norwegian grid and the Danish grids using wind power and fossil fuels can be seen in Figure 4.10.

To account for different price levels during different years affecting standard deviation, an adjustment was made to the data in Figure 4.10 by dividing standard

[1] At least periods of strong wind that can be predicted a day in advance, when trading on ELSPOT is made.

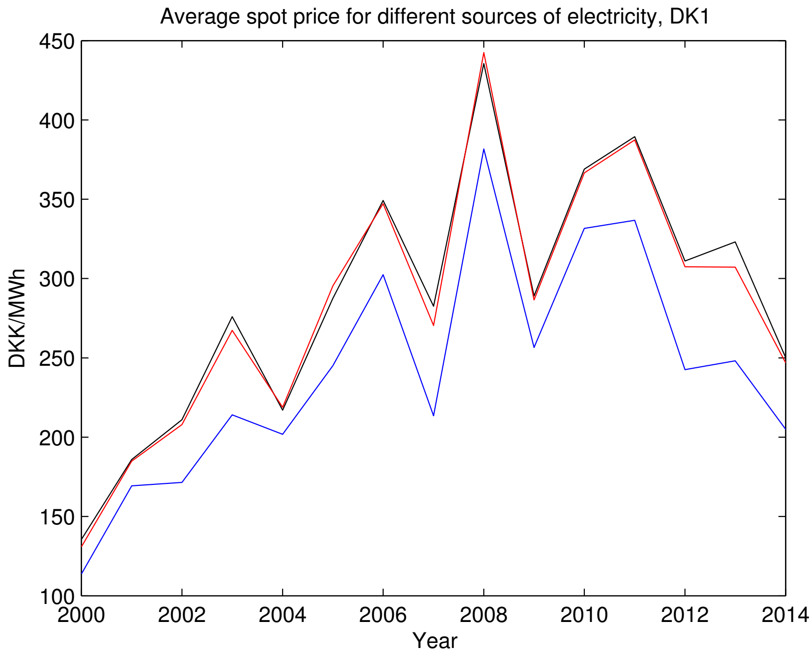

Figure 4.8: Average yearly spot price for different sources. Red is central production, black non-central and blue wind power.

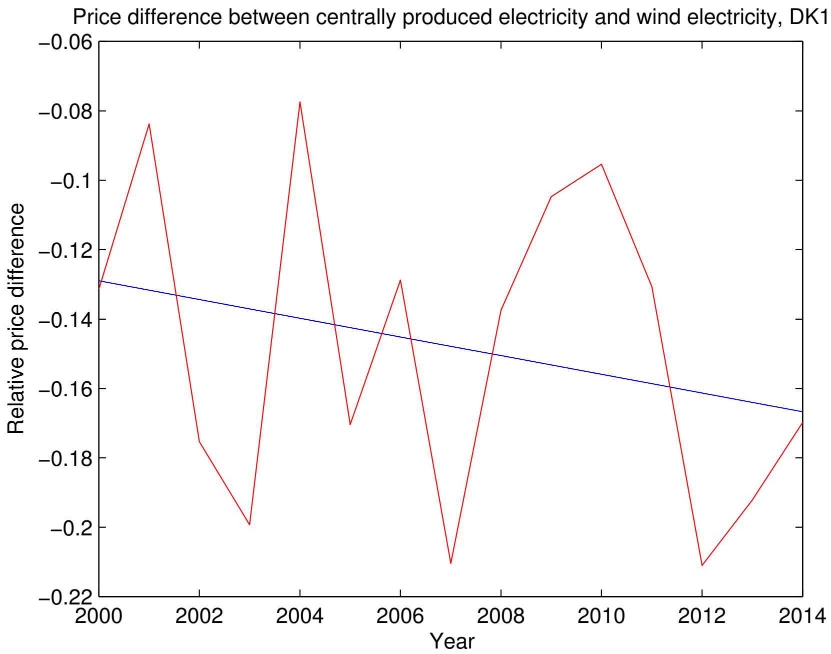

Figure 4.9: Relative difference in yearly average price between centrally produced power and wind power. Wind power electricity sold at 8 to 22 % lower yearly average prices over the years studied.

deviation with the mean price for every year respectively. The result of this can be seen in Figure 4.11. The adjusted standard deviations show almost no trend but large variation, attempts at correlating this data were therefore abandoned.

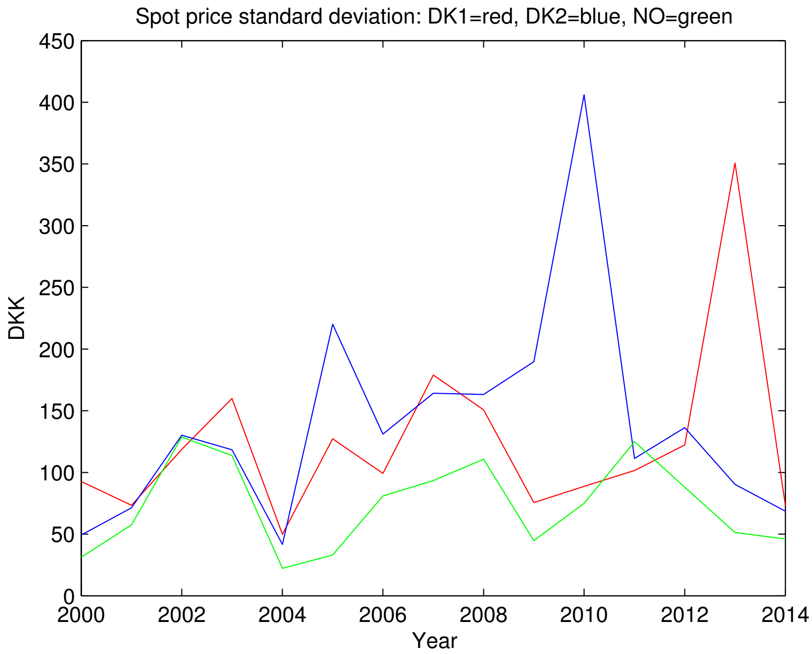

Figure 4.10: Annual standard devations of spot price for three Nord Pool bidding areas: DK1 (red), DK2 (blue) and NO2 (black). The deviation in spot price is notably higher in the Danish regions.

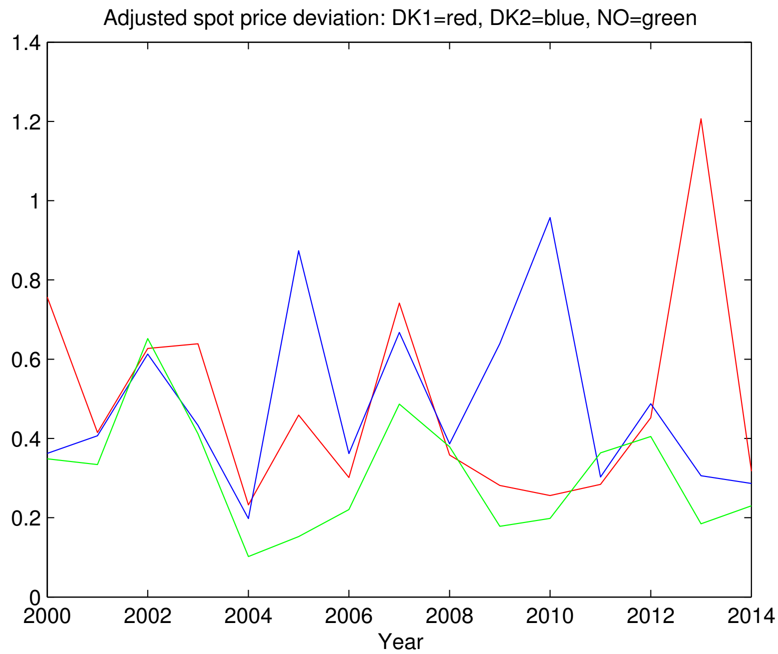

Figure 4.11: Annual standard devations of spot price for three Nord Pool bidding areas: DK1 (red), DK2 (blue) and NO2 (black). The deviation in spot price is notably higher in the Danish regions.

4.3 Electricity trade

Electricity is constantly traded between the Danish bidding areas and their connected neighbors, this trade was analyzed by using hourly data on spot prices, flows on the spot market and production mix to obtain data on how wind power expansion affects trade on the market.

4.3.1 Trade balance over time

The total import and export volumes for the two Danish price regions can be seen in Figure 4.12, as is visible the exported amounts stay more or less flat during the interval while imports have risen.

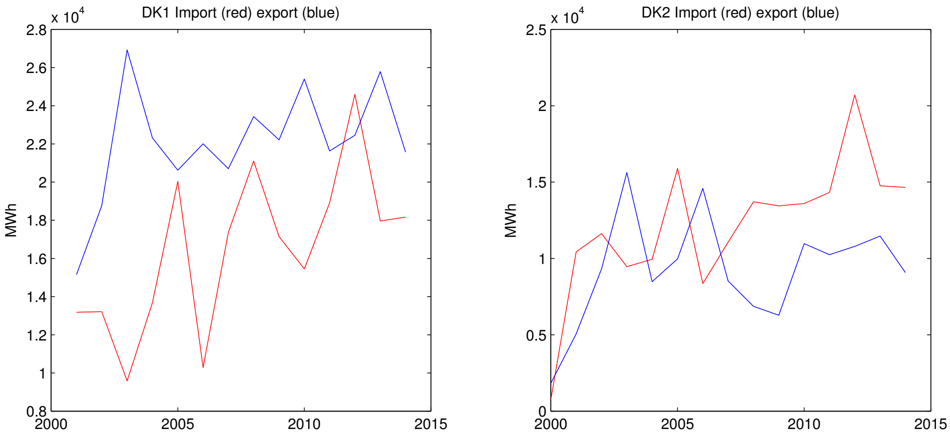

Figure 4.12: Import and export of electricity in the two Danish price regions.

Combining the data on imported and exported volumes with the spot price in the home market a measure of total trade balance was obtained. Important to note is that when prices are different in two markets that are connected by transmission cables the buyer in the importing market pays his market price and the seller obtains her market price. The trade balance for Denmark is therefore only affected by the *Danish* spot price at every trading hour, since the price difference is collected by the cable operator rather than the power producers.

Trade balance is affected by wind power production: daily import/export balance and wind power production can be combined to visualize the correlation between the wind and export. The papers [6]&[7], referred to in Section 1.7 only looked at the correlation for one year. In order to update the results to the present situation, scatter graphs were plotted and linear models estimated for daily wind power and net electricity export during all years 2000-2014. The most recent, and most strongly correlated, plot is seen in Figure 4.14.

To illustrate whether the link between export and daily wind power production has changed as more wind power capacity has been added, the coefficients of correlation and R^2-values are shown in Figure 4.15. The correlation coefficient between wind power and export has rather unexpectedly *weakened* as more wind power capacity has been added to the West Denmark grid. It is possible that wind power has come to produce more of the baseline electricity, decreasing the fraction of additional

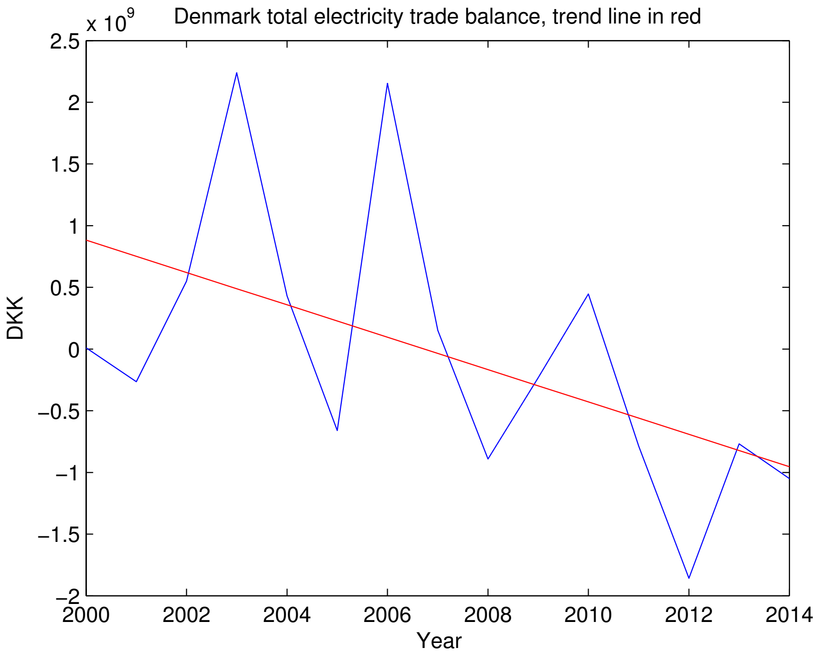

Figure 4.13: Danish trade balance on the Nord Pool Spot market, blue are annual figures, red is trend line.

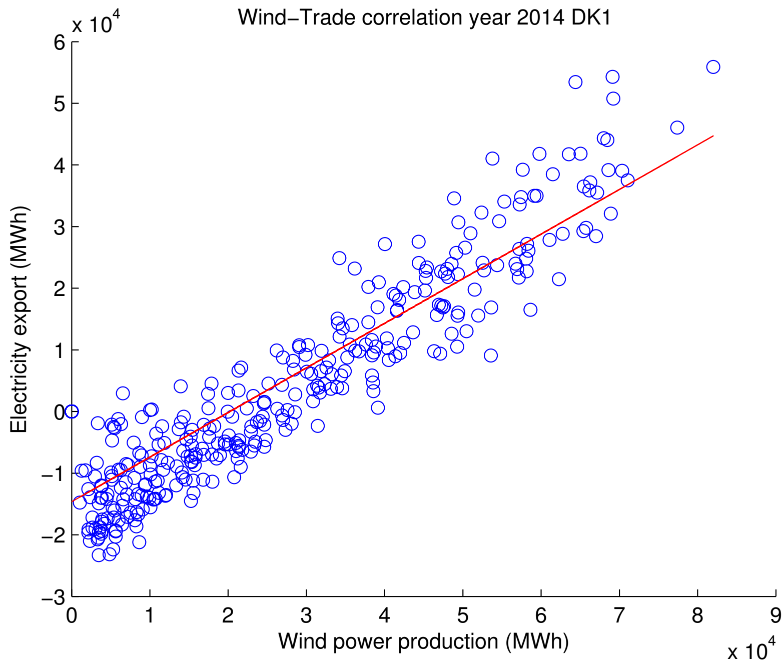

Figure 4.14: Scatter of daily wind power production and electricity export for DK1 during 2014, trend line in red.

wind power that is exported. The goodness-of-fit, measured by R^2 did however increase during the time period, as wind power expanded, constituting a larger and larger proportion of electricity exports. To summarize, a slighly decreasing share of wind power production was exported, but a larger proportion of exports was made up of wind power.

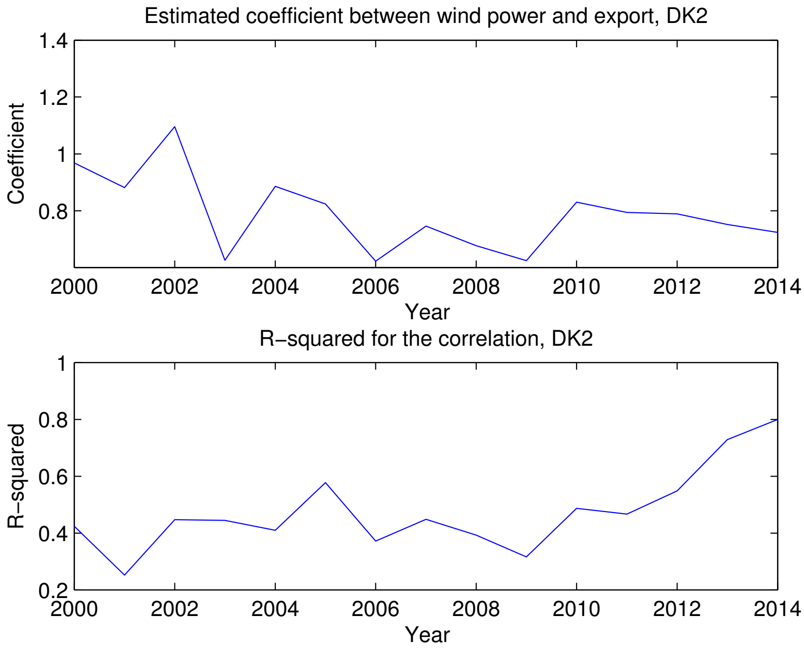

Figure 4.15: Trend line coefficients between wind power production and electricity in top pane and R-squared values showing goodness-of-fit in bottom pane.

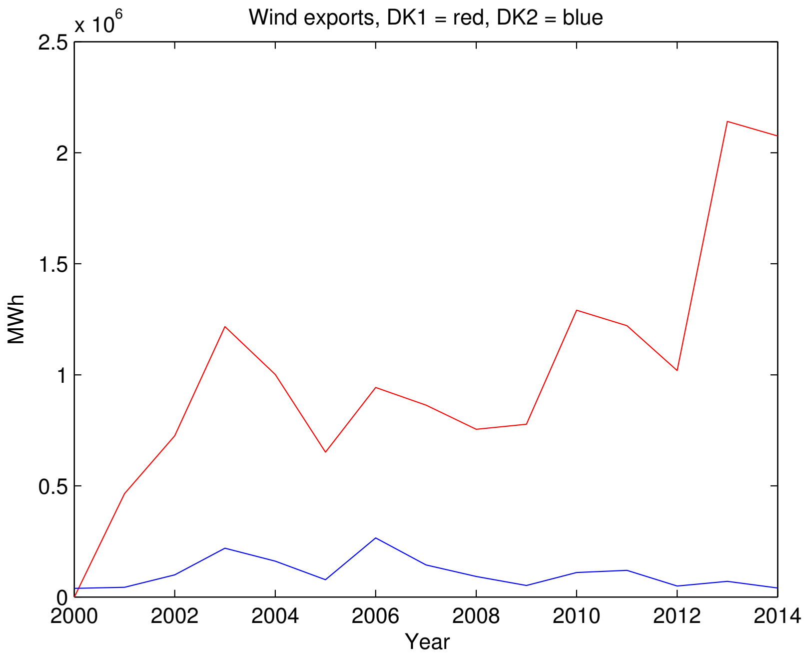

Figure 4.16: Total yearly exports of wind power from the two Danish regions. West Denmark exports are rising along with wind power capacity whereas East Denmark exports are declining despite increased capacity during 2009-2014.

The total wind power exports from both Danish regions were computed by multiplying exported electricity with wind power share in production during every hour. The results of this are found in Figure 4.16, it can be seen that the exports from the DK1 region are rising but showing a stagnant period between 2004 and 2009, quite in line with the development of wind capacity. The DK2 data is very different however, wind exports peak at 2006 and thereafter decrease even though more wind power is added to the grid. The other changes in the energy balance of the region must therefore be strong enough that an increasing fraction of wind power produced is consumed locally.

4.3.2 Transmission capacity

An important question to answer was whether there would be a need for more transmission capacity between bidding areas as wind power capacity increases. To obtain a background for this question, past transmission capacities were examined. The total transmission capacity connecting the Danish regions to their neighbors can be seen in Figure 4.17. In the DK1 price region, total yearly transmission capacity ded-

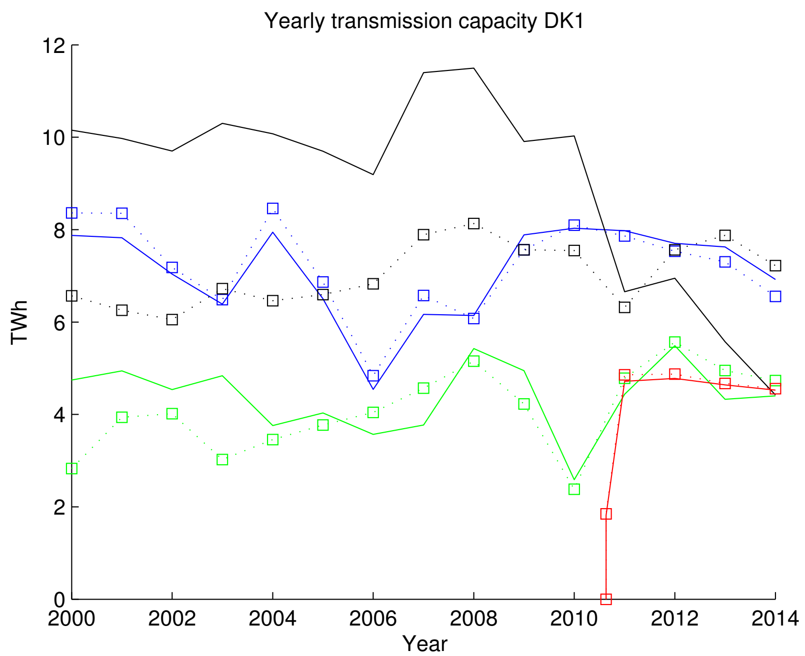

Figure 4.17: Total yearly transmission capacities to and from DK1, solid lines are export, dashed lines with boxes are imports, black is DE, green is SE3, blue is NO and red is DK2

icated to imports has increased by 30% and that dedicated to exports has decreased by 11 %. The wind power capacity has, during the same time, increased by 139 %. The corresponding figures for DK2 were a 26 % increase in import capacity and a 7 % increase in export capacity with a 131 % increase in wind power capacity. The total capacity for both import and export in the region was helped by the opening of a new link between the Danish areas in 2010. The large increase in wind power has not been followed by corresponding rises in bilateral transmission capacity as could be expected. The following section is devoted to investigating whether the increasing intermittent capacity combined with stable transmission capacity has increased the transmission profits. If these were to rise it would signal that it could be profitable to invest in greater transmission capacity.

4.3.3 Transmission profits

As explained in Section 2.2.1, the owners of a transmission link can buy and sell electricity at the going market rate on both sides of the link, claiming the difference for themselves. This transmission profit, or potentially *rent*, and its development over time was computed by multiplying hourly trade flows between areas with hourly *absolute value* price differences and summing up the profits by year, the result is seen in Figure 4.18.

The curves in Figure 4.18 show that transmission profits have changed over time but their development is not especially correlated with wind power expansion, in fact the biggest changes in transmission profits occur during the years 2004-2008 when wind capacity was almost constant. The curve in Figure 4.18 does however bear resemblance to the development of electricity spot prices seen in Figure 4.8, indicating that transmission profits have largely followed spot prices during the interval. Other factors such as fossil fuel prices and changes in consumption could also be important predictors during the time period studied. Since there have not been any great increases in the transmission profits generated on existing transmission links it is unlikely that the "need" for new cables, as seen by the operators at least, has increased.

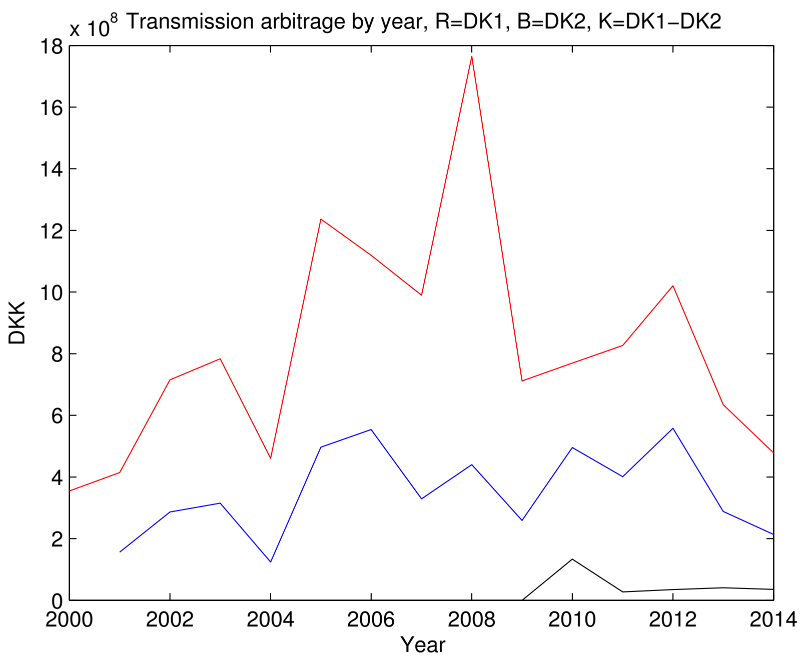

Figure 4.18: Total transmission profits by year for international trade from two Danish price regions, Red curve is DK1 and blue curve is DK2. The profits from transmitting electricity *between* the two Danish regions can not be ascribed to one or the other, and is therefore shown separately in black.

4.4 Subsidies for wind power

The Danish wind power subsidy policies for turbines installed in the 21st century are shown in Table 4.6. It is important to note that a turbine, *throughout all of its operating life*, is subject to the subsidy rules that were in place at the time of its connection to the grid. The base subsidy is given to every turbine throughout its life, main subsidies and guaranteed price subsidies are dependent on price and limited to 20 years of operation or an almost equivalent number of full-load production hours. A subsidy ceiling means that main subsidies will not be given to a sum of price and subsidy exceeding the ceiling. Guaranteed price subsidies mean that subsidies will make up the difference between price and guaranteed price. Offshore turbines have at times been treated differently than onshore ones, sometimes with subsidy levels decided on site-by-site basis, and are therefore excluded from the table.

Connected after	Base subsidy	Main subsidy	Ceiling	Guaranteed price
2014-01-01	23	250	590	
2008-02-20	23	250		
2005-01-01	23	100		
2003-01-01	23	100	360	
2000-01-01	23			430

Table 4.6: Danish wind power subsidies in DKK/MWh for turbines on land.

Subsidy payouts were calculated the "long way" by implementing the subsidy requirements for turbines installed different years and looking at the yearly power production from all individual Danish turbines to calculate their respective subsidies. This was not trivial since subsidies vary by hourly production and price so averaging these would create a measure of inaccuracy: to utilize the available data (year-by-year production for every turbine and hour-by-hour prices and total wind energy production) fully the share of production by turbines in different subsidy groups was computed from turbine data and subsidies for each group were computed using hourly price and wind energy production data. Using this technique, measures of total subsidies and average subsidy per MWh could be computed for turbines in different regions. Figure 4.19 shows the subsidies paid by year for all wind turbines installed in Denmark[2]. The rules in Table 4.6 are only an extract of the full legislation so in order to make computations manageable all subsidies were taken to expire after 20 years and offshore turbines were treated as onshore ones[3]. To asses how much subsidies were being "exported", as in how much subsidies were paid to wind power production that was consumed abroad, several data set had to be combined and calculated. Hourly data on wind power production and prices were combined with subsidy rules and yearly measures of how much wind power came from turbines installed during the different subsidy rule periods. This data combined with hourly export data went into producing an estimate of total annual subsidy export. The result of this calculation process can be seen in Figure 4.20.

[2]Subsidy levels for turbines connected prior to 2000 could not be found and these turbines are therefore assumed to follow the same rules as those installed 2000-2002.

[3]In the hourly production data, no distinction is made between onshore and offshore wind energy production.

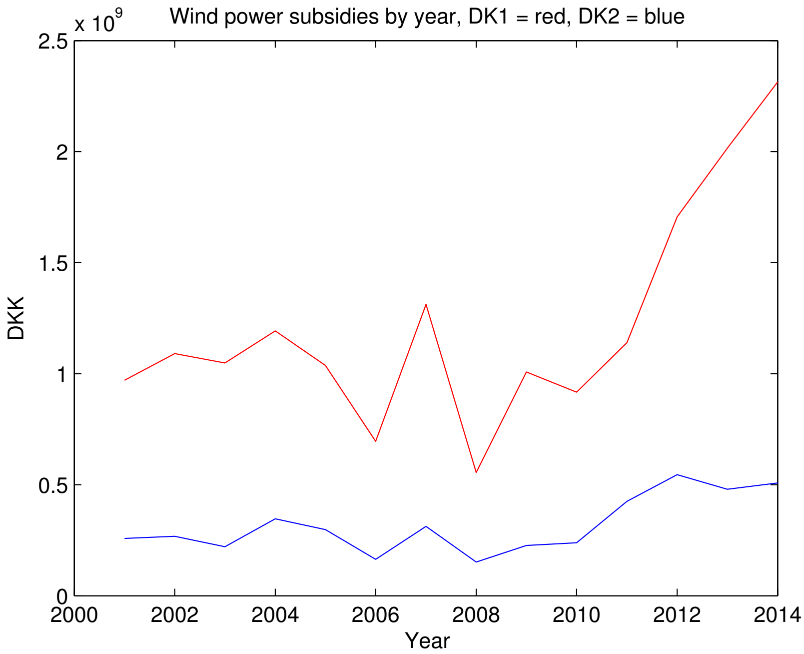

Figure 4.19: Subsidies paid by year for wind turbines in the two Danish price regions.

Adjusting this data for total subsidy payouts the share of subsidies being exported was obtained, this share can be seen in Figure 4.21

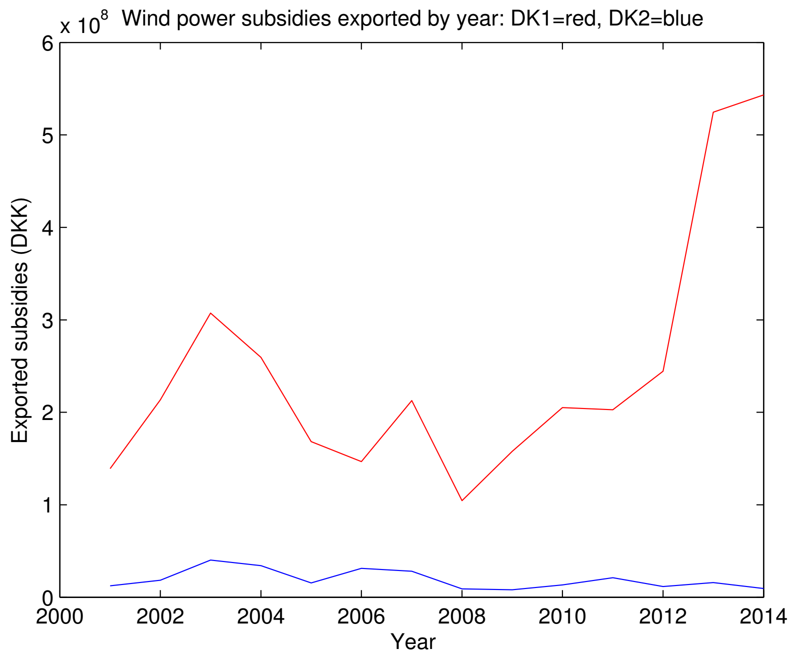

Figure 4.20: Wind power subsidies exported, calculated by year. Red curve is DK1 and blue curve is DK2.

For every year during the period an "expected subsidy" was also calculated, this was based on the previous year's hourly wind power production and hourly spot prices and current year's subsidy rules. These expected subsidies are a measure of

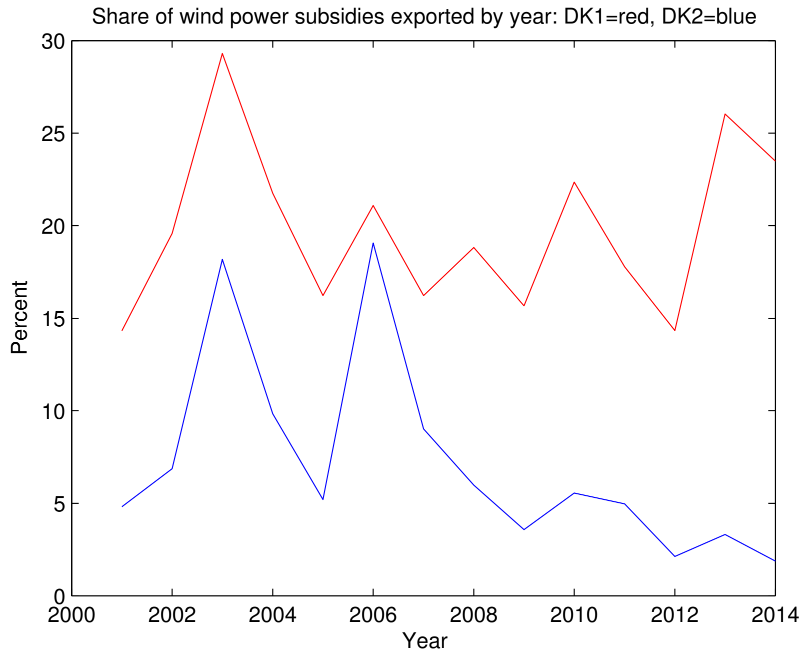

Figure 4.21: Percentage of subsidies going to exported wind power production. The ratio in DK1 is stable whereas that of DK2 decreases as the region's trade balance has worsened.

what an investor could look at when investing in a wind turbine, they are shown in Figure 4.22.

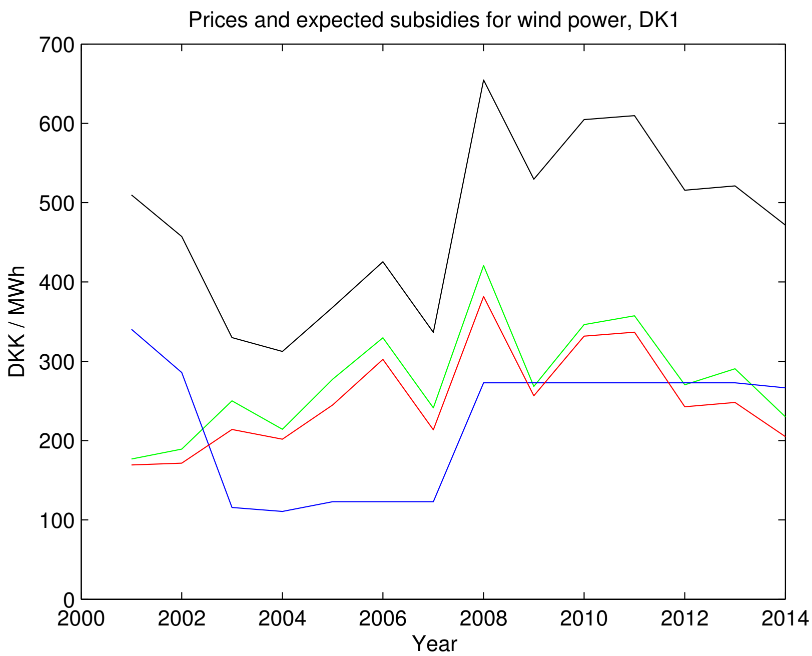

Figure 4.22: Prices and subsidies for wind power in DK1. Blue is expected subsidy, green is average electricity spot price, red is average wind electricity spot price and black is the sum of subsidies and wind electricity price obtained by wind energy producers.

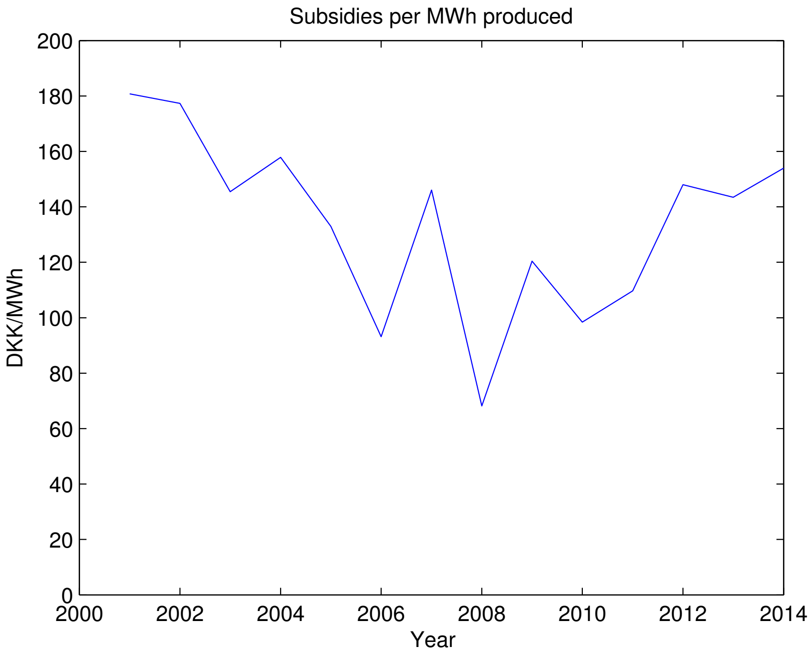

Figure 4.23: Average subsidy level paid to Danish wind turbine operators during the 21^{st} century.

The subsidy data was tested for correlation against new wind power capacity. A model was assumed where the expected subsidy level for one year would linearly effect a relative change in wind power capacity. The results of these tests are found in Table 4.7. To obtain a measure of the effectiveness of subsidies the subsidy payouts

Case	Coefficient	P-value
DK1	0.00045	0.0505
DK2	-0.00007	0.855
DK1 (lag)	0.00056	0.0143
DK2 (lag)	0.00063	0.111

Table 4.7: Correlations between subsidy levels and wind power expansion, the mysterious behaviour of the DK2 data, which in real time is more anti-correlated than correlated, is explained further in the discussion.

in Figure 4.19 were divided by total wind production to display the taxpayer cost per MWh of wind electricity, this measure can be seen in Figure 4.23. To relate these subsidy levels to greenhouse gas emissions a crude but efficient calculation is to assume that this electricity, had subsidies not been present, would have been in its entirety from modern fossil fuel plants such as Avedøre 2 burning natural gas. A plant such as this, with a 48.2 % efficiency rating, produces 380 kg CO_2 per MWh, giving wind power subsidies a CO_2 abatement cost of 410 DKK (~55 €)per ton in 2014[10]. This abatement cost is significantly higher[4] than widely published figures from McKinsey & Co putting wind power at about 20-35 €/ton CO_2 [11].

[4] Assuming instead that a 30% efficient coal power plant is replaced, however, brings the figure to ~18 €/ton CO_2

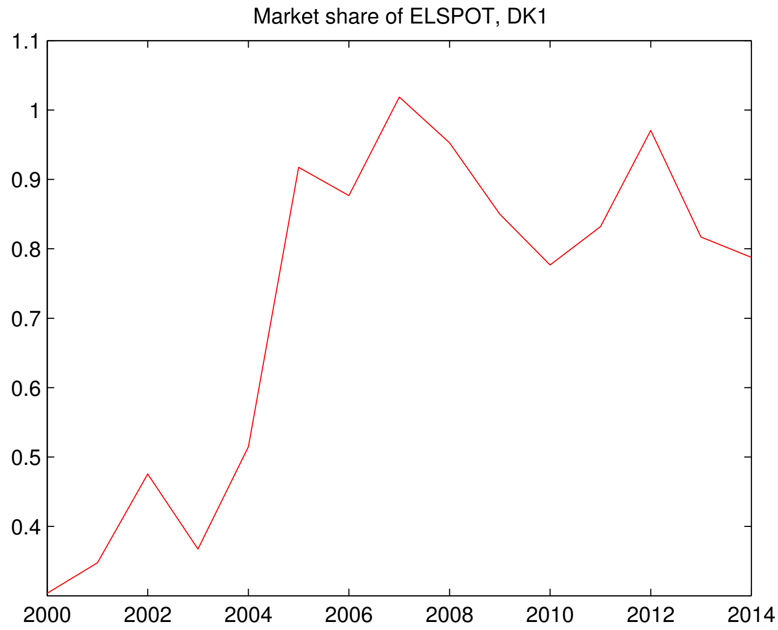

Figure 4.24: ELSPOT trade share of consumption in DK1.

4.5 Market efficiency

The research question pertaining to market efficiency was whether increased wind power capacity increases the market share of intra-day and regulating power or if the day-ahead market ELSPOT retains its predominant position. The share of total Danish consumption traded on ELSPOT was computed by year and region and is shown in Figure 4.24. It can be seen that the market share of ELSPOT is initially increasing over time, possibly due to long term contract trade migrating to the ELSPOT market, but later starts dropping. Due to different market structures of ELBAS (where every transaction has its own price rather than one price being determined for all trading during a production hour) and issues with data this market fell outside the scope of the project. The data on the regulating power market was also not as extensive as that on the spot market and the analysis was limited to up- and down-regulating volumes in the DK1 area. The total regulated power traded, both for up- and downregulation, in DK1 is shown by monthly total in Figure 4.25. The regulating power volume traded fluctuates around one mean during 2000-2008 and after a marked shift in June 2008 it then fluctuates around a new mean approximately 60 % lower. This shift was not possible to explain: the introduction of the ELBAS intra-day trading system could be expected to decrease the need for regulating power but this was rolled out in DK1 already during April 2007. Due to the lack of understanding of regulating power data, no attempts to correlate this to wind power production were made.

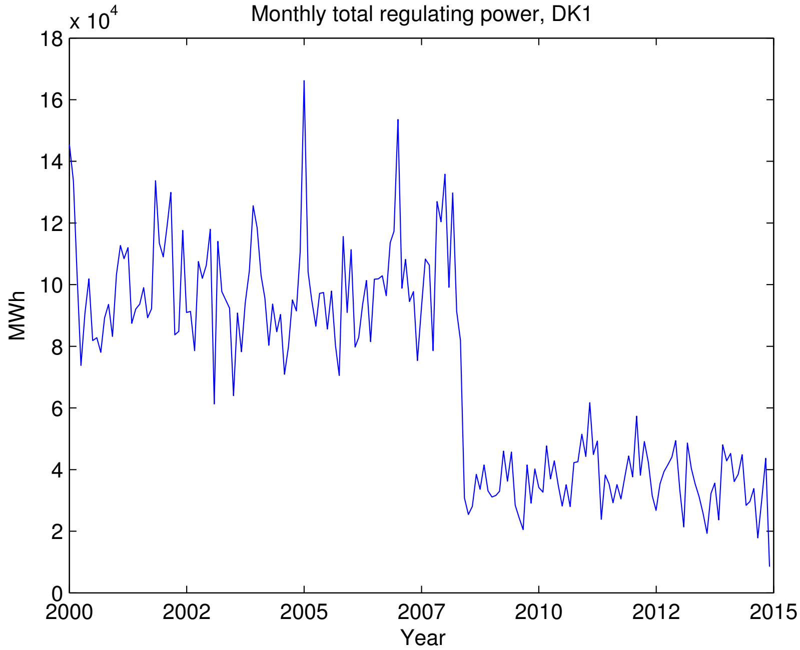

Figure 4.25: The total regulating power traded on a monthly basis in DK1. There is a notable shift in volume during 2008.

Chapter 5

Discussion

5.1 Results

5.1.1 Wind power capacity and generation

The results on wind power capacity and power generation were both in line with and contrary to expectations. Total wind turbine capacity and wind power produced has increased impressively over the last one and a half decade. Power output from wind power was found to be highly intermittent, as was expected, but output per MW installed capacity was improving over time rather than experiencing diminishing marginal returns. Improvements in turbines, quality and maintenance must therefore outweigh any potential effect from lack of suitable sites. Assumptions of diminishing marginal returns on investment are normally made while keeping the technology constant, in this case that is not true since the comparison is between, for example, turbines made in 1985 (and weathered and worn since) and turbines from 2010.

However: it can be concluded that there are still enough turbine sites available that newly installed turbines can generate more of their maximum production than older ones. Factors that could cause higher output on newer turbines are, amongst others: less downtime for repairs, taller towers (turbines have gotten larger) giving steadier winds as well as the fact that older wind turbines have aged and lost efficiency. It is also possible that better modelling and planning have enabled turbine operators to continue finding good sites, despite more wind turbines already being installed. Since no two wind-years are alike it was not deemed reasonable to compare different turbines during different years, therefore there is no correction for aging of turbines.

Wind power expansion was found to decrease total and peak production from other sources, but the former more than the latter. The operators of thermal power plants are negatively affected by this development since they have capital costs associated with the capacity they keep (and have invested in) but increasing wind power gives them a smaller overall market share to recuperate those costs with as their capacity grows more under-utilized. This development can be problematic for the grid since capacity needed to generate when wind power is low must be maintained by ever smaller profits from total generation in those plants. This development along with untimely investments are claimed to have cost European utilities half a trillion Euros in market capitalization [12]. The fact that conventional fossil power production decreases overall is however positive from an emissions perspective, which is the motivation behind wind power subsidies. As markets adjust it is possible that total thermal capacity will decrease and Denmark will rely more on imports, storage and demand management when wind power generation is low. Financial markets can also help to balance supply, for example by creating contracts where producers sell their capacity and consumers pay a premium to avoid the risk of spot price variance.

5.1.2 Spot prices and wind power

The differences between prices in different regions were in practice to complex for this thesis to model, large variations obscure trends and too many factors affect the prices to simply model them as a function of wind power alone. The comparison of spot prices between DK1 and Norway found that Danish electricity had gotten more expensive relative to Norwegian during the time studied, the development was however very erratic and can not be attributed to wind power alone. Increasing Danish electricity prices compared to neighbors could decrease industrial competitiveness and economic growth. Wind power production was, combined with calendar month dummy variables capturing some demand and weather effects, found to be a useful predictor of electricity prices on a daily time-scale. Along with the need to balance the grid, this will continue to increase the importance of accurate wind forecasts to be able to control and profit from wind power production. Price levels for wind power production were found to be lower than those for alternative power sources, and prices were negatively affected by increases in wind power production: all in line with expectations. This trend could be problematic as it implies more and more electricity is generated at increasingly ill-chosen time. This trend could imply that price variance would increase, which has not been observed.

Computing the producer cost of electricity sold at negative prices showed that these instances were still relatively rare. It is therefore reasonable to assume that periods of negative prices should not be major concerns for producers yet: the loss was around 0.2% of revenue during 2013. The number of hours with negative prices looked likely to decrease in both DK1 and DK2 during 2014 (data was not yet available for the entire year at the time of writing). It is practically possible to invest in "consuming capacity" to make profits from negative electricity prices, for example by buying electric radiators[1] and actively the spot market bid at negative prices. Therefore it is unlikely that the aggregate production losses could become very large, as it would drive investment in capacity to consume electricity.

The analysis of electricity spot price fluctuations showed no obvious dependence on wind power capacity, correcting the standard deviation for average price instead revealed that standard deviations had shown no clear trend during the time studied. The electricity price variance can be affected by many sources other than intermittent renewables. The largest deviation found in any Nordic region occured in Sweden and East Denmark during February 2010, simultaneous un-scheduled stops at three Swedish nuclear reactors, combined with low reservoir levels and a very cold month meant that the spot price ballooned to 50 times its average. This lasted only a few hours but affected the monthly and yearly standard deviation greatly.

[1]Or invest in a useful endeavour, such as an aluminium smelter.

5.1.3 Electricity trade

The results on trade flows and wind power capacity were inconclusive, there was no link to be found and although trend lines were sometimes possible to discern, as for the degrading Danish-Norwegian trade balance, they were often overshadowed by large variances.

These results do not necessarily mean that there isn't a correlation between wind power capacity and trade balance, a key issue that was not addressed due to lack of data was the bi-directional trade price of wind power between the Danish, Swedish and German regions. Since all three countries have witnessed large expansions in wind power capacity and the German and Swedish wind turbines are somewhat clustered near their respective borders with Denmark[2] it is possible that the difference in wind power share between two regions plays a role in their trade balance but that simultaneous increases have blurred the results of this.

Transmission capacities have, despite increasing intermittent capacity, not increased during the period. That profits from price differences between regions have also not increased discarded the hypothesis that increasing wind power capacity would necessitate greater transmission capacity and provide greater profits to transmission cable operators.

The papers mentioned in the Introduction, [6]&[7], argued over the goodness of fit between daily wind power production and electricity export during a year. This thesis expanded that question to looking at the development of wind power production and electricity export over time as well calculating how much wind power was actually exported. It was found that in DK1 the wind power production became a decent predictor of wind power exports, $R^2 = 0.8$, and total wind power export grew along with installed wind capacity. The situation in DK2 is however more complex, as wind power exports have *decreased* over the last years in nominal terms despite greatly increased capacity. This shows that the trade balance is most often too complicated to be predicted by one variable on the supply side.

5.1.4 Subsidies for wind power

For the calculations on total subsidies it would have been easier to simply look up how much money was paid in subsidies every year from the government budgets rather than calculating it from individual turbines or hourly production data. The approach taken did, however laborious is was, provide subsidy data with great detail. The lack of information on subsidies in place prior to 2000 did however influence the calculations, as all older turbines were simply prescribed the same rules as those installed 2000-2002.

The government bill for subsidizing wind turbines has grown rapidly in recent years. The increase in subsidies introduced in 2008 accelerated the pace of expansion as well as (obviously) paying more to new turbines than previously. Although subsidies during 2003-2007 appeared too low to warrant much investment it is likely that the "required subsidy" to make investments widely profitable has decreased substantially since 2002 (when subsidies last were at a similar level). These changes have increased the cost to the taxpayer significantly and proposals have been put

[2]The German border region of Schleswig-Holstein met over 40% of its electricity consumption through wind power in 2010 [13]

forth to phase out subsidies entirely [14]. Bar any unexpected changes to the legislation, current and planned turbines will however receive subsidies for a long time. The subsidies in place at different times were found to be good predictors of wind power expansion, electricity prices themselves also played a role but the uncertain long-term prospects of these can be a reason for why subsidies are so important for investments in wind power. It was furthermore found that subsidies make up a significant portion of the revenue from producting wind energy, especially as electricity prices have decreased. Carbon dioxide abatement costs from wind power subsidies were found to very expensive compared to references, this is partly due to the fact that coal power electricity generation has been outlawed in Denmark for decades; thus the low-hanging fruit has already been picked off. Further expansion is likely to be even less effective at reducing CO_2 emissions as Danish CHP plants nowadays burn lots of biomass, and will be required to continue running to provide district heating regardless of electricity prices. The question of subsidy exports was settled in numbers and it is evident that a large fraction of subsidies has gone to electricity production that is exported: over 20 % in 2014. This does not necessarily mean that subsidies are wasted, wind power export fuelled by subsidies improves the terms of trade and could serve to substitute less environmentally friendly energy sources abroad.

5.1.5 Market efficiency

The market share of day-ahead ELSPOT trading increased greatly during 2000-2007 but subsequently fell slightly. Due to limited data on ELBAS trading it was not possible to see whether the decrease in trading share since 2007 had been caused by trade migrating to intraday markets and if this correlated with wind power production. A continuing decrease in spot market share could be caused by some interesting factors, for example competition from other market systems.

The regulating power markets proved cryptical, the fact that such a marked shift was found in the data could have been triggered by some change in the market, such a change has however not been identified.

5.2 Method

5.2.1 Data sources

The data sources used in the project were very extensive and impossible to manually inspect for irregularities, some minor oddities were found and their significance as error sources is discussed below.

- Daylight savings time was dealt with differently in different data sets and the shift to summer time in March caused a few problems as some sources put production and trade to zero on the 23-hour day, others put an empty cell and others deleted the hour from the time axis. This often varied between years and regions in the same database. The shift back to winter time was also handled differently in different sources, some sources averaged over the 2 hours between 2 and 3 a.m and others used the total generation or flow. Since most analyses in this project calculated averages by month or year these potential disagreements were judged to not be significant error sources.

- The master document detailing the electricity production from all Danish wind turbines was very large and certain oddities were necessary to handle. The pre-2000 production from older turbines was often found to be exactly identical from year to year which led to the assumption that the reporting prior to this year was crude (maybe based on some average capacity factor times turbine capacity). This lack in detail led to limitation of the analysis of capacity utilization to the years 2001-2013. Certain turbines also registered production for one or several years *before* their grid connection date, these values were excluded from all analysis.

The data sets were very large and extensive but did only reach back to the year 2000, a large expansion in wind power started already in 1996/1997 and this was therefore not present in the correlation. The fact that wind power levels were virtually constant during a subset of the years studied was a blessing in disguise since it could act as a test for causation over correlation. Had the wind power expansion been smooth and linear it would have been hard to distinguish other changes that took place at the same time, but where not caused by wind power.

5.2.2 Statistical analysis

The statistical analyses undertaken during the project were mostly simple tests on several possible correlations. A more focused effort on one or a few correlations could have produced more satisfactory results, due to the extensive scope of the project it was not feasible to bring in more data on other variables that could affect supply and demand. Possible correctors could be detailed weather data, fuel prices and GDP growth.

5.3 Conclusions

5.3.1 Summarized results

It was found that investments in wind power capacity had not experienced decreasing marginal returns but that wind power had reduced the capacity utilization of conventional Danish power plants. Wind energy was found to be sold on average at 10 % lower prices than conventional energy, due to absence of output-control. Danish prices were found to have increased relative to Norwegian prices, although causation in wind power expansion can not be proven. Spot price standard deviation did not increase notably during the time span examined.

As wind power capacity increased, wind power production became an increasingly accurate predictor of electricity export and Danish trade balance did worsen, although not in a statistically significant manner. Neither transmission capacity nor profits made by operators of transmission cables increased during the period.

Subsidies were found have expanded rapidly during the 21st century, especially as wind power capacity picked up around 2009. Subsidies were shown to be good predictors of wind power capacity expansion, with a lag of 1-2 years. Around 20 % of wind power subsidies were exported during the period studied.

The market structure investigation showed that the ELSPOT market was the most important market for electricity trading during the greater part of the 21st

century. Correlation to wind power capacity did not yield any significant results and question marks remain concerning regulating power markets developments.

The thesis concludes that the Nordic electricity market has incorporated large volumes of intermittent power capacity without any radical effects on trade or prices, plausibly due to large hydro-electric capacity, and with a likely decrease in $C0_2$ emissions.

5.3.2 Implications for future electricity markets

A development towards an ever more interconnected Nordic and European electricity grid with an increasing production share coming from intermittent wind and solar power is likely to further press profit margins of conventional thermal power plant operators. Longer and more frequent periods of very low or negative power prices are likely to hit nuclear power stations especially hard since these can not regulate their output. Corresponding shortfalls in supply will likely prove benefit hydro-power and gas turbine operators as these can regulate supply quickly. If the supply side can not regulate away the intermittency caused by wind and solar power there will be a need for developments in demand-side regulation, possibly by utilizing electric car batteries as reservoirs or other technologies in the field of smart grids. The analysis in general has however concluded that the Danish grid has been remarkably efficient at incorporating very large quantities of intermittent power without altering the market more than has been shown. A caveat to application of this conclusion to other markets is however that Denmark is both a net natural gas exporter and a neighbor of Sweden and Norway: countries that with their exceptionally large hydro-power capacities can act as overseas reservoirs for the Danish grid. There is, however, cause for hope and belief that even greater renewable intermittent capacity can be incorporated in many markets by continuing developments in forecasting, demand management and smart grids.

5.4 Further research

Interesting topics for further research could include looking at the effects of wind power expansion on actual CO_2 emissions, operations and profitability of CHP plants as well as market valuations for utility companies based on their energy mix. Including more predictors such as those mentioned in Section 5.2.2 could possibly yield more accurate models on the data studied in this project.

Chapter 6

Bibliography

[1] History, NordPoolSpot
Retrieved on 2014-12-16
http://www.nordpoolspot.com/About-us/History/

[2] Danske Regioner, Statistik
http://www.regioner.dk/om+regionerne/statistik+ny
Retrieved on 2014-09-22

[3] Prognosis for trading capacities
NordPool retrieved on 2014-12-11
http://wwwdynamic.nordpoolspot.com/marketinfo/transmission/show-transmission.cgi

[4] The NorNed HVDC Connection, Norway – Netherlands
ABB AB, 2007
http://www05.abb.com/global/scot/scot245.nsf/veritydisplay/2402665447f2d054c12571fb00333968/$file/project%20norned%20450%20kv%20dc%20mi%20sub.pdf

[5] Germany's energy transition: Sunny, windy, costly and dirty
The Economist, January 16th 2014

[6] Wind Energy, The Case Of Denmark
Center For Politiske Studier
September 2009
http://www.cepos.dk/fileadmin/user_upload/Arkiv/PDF/Wind_energy_-_the_case_of_Denmark.pdf

[7] Danish Wind Power Export and Cost
Lund, Hvelplund et. al.
February 2010
http://www.windpower.org/download/541/DanishWindPower_Export_and_Cost.pdf

[8] Figure of supply and demand in the electricity market.
Peakoil.com from Kroon 2009
Added 2011-05-09

Retrieved on 2014-12-18
http://peakoil.com/alternative-energy/a-review-of-green-energy-growth-prospects

[9] Oversigt over støtteregler mv. for elproduktion baseret på vedvarende energi og anden miljøvenlig elproduktion
Danish Energy Agency
17 September 2014
http://www.ens.dk/sites/ens.dk/files/undergrund-forsyning/el-naturgas-varmeforsyning/elforsyning/elproduktion/oversigt_over_stoette_til_elproduktion.pdf

[10] Avedore, Denmark
PowerTechnology.com
Retrieved on 2014-12-29
http://www.power-technology.com/projects/avedore/

[11] Impact of the financial crisis on carbon economics
McKinsey & Company, 2010
http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves

[12] European utilities, How to lose half a trillion euros
The Economist, 10 October 2013

[13] Status der Windenergienutzung in Deutschland - Stand 31.12.2011
Molly, J.P. DEWI Gmbh
http://www.wind-energie.de/sites/default/files/attachments/press-release/2012/jahresbilanz-windenergie-2011-deutscher-markt-waechst-wieder/statistik-jahresbilanz-2011.pdf

[14] Slut med støtte til billig vindkraft
Berlingske Business, 2014-07-17
http://www.business.dk/green/slut-med-stoette-til-billig-vindkraft