FACULTY OF SOCIAL SCIENCES

DET SAMFUNDSVIDENSKABELIGE FAKULTET

Integration of Wind Power into the Danish Power System

Viktor J. Rácz

Priyadarshini Yadav

Niels Vestergaard

Department of Environmental and Business Economics (IME)

University of Southern Denmark

IME Report 14/13

Integration of Wind Power into The Danish Power System

<u>Authors</u>

Viktor J. Rácz

Priyadarshini Yadav

Niels Vestergaard

Esbjerg, 31.01.2013

Department of Environmental and Business Economics
IME REPORT 14/13

ISSN 1399-3232

Viktor J. Rácz
Department of Environmental and Business Economics
University of Southern Denmark
Niels Bohrs Vej 9-10
DK-6700 Esbjerg
Tel.: +45 6550 4164
Fax: +45 6550 1091
E-mail:racz@sam.sdu.dk

Priyadarshini Yadav
Department of Environmental and Business Economics
University of Southern Denmark
Niels Bohrs Vej 9-10
DK-6700 Esbjerg

Niels Vestergaard
Department of Environmental and Business Economics
University of Southern Denmark
Niels Bohrs Vej 9-10
DK-6700 Esbjerg
Tel.: +45 6550 4181
Fax: +45 6550 1091
E-mail: nv@sam.sdu.dk

Table of content

Figure content

Table content

Abstract

Wind energy is a major player in the Danish electricity market with an ambitious goal to pursue 50% of the electricity market by 2020. This paper examines the economic impacts of increasing integration of large-scale wind power to the existing electrical grid. Firstly, we survey the literature in this regard, which introduces the advent of wind energy in Denmark through the years and policies behind its success. We describe the Danish electricity market and its collaborated functioning with the Nord Pool Spot market, so as to introduce the functioning of the electricity market that determines the price of electricity. We have observed the degree of influence of the fossil fuel prices, total demand, wind power production and import on the electricity price and the individual co-efficiency for the years 2000, 2005 and 2010, according to the energy mix. Using a grid management model for the Western Denmark region, we simulate the effect of an increase in wind penetration level on the electricity generation costs and on the CO_2 emissions at various penetration levels. The results show that as the wind penetration level increases the cost of electricity production rises thus, reducing the CO_2 emission becomes price contradictory.

1 Introduction

The fossil fuels have played a major role in the development of industrial economies for a very long time. Power generation and electricity supply are heavily dependent on the fossil sources. On the other hand, burning of the fossil fuels transforms the carbon stored in the Earth's crust into the atmosphere as CO_2. This has led to an increase in the CO_2 content of the atmosphere resulting into an overall increase in average temperatures across the globe and the depletion in the existing fossil fuel reserves. Apart from the climate changes there are other political, economic and social impacts of this heavy dependency on fossil fuels. The concentration of the fossil fuels in the few parts of the world creates high dependency for the countries outside this area regarding fossil fuel imports. The countries in possession of the fossil fuel reserves, for e.g. the Middle East and Russia, are not politically stable. Therefore, development and implementation of the renewable energy systems will decrease the dependency on fossil fuel imports and create renewable energy supply source such as wind, solar, tidal and biomass resources. A shift to the renewable energy systems not only contributes to the establishment of new enterprises, creating job opportunities but also to the fulfillment of the European Union's renewable energy production targets, reducing greenhouse gas emissions.

Wind is one of the fastest growing renewable energy sources which could, even if only in a small amount, replace fossil fuels in electricity generation. The Danish government has proposed a target of 30% renewable energy for the year 2025 as a milestone of the long-term project to make Denmark a fossil fuel independent nation by the year 2050, thus meeting the gross energy demand by renewable energy sources.

There is a tremendous wind potential and also a powerful urge in Denmark to utilize the power of wind. Due to the fact that wind is not continuous in all the time it is necessary to determine the optimal rate of wind energy source and the way of the utilization of the produced energy. At present, Denmark has a total installed wind capacity of 3.871 MW and is the country with the highest share of wind power (25.9%) in electricity consumption.

We start this study by explaining the Danish national energy plans since 1976 until present in Section 2, where we discuss the change in focus of the energy plans due to the prevalent circumstances. In Section 3 and 4 we introduce the Danish electricity market and the Nordic

Exchange market, respectively, in order to provide a general understanding of the basic functioning of the electricity market and its actors. In Section 5 we discuss the change in wind capacity and in wind power production in Denmark in the selected years 2000, 2005 and 2010.

Later in Section 6 we introduce a price analysis showing the influence of the different price determinants on the Danish electricity price through a regression calculation. In Section 7 we present our empirical analysis where we focus on the economic criteria's of integrating large-scale wind power to the existing electrical grid mainly focusing on how the conventional generators adjust to the increasing share of wind power, using Van Kooten's (2009) Grid management model. The main objective of employing this approach in the research study is to visualize the problems associated with the integration of wind power into existing electricity grid with different wind power penetration. We end this section by presenting the results of the empirical analysis. Finally, in the Conclusion we present the findings of the research study.

2 National Energy Plans in Denmark

The Danish Prime minister in his opening speech to the Danish Parliament in October 2006 announced complete (100%) independency of fossil fuel and nuclear power as long term target of Denmark.

In the renewable energy targets the main goal was to achieve that the share of renewable energy from the gross energy consumption reached 20% in 2011. Subsidies were introduced to enhance the utilization of renewable energy – subsidies for biomass and for onshore/offshore wind farms – while green taxes also supported these ambitions. This great bend towards 100% renewable energy system stems from the concern of security of supply and make Denmark an energy independent country. Denmark was highly dependent on oil for energy supply during the time of the first oil crisis (around 90% of energy supply was covered by oil) as shown in Fig 1.

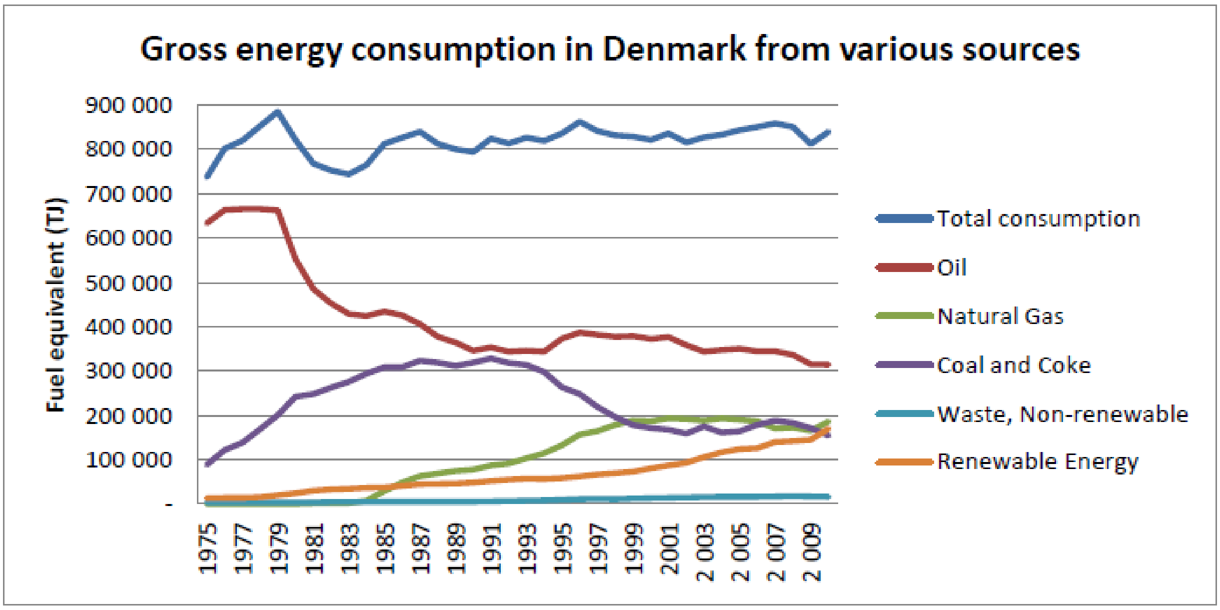

Figure 1 Gross energy consumption in Denmark from various sources

The first national energy plan, the Dansk Energipolitik in 1976 focused mainly on replacing oil imports by coal and energy savings. This led to high coal imports as Denmark was not in possession of coal reserves, which resulted in security of energy supply, as the availability of coal was abundant. The second national energy plan, the Energiplan 81 (Danish Energy Authority and Kommunikationsbureauet Rubrik, 2003) focused more with on the domestic primary energy production since this plan laid the ground for widespread oil and natural gas exploitation from the North Sea. It also introduced subsidies for operation of wind and biomass plans and establishment of natural gas grids in Denmark. However, this lead to an increase in coal consumption which exceeded 30% of the total fuel consumption at the beginning of the 1980's and culminated in 1990-91 by 40%. The year 1984 marked the widespread production of natural gas, exceeding its share of 10% in the total energy consumption by 1990. By the year 1997 the total share of natural gas exceeded 20%.

After the government ensured the safe and continuous energy supply in regard to reduced oil imports and domestic energy production, environmental concerns regarding energy sector started to sink in. Therefore, there was shift towards environmentally desirable energy supply since 1990. The third energy plan, Energi 2000 (International Energy Agency, 1998) advocates the reduction of the CO_2 emissions by 28% in 2005 compared to 1988 emission levels, reduction of coal consumption by 45% and an increase in natural gas consumption with the introduction of decentralized and small Combined Heat and Power, in order to ensure energy efficiency and utilization. Formation of Acts, besides the energy plans, such as the Electricity Supply Act, Heat Supply Act, and Traffic 2005 focused more on 'green taxes' and subsidies in order to encourage the environmentally more desirable energy sources.

Fig 2 shows the changes in the Primary energy production from various sources. The growth in the gross oil production is perceptible after 1976 – when the first national energy plan was released – significant increase occurred after the second energy plan was introduced in 1981 when the main focus was on reducing dependency on imported fuels.

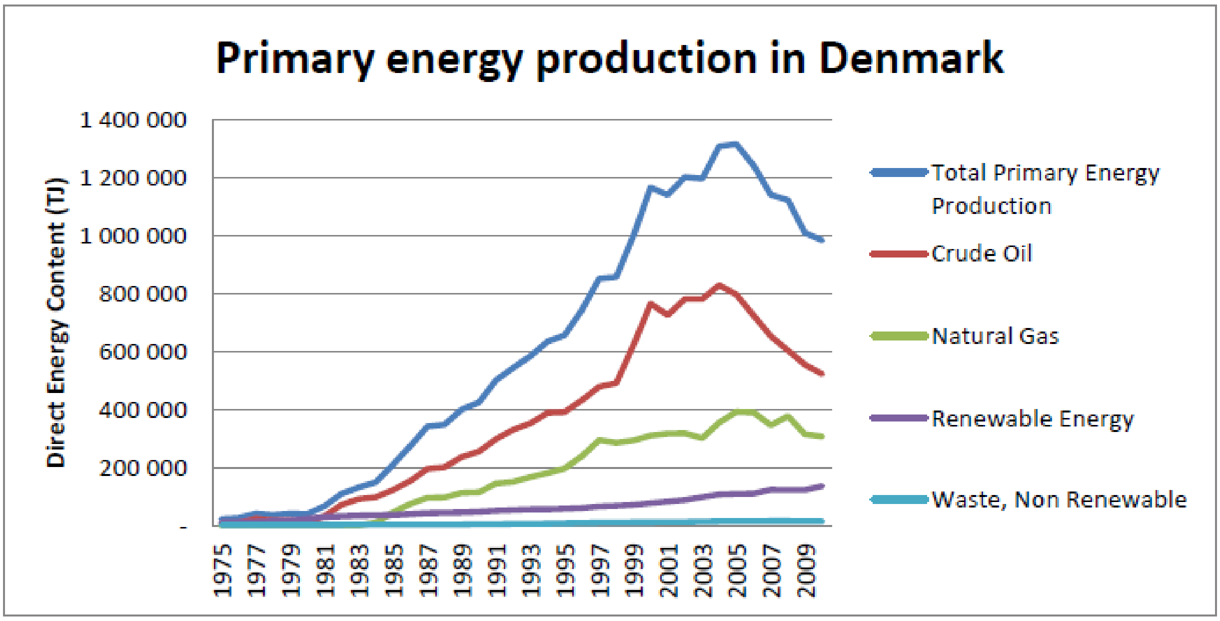

Figure 2 Primary energy production in Denmark

Due to this target the extraction of natural gas from the North Sea has also begun in the middle of 1980's and it lasted until 2005 when it peaked. An almost linear growth of the production of crude oil and natural gas can be observed from the beginning of the 1980's until the middle 1990's and due to the dramatically growing level of oil export the gross primary oil production was increasing by 55% in two years – from 1998 to 2000. After 2005 significant decrease in both of the oil production and of the total primary energy consumption was due to the drop of the oil export.

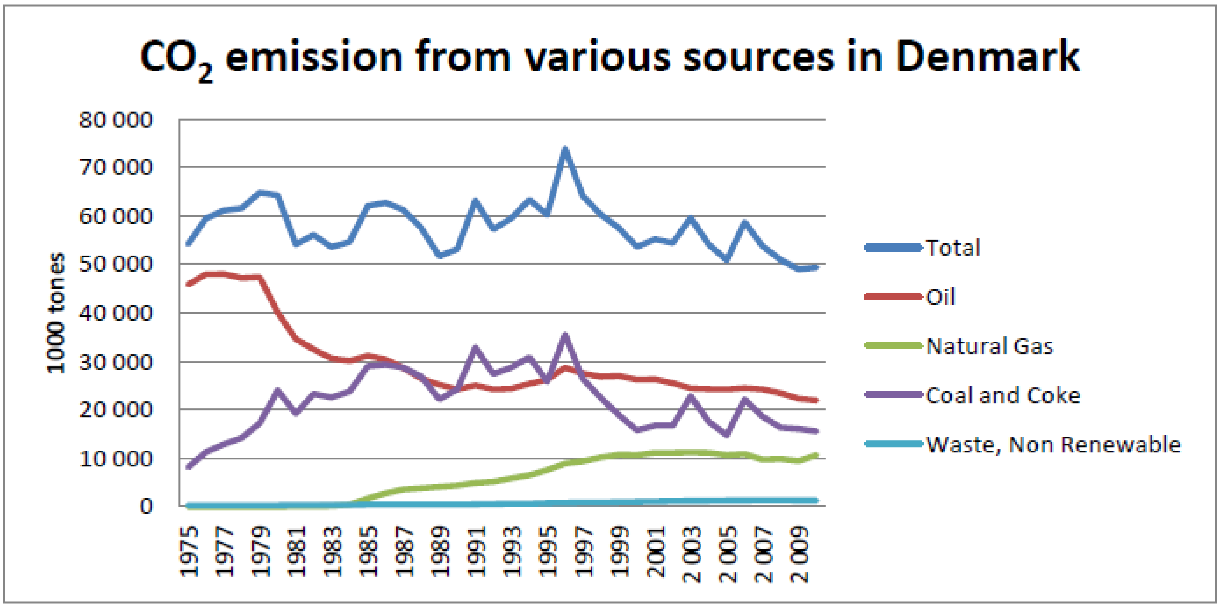

Figure 3 CO_2 emission from various sources in Denmark

Figure 3 shows us the total CO_2 emission and the emission from various sources in Denmark from 1975 until 2010. The Figure clearly shows the 'environmental results' of the Danish national energy plans targets, namely the significant drop of the CO_2 emitted by oil refinery at the beginning of the 1980's as the import of this primary energy source was cut off at that time but the gross production was not started yet. The CO_2 emission by burning natural gas was due to its gross exploitation and consumption. The amount of CO_2 emitted by burning coal and coke was significantly increasing from 1980 – as the oil was replaced by mostly coal – until it peaked in 1996 and after that – due to the Energy 21 energy plan – the level of the emission dropped notably. However from the middle of the 1990's the emission from burning oil, natural gas and non-renewable waste – which is negligible – was constant while the changes in the level of CO_2 emission by burning coal altered the level of the total emission.

These previous developments have formed a base for the future and the new energy plans and strategies, with long-term targets of designing a 100% renewable energy system, replacing the fossil fuels and saving energy with significant technological efficiency improvements in energy production as well as in energy consumption. Besides the focus on the renewable energy sources and energy savings, the latest national energy plan (Energy Strategy 2050) highlights the importance of research, development, demonstration and innovation (RDD&I).

3 Danish electricity market

The Danish electricity market organizationally comprises of the following market players:

- Central power plants and major local power plants serving the free market. Central power plants are major power plants located at central power plant sites as stated in the Danish electricity legislation.

- Wind-generators, smaller local CHP plants and industrial co-generating plants receive politically determined prices or subsidies for electricity generated. The electricity from these plants is sold in the Nordic power exchange by either the generator or the national transmission system operator (Energinet.dk). The generator, in addition, receives a subsidy reflecting the difference between the actual price in the wholesale market and the politically fixed prices or the fixed subsidy. Subsidies are financed by the end use customer payments (‘PSO payment’) which is paid alongside with the network tariffs.

- Distribution network companies and regional transmission network companies primarily ensuring local and regional technical security of supply. They perform a number of consumer related services and their revenues are subject to individual caps fixed by the Danish Energy Regulatory Authority (DERA).

- Electricity trading companies selling electricity to customers subject to mutual competition. These companies with a license of ‘obligation to supply’ must sell electric energy to consumers, who have not taken the opportunity to choose another supplier in the free market and their prices are regulated by the Danish Energy Regulatory Authority.

- The national system operator (Energinet.dk) is responsible for the overall security of supply and ensuring a well-performing electricity system. Energinet.dk owns the 400 kV transmission system interconnecting the neighboring countries and part of the 132/ 150 kV grid.

4 Nordic Exchange market

The Nordic electricity exchange covers Denmark, Sweden, Norway and Estonia. The regulating power market is managed by the TSO (Transmission System Operator) maintaining the stability of frequency in the transmission grids. The TSO procures 'up regulation' in case when the frequency of the alternating current falls below the value of 50 Hz, by buying electrical power from producers with excess generation capacity, and 'down regulation' where it sells electrical power to the producers, causing them to reduce electricity generation. The up regulated price is set by the price of the last up regulated MW and the down regulated price is set by the price of the last down regulated MW.[1]

The Nordic countries are divided into different bidding areas and any two Nordic commercial players situated in different bidding areas cannot involve in electricity trading because the Nord pool spot manages all the cross-border trading capacity on behalf of the TSO. In order to trade in different bidding areas, the Nordic players can use the financial electricity market. The financial electricity market is used for price hedging and risk management where the retailers and suppliers sign a future contract with a certain delivery period. The idea behind the concept is the ability to always buy and sell electrical power. The financial electricity exchanges need to be cleared as the financial exchange is anonymous; hence, the contracts have to be cleared so the clearing house sits between the parties.

The intraday market, Elbas (Electricity Balance Adjustment Service)[2] is a continuous trade until 1 hour before the delivery time. Originally introduced in Finland, the concept merged later with the Nord pool. This market specializes in meeting requirements of large electricity consuming industries.

Eastern and western Denmark areas are different bidding areas with separate hourly area prices for the Nord pool power exchange. The share of wind power on an annual basis has increased to 25% in western Denmark. Thus the wind power has an important effect on the hourly prices on the day ahead and intraday markets.

---

1 Houmøller, A. P. (2004). Retrieved September 2011, 10, from Nord Pool Spot: http://www.nordpoolspot.com/Global/Download%20Center/Rules-and-regulations/The-Nordic-Electricity-Exchange-and-the-Nordic-model-for-a-liberalized-electricity-market.pdf

2 Poul Erik Grohnheit, F. M. (2011). Area price and demand response in a market with 25% wind power. *Energy Policy, Volume 39, Issue 12* , 8051–8061.

5 Wind energy in Denmark

The renewable energy constitutes of around 20.7% from the total primary energy supply. Bio-fuel and wastes comprise of 17.1% and wind shares 3.4% from the total primary energy supply. However, wind has a higher share in electricity market compared to the contribution from bio-fuel and wastes, 20.2% and 13.2% respectively. With the goal to reach 50 % of electricity supply by the year 2020, wind is a major player in the Danish electricity market.

The wind energy has been promoted in Denmark, evidently since the mid-1970s, as a result of the energy crises in 1973 and 1979. With a long-term support from the government in the areas of research and development, feed-in tariffs and regulations, investment subsidies, the Danish wind energy industry has grown rapidly from 3% electricity share in 1991 to more than 25% at present. Fig 4, depicts the growth of wind turbines and capacities in Denmark from the year 1977 till present. The subsidy scheme between the years 1979 – 1982, providing a 30% of the total investment cost for installing wind turbines, played a vital role in the rapid expansion of wind capacity.

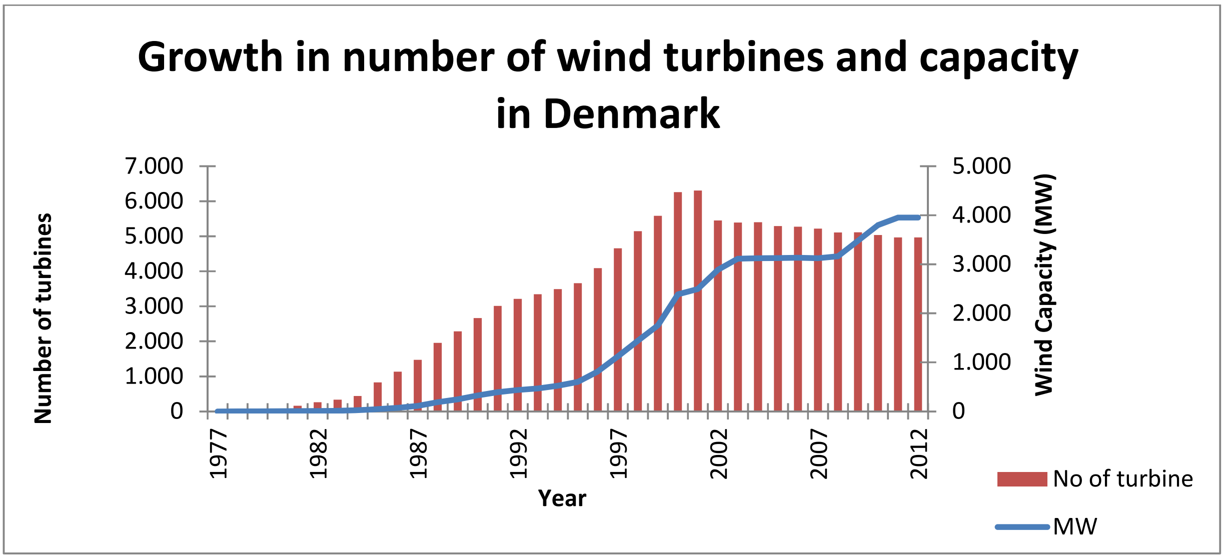

Figure 4 Growth in number of turbines and capacity in Denmark

This study undertakes an observation of changes in Primary production, Local production and wind power production in 10 years (2000-2010). The 'Primary capacity' shows the electricity capacity of the centralized power plants (CHP) and the 'Local capacity' describe the electricity capacity of decentralized, heating, solar, industry, local and hydropower plants. The study is in regard to the data from Jutland in the years in the years 2000, 2005, 2010.

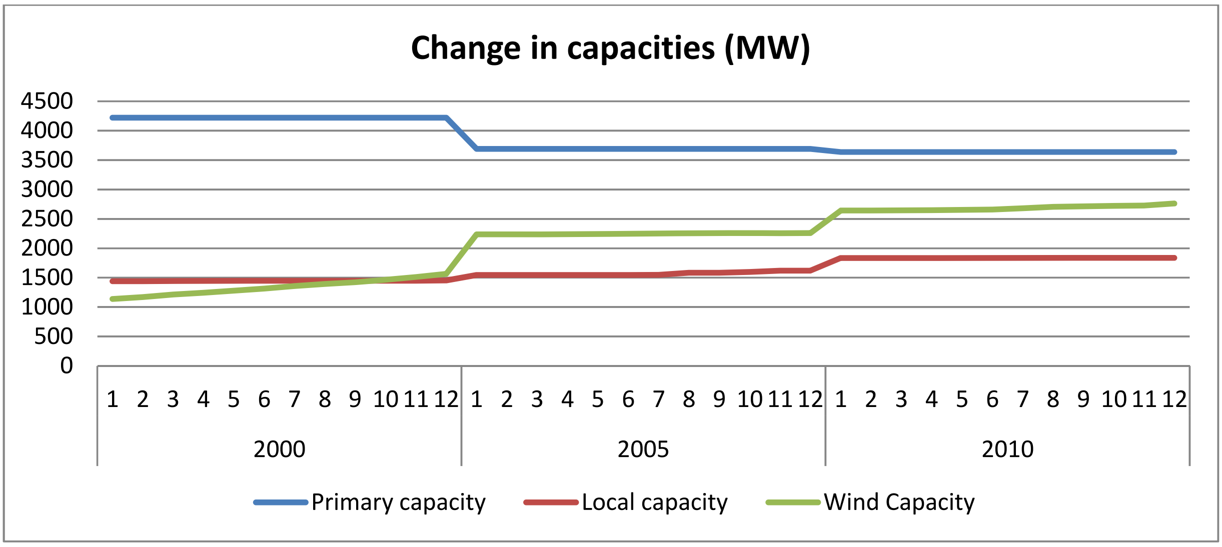

Figure 5 Change in capacities (MW) in the observed years

Figure 5 shows the changes in the capacities regarding to the three different kinds of energy sources. The essential tendency is that the capacity of the 'Local' and 'Wind' power sources have been increasing from 2000 to 2010 and at the same time the 'Primary' capacity was decreasing. The Wind capacity exceeded the Local capacity in October 2000 and has, since then, experienced a faster growth.

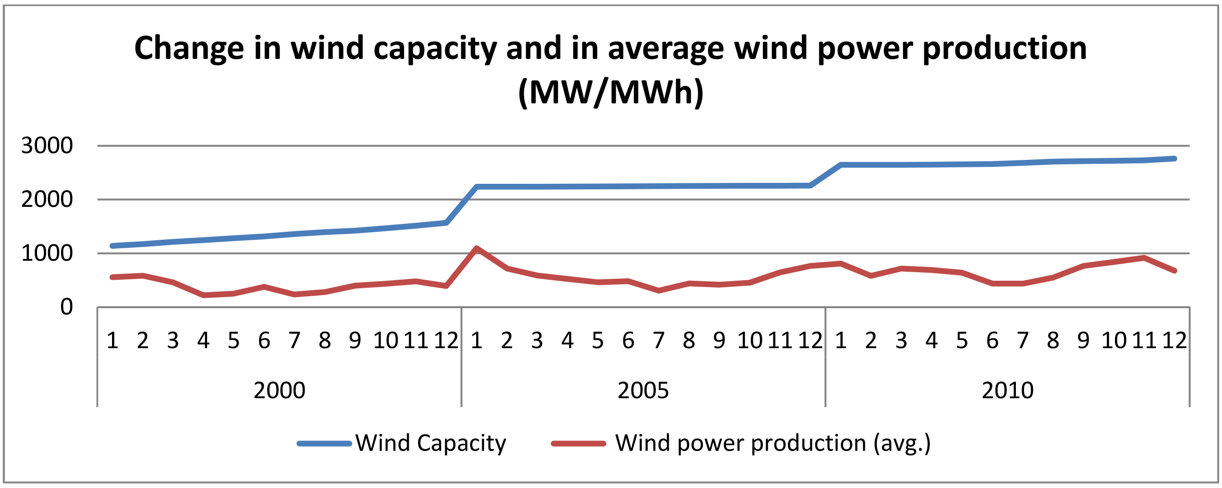

Figure 6 Change in wind capacity and in average wind production

Figure 6 shows the changes in the size of wind capacity and the monthly average wind power production in the years 2000, 2005, 2010. Although we cannot draw far-reaching consequences from the figure, but we can see clearly that the minimum and maximum monthly average level of wind production are increasing according to the increasing level of Wind capacity (except January 2005), however the gap between the wind capacity and the wind power production is widening.

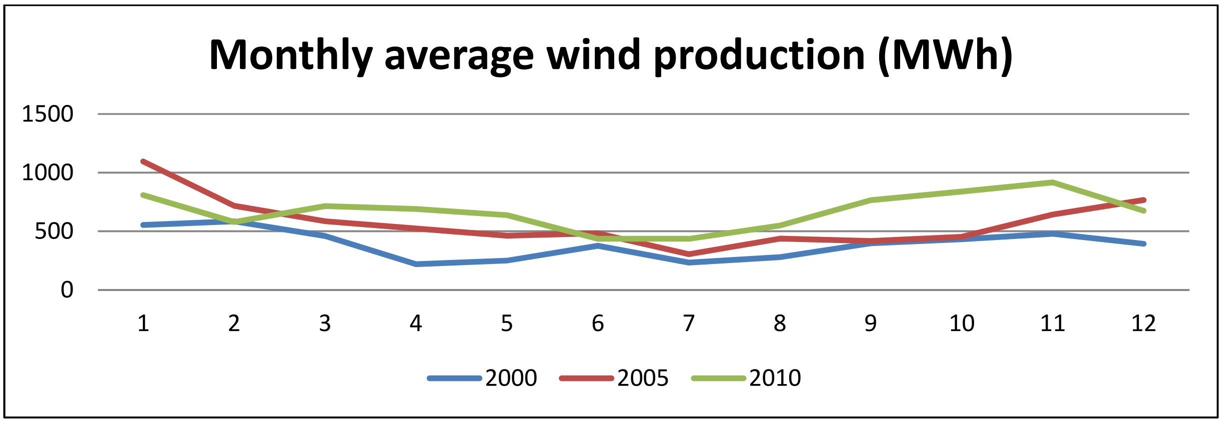

Figure 7 Monthly average wind power production for years 2000, 2005, 2010

The observed years show a 'U' shaped bend in the summer months as evident from Figure 7. This phenomenon can also be observed in figure 8 where the average Nord pool purchases exceed the Nord pool sales, showing a dip in the average net export in the DK-West. The monthly average wind power production for the year 2010 was higher compared to years 2000 and 2005. As a result the Nord pool purchases from the DK-West region were much higher in the years 2000 and 2005 than 2010, with the average net export/import goes as low as -1000 MWh between the months April and November in the year 2005 and -500 MWh between the months May and September in the year 2000.Taking into consideration the year 2000 we can see that during this year the size of Wind capacity was increasing constantly but the average Wind power production was intermittent and did not follow the increasing size of the capacity. During the year 2005 the Wind capacity was increasing only with 22 MW and the monthly average Wind power production curve had the 'regular' (more production during winter time and less during summer time) intermittent shape.

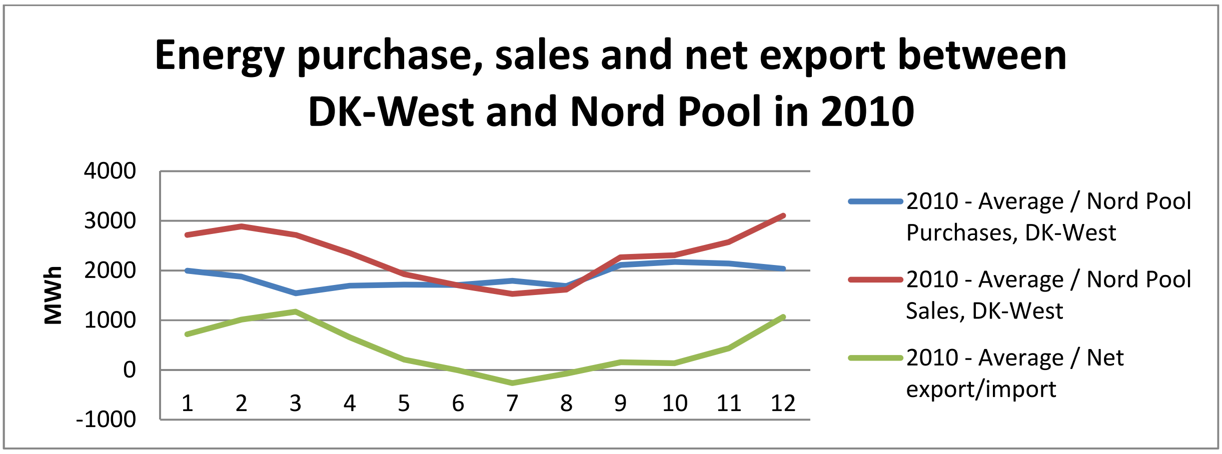

Figure 8 Energy purchase, sales and net export between DK-West and Nord Pool in the year 2010

The wind capacity in the Jutland region was growing with 135% from the beginning of the year 2000 until the end of the year 2010 while the Primary capacity was decreasing with 14% and Local capacity was increasing with more than 27% (see Table 12.–14. in Appendix I.). Until the end of 2000 the level of wind capacity exceeded the level of Local capacity and almost reached the 2800 MW at the end of 2010. In the same time the levels of Local and Primary capacities were around 1800 MW and 3600 MW respectively.

During the analyzed three years (2000, 2005, 2010) the total and the hourly average wind power production was increasing (from 3,397.88 GWh to 5,875.61 GWh and from 386.87 MWh to 670.81 MWh respectively) (Tables 1) and the maximum wind power output was also growing. According to the increasing level of wind capacity the lower and the higher quartiles of energy output was also growing which means that during the given years the level of production was increasing (as also shown in Table 1) and it can also be seen that the level of standard deviation was also increasing thus we can conclude that higher the capacity is, higher is the fluctuation of the wind energy output.

Table 1 Wind power production in the observed years (2000, 2005, and 2010)

Year	Sum	Average (hourly)	Min	Max	Quartile1	Quartile2 =Median	Quartile3	Quartile4	Standard Deviation
2000	3397883	386,87	-0,7	1715,6	97,95	272,2	598,85	1715,6	353,39
2005	5021948	573,35	0,3	2230,3	161,1	416,8	853,45	2230,3	511,40
2010	5875607	670,81	0,4	2488,5	205,05	522,6	1003,65	2488,5	561,64

In order to depict the average yearly wind penetration a Residual Load duration Curve was used to study the three selected years. The load duration curve (LDC) illustrates the variation of electricity load over a specific period of time, involving hourly load values spanning over a year. With the installed wind power on the power system, the expected output and the installed capacity has been determined. Therefore, LDC is replaced by a residual load duration curve (RLDC). A residual load is the total hourly load subtracted by the simultaneous wind power output.

$R = L - W$

Where, R= residual load; L= hourly load; W= hourly wind power output. The average yearly wind penetration for the year 2000 is 16.49%, for the year 2005 is 23.9% and for the year 2010 is 27.81%. The figures 20 and 21 in Appendix IV illustrate the RLDC for the year 2000 and 2005 depicting the average of the gross consumption data (moving average of the sorted data from highest to lowest) for DK-west and the residual load, derived from the above calculation.

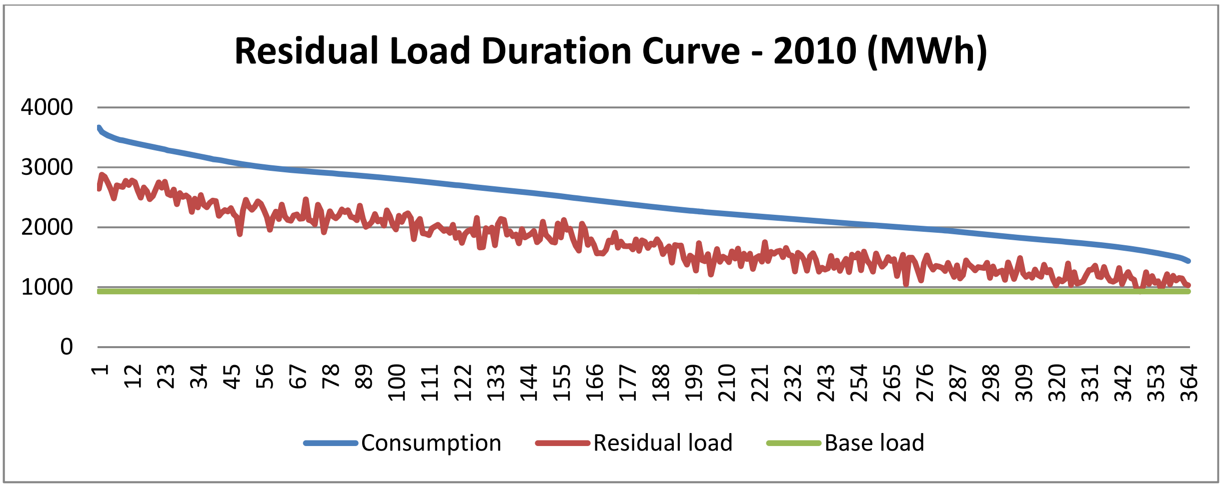

Figure 9 Residual Load Duration Curve for the year 2010

The Figure 9 above shows us the residual load duration and base load curves based on aggregated daily data for the year 2010. The base load curve indicates the amount of electricity have to be met by backup systems all the time. This value in 2010 was 928MWh over against the 1075MWh and 1015MWh base loads from 2000 and 2005. The decreasing tendency of base load curve over time shows us that the increasing wind power penetration level can results in less production needed from conventional power plants.

6 Price Analysis

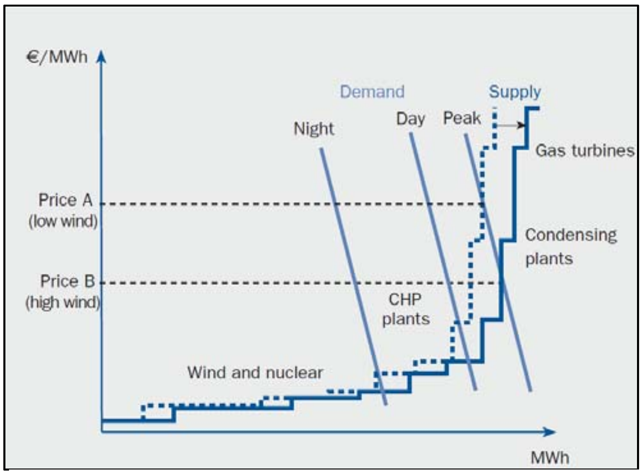

Figure 10 Source: Risø DTU

The wind power influences the power price on the spot market in mainly 2 ways: Having a low marginal cost the wind power enters near the bottom of the supply curve shifting the supply curve to its right, resulting in a low power price, depending on the price elasticity of the energy demand. According to Figure 10 the price reduces from Price A to Price B when there is a decrease in wind power supply during peak demand. It is generally expected the power price to be lower during periods of high wind than with periods of low wind. This phenomenon is known as merit order effect.

High wind power generation creates congestions in power transmissions and thus the failure of the transmission capacity to cope with the required power exchange separates the supply area from the power market, constituting its own price area. Therefore conventional sources have to reduce their production, with an excess power supply in this area as it is economically and environmentally not viable to limit the production of wind. This leads to lower power price in this submarket. High wind production during the day can be consumed due to peak demand implying steep part of the supply curve, reducing the spot power price significantly whereas high wind produced electricity in the night time contributes to a flat supply curve, thus having a lower impact on lowering prices.

The data used in this research study to show prices of coal, oil and natural gas were derived from the International Energy Agency (IEA) statistics[3] using the quarterly data available. The prices refer to the daily averages of the quarter and they are in percentages compared to the base price (in case of prices of natural gas and oil products; 1995=100, and in case of prices of coal; 2000=100).

3 International Energy Agency.(2001). *Energy Prices and Taxes.* International energy Agency.
International Energy Agency.(2006). *Energy Prices and Taxes, Volume 2006 Issue 1.* International Energy Agency.
International Energy Agency.(2011). *Energy Prices and Taxes, Volume 2011 Issue 1.* International energy Agency.
International Energy Agency.(2011). *Energy Prices and Taxes, Volume 2011 Issue 1.* International Energy agency.

The main determinants of price of electricity is considered to be the prices of coal, oil, natural gas, demand for electricity, energy import and wind production according to their share in the energy mix.

$\Delta P_{el}[P_{ff}, D, WP]$

Where, P_{el}=price of electricity; P_{ff}= Price of fossil fuels[4]; D= demand for electricity; WP= Wind power production.

Table 1 shows the influence of the above mentioned components on the electricity price and the individual co-efficiency for the years 2000, 2005 and 2010. The degree of influence of the fossil fuel prices, total demand, wind power production and import on the electricity price is 65.59%. The minus 0.05 coefficient value of wind power production indicates a decreasing the electricity price when the wind power production increases. With other words: increasing the wind production by 10% will induce a 0.5% decrease in the electricity price.

Table 2 The influence of the components on the electricity price

FF components	**Coeff.**	**R-squared**	**Root MSE**	**t**	**[95% Conf. Interval]**	
Price of coal	-1.438326	0.6559	82.245	-13.15	-1.652785	-1.223867
Price of oil	.6095129			30.80	.570728	.6482979
Price of natural gas	2.455723			32.92	2.309492	2.601955
Demand	.1047154			111.39	.1028729	.106558
Wind power production	-.0568378			-53.25	-.05893	-.0547457
Constant	-445.0533			-33.10	-471.4058	-418.7008

Table 15 in Appendix V shows the degree of influence of each individual component alone on the electricity price. Considering the total demand along with the price of fossil fuels in table 15, shows an influence of 61.88% on the electricity price. The demand alone is responsible for the influence of 14.09% on the price of electricity. Table 2, includes wind power production as another component, which raises the rate of influence of the mentioned components on the electricity price to 65.59%, an increase by 3.71%.

4 Energi Styrelsen.(2011). Retrieved december 21 , 2011, from Energi Styrelsen : http://www.ens.dk/da-DK/Info/TalOgKort/Statistik_og_noegletal/Energipriser_og_afgifter/Oliepriser/Sider/Forside.aspx

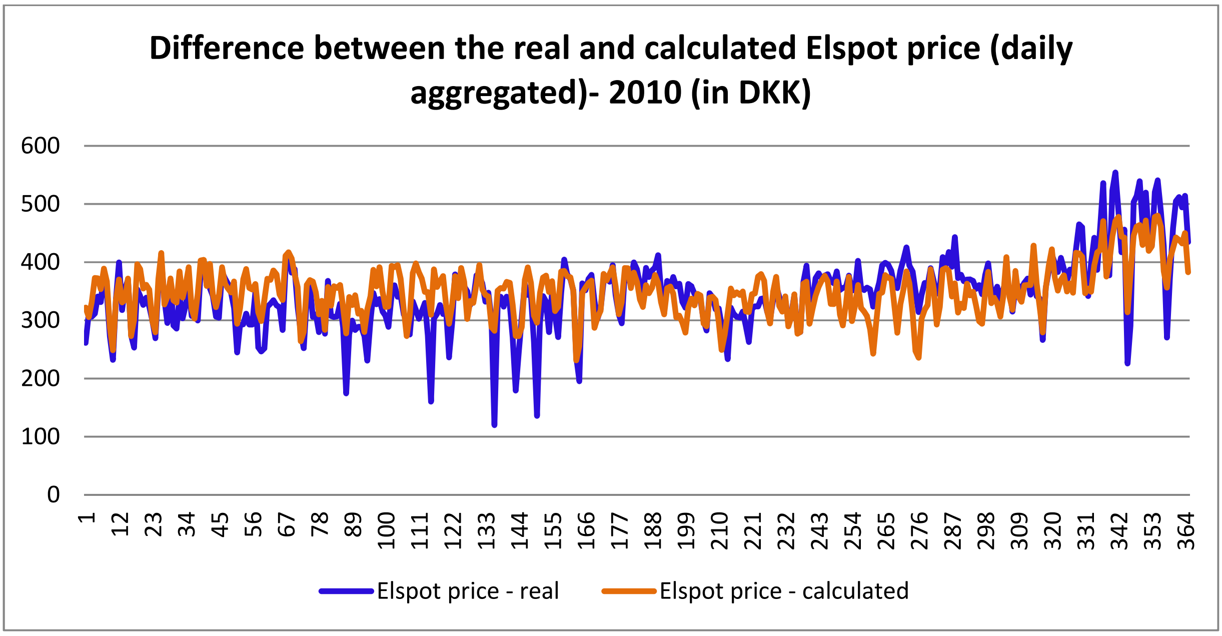

Figure 11 The real daily aggregated Elspot price against the calculated daily aggregated Elspot price (in DKK), 2010

The overlap of the real and calculated daily aggregated Elspot prices on Figure 11 above underpin the precision of the results of the regression calculation introduced above, thus we can conclude that there is a weak but negative relation between wind power production and electricity prices.

7 Empirical Analysis

7.1 Grid management model

In this empirical research, a cost minimization problem was considered in order to introduce how the increasing wind penetration level would have an effect on the cost of electricity generation in the Western Denmark region. Using the results of this optimization problem we will show how the cost of CO2 emission reduction would have changed, taking into consideration different optimal wind power penetration scenarios. To be able to do that we applied van Kooten's (2009) grid management model in the Danish circumstances (1).

The focus of the grid management model is to minimize the yearly total cost of generating electricity from different energy source used power plants, while the electricity demand is met by the supply in every hour. The grid management model takes into consideration the variable costs of power supply (operation and maintenance and fuel costs) and optimizes the output from the different fuel based power plants to minimize the total cost:

$$Minimize_{Q_{t,i}} TC = Minimize_{Q_{t,i}} \sum_{t=1}^{24\times d} \left[\sum_{\mathrm{i}} (\mathrm{OM_i} + \mathrm{b_i})\, \mathrm{Q_{ti}} \right] \quad (1)$$

Where, TC is the total cost (in DKK); *i* are the respective generating source (coal, CCNG, oil, biomass and wind); *d* is the total number of days (365); *t* is the number of hours (8760); OM_i is the operation and maintenance costs (in DKK/MWh); b_i is the fuel cost (in DKK/MWh); Q_{ti} is amount of electricity produced by the generator *i* in the hour *t*. The cost functions (O&M costs and fuel costs) used here, are mentioned below. The model is subject to constraints:

a. Demand constraint:

$$\sum_i Q_{t,i} \geq D_t, \;\; \forall t = 1, \dots, 24Xd \quad (2)$$

b. Ramping-up constraint:

$$Q_{t,i} - Q_{(t-1),i} \leq \frac{C_i}{T_i}, \;\; \forall i \quad (3)$$

c. Ramping –down constraint:

$$Q_{t,i} - Q_{(t-1),i} \geq -\frac{C_i}{T_i}, \;\; \forall i \quad (4)$$

d. Capacity constraint:

$$Q_{t,i} \leq C_i \quad \forall i \tag{5}$$

e. Non-negativity factor:

$$Q_{t,i} \geq 0 \quad \forall i \tag{6}$$

Where, D_t is the electricity demand in hour *t*, which has to be met by the electricity supply, C_i is the capacity of the generating source *i*; T_i= time required to ramp up production from generating source *i*. The ramping up constraint represents the time required by the generating source to adjust its production.[5]

This model was solved for a year time scale (8760 hours) taking into consideration three different scenarios with three different wind power penetration levels (35%, 50%, 75%) in the system, where the wind power penetration denotes the share of the installed wind capacity from the total installed capacity.

7.2 Source of data

The year 2010 was considered as a baseline scenario thus the hourly based electricity demand and wind power production data in the Western Denmark region (including Jutland peninsula and Fyn Island) from this year was included in our simulation. Since the installed wind capacity from the total installed capacity was around 35% in 2010, in the "optimized" *35% wind penetration* scenario the hourly wind power production values remain the same, while in the *50% wind penetration* and 75% *wind penetration* scenarios the hourly wind production figures were increased by 43 and 114%, respectively, assuming unchanged wind capacity factor. On the other hand the electricity demand remained the same in every scenario. Table 3 introduces the installed capacity of the existing generators and their net generations in the year 2010 as baseline scenario.[6] The estimated wind power capacities in the different scenarios are shown in Table 4,[7] while the capacity of the fossil fuel and biomass based power plants were assumed to remain at the same level in every scenario.

5 One hour ramping up time was assumed for the natural gas and oil fired power plants as well as in the case of wind power, while in the case of biomass and coal based power plants this period last for three hours (Kooten, 2009).
6 Data was provided by the Danish TSO (energinet.dk).
7 The installation cost for wind turbine is expected to be 16,75 million Danish kroner/ MW (Source: Teknologikatalog Juni 2010 (ens.dk); Planning of national power systems).

Table 3 Generating sources with their installed capacity and net generation

Main energy source	Installed capacity (MW)	Net generation (GWh)
Wind turbines	2,839.5	5,874
Biomass	198.4	1,448
Natural gas (CCNG)	1,679.2	5,011
Oil	292.2	135
Coal	2,825.5	11,311
Total	**7834,7**	**23778**

Source: energinet.dk

Table 4 Wind capacity in the different scenarios

	Baseline	35% wind penetration	50% wind penetration	75% wind penetration
Wind capacity (MW)	2,839.5	2,839.5	4033.9	6050.85

Furthermore, beside the capacity feature of the different fuel based power plants their CO_2 emission factor and operation and maintenance and fuel costs have to be considered when the cost of the electricity supply is minimized (Table 5. and 6.). Due to the fact that the *50% wind penetration* and *75% wind penetration* scenarios describe future cases of the Danish power system, where the share of the installed wind power capacity from the total installed capacity are 50% and 75%, respectively, and the wind power production in 2020 is expected to be 50% while in 2050 more than 70% (The Danish Government, 2011), calculated future fuel prices for the year 2020 and 2050 were applied in our simulation. Thus fuel prices from the year 2010 were used to calculate the total cost of electricity supply for the baseline and "optimized" *35% wind penetration* scenarios, while the fuel prices from 2020 and 2050 were applied in the *50% wind penetration* and *75 wind penetration* scenarios, respectively (Table 6). Constant CO_2 emission factors and operation and maintenance costs were assumed in all scenarios.

Table 5 The emission factor and O&M costs associated with the generating sources

Main energy source	CO_2 Emission (ton CO_2/MWh) avg.[8]	Total O&M cost (DKK/MWh)[9]
Wind turbines	0.019	115.43
Biomass	0.067	234.58
Natural gas	0.61	31.28
Oil	0.85	204.80
Coal	1.1	52.13

Table 6 Fuel prices in the different scenarios (in DKK/MWh)

Main energy source	Baseline	35% wind penetration	50% wind penetration	75% wind penetration
Natural gas	209.38	209.38	238.27	335.74
coal	54.15	54.15	75.81	86.64
oil	317.69	317.69	436.82	610
Biomass	361	361	361	361
wind	0	0	0	0

Source: Danish Comission on Climate Change Policy (2010)

7.3 Modeling results

The purpose of this simulation is to introduce how the Western Denmark region's electricity demand from 2010 would have been supplied in variant wind penetration scenarios by the different energy sources. Furthermore, the forecasted price of decreasing the CO_2 emission and the expected increasing price of electricity production by increasing the wind power penetration will be estimated based on the model results.

7.3.1 Output results

In Table 7 the electricity production and CO_2 emission by generating source are shown. From these results two main observations can be found; from one hand comparing the baseline case to the optimized 35% wind penetration case we can see a more than 16% decrease in the total electricity output and a more than 4% increase in emission. The difference between the two output results mostly occurs due to the efficiency of the prediction of the wind power production; since in the baseline scenario overproduction arises from backup systems, while in the "optimized" 35% wind penetration scenario the prediction effectiveness was around 100%, since

8 Weisser (2007).
9 Teknologikatalog Juni 2010 (ens.dk).

the excess electricity production generated by conventional power plants could occur owing to their ramping-up and ramping-down features. On the other hand, there is no information about the quantity of the electricity generated directly to export in the baseline scenario, while in the optimized 35% wind penetration scenario, a closed power system was assumed without any interconnection to other bidding areas, thus the directly exported electricity could also contribute to a higher difference between the two output data.

Table 7 Electricity output and CO2 emission by generating source for different wind penetration levels

Baseline	**Output (GWh)**	**Emission (Mt CO2)**
Natural gas	5172	3.15
Coal	11102	12.21
Oil	486	0.41
Biomass	2811	0.19
Wind	5875	0.11
Total	**25448**	**16.08**
35% Wind penetration	**Output (GWh)**	**Emission (Mt CO2)**
Natural gas	146	0.09
Coal	15108	16.62
Oil	0	0.00
Biomass	0	0.00
Wind	5875	0.11
Total	**21129**	**16.82**
50% Wind penetration	**Output (GWh)**	**Emission (Mt CO2)**
Natural gas	118	0.07
Coal	12922	14.22
Oil	0	0.00
Biomass	0	0.00
Wind	8347	0.16
Total	**21388**	**14.45**
75% Wind penetration	**Output (GWh)**	**Emission (Mt CO2)**
Natural gas	92	0.06
Coal	10190	11.21
Oil	0	0.00
Biomass	0	0.00
Wind	12520	0.24
Total	**22803**	**11.50**

At the same time together with the decreasing electricity output the amount of the emitted CO_2 is increasing due to the raised share of electricity produced by coal fired power plants from the total production and the high emission factor of these plants.

The second main observation is that comparing the optimized scenarios to each other we can find that the increasing wind penetration results in increasing total electricity output and in decreasing CO_2 emission. The total electricity output rises in direct ratio to the wind penetration due to the excess wind production and since the excess electricity cannot be stored it has to be exported. The CO_2 emission changes in inverse ratio to the wind penetration owing to the small emission factor of the wind power. Table 8 introduces the changes in output comparing the figures of the 50% and 75% wind penetration scenarios to the 35% wind penetration scenario by generating sources. Table 9 shows the same comparison focusing on the CO_2 emission results of the different scenarios.

Table 8 Changes in output compare to the 35% wind penetration scenario by generating source

Main energy source	50% wind penetration	75% wind penetration
Natural gas	81%	63%
Coal	85%	67%
Oil	0%	0%
Biomass	0%	0%
Wind	142%	213%
Total	**101%**	**108%**

Table 9 Changes in CO_2 emission compare to the 35% wind penetration scenario by generating source

Main energy source	50% wind penetration	75% wind penetration
Natural gas	81%	63%
Coal	85%	67%
Oil	0%	0%
Biomass	0%	0%
Wind	142%	213%
Total	**86%**	**68%**

7.3.2 Cost results

In this section the costs of the previously introduced changes in the electricity output and emission are shown, assuming that the capacities of the different generating sources are unchanged except for that of wind power. The installation cost of the newly established wind capacity is considered for a one year period. Calculating the annuity for one megawatt wind capacity a 4,1% interest rate, 20 years lifetime and 16 million Danish kroner per megawatt capacity were assumed.

Table 10 Electricity generated, costs and emissions by different wind penetration levels

Scenario	Non-wind electricity generated (GWh)	Non-wind cost (DKK mil)	Additional Wind Capacity (MW)	Wind installation cost (DKK mil)	Total cost (DKK mil)	Electricity cost (DKK/MWh)	Emission (Mt CO2)
Baseline	19572	4353	0	0	5031	197.7	16.0
35%	15254	1640	0	0	2319	109.7	16.8
50%	13040	1685	1194	1486	4135	193.3	14.4
75%	10283	1448	3211	3996	6890	302.1	11.5

As it was settled above the higher the wind penetration the lesser the CO2 emission of the electricity supply in Western Denmark region would be. Although the amount of electricity generated by non-wind power plants are decreasing, the non-wind related costs are getting higher due to the increasing fuel prices, when the wind penetration goes 35% to 50%, but would become lower again when the wind penetration is increased to 75% (due to highly decreasing share of electricity generated by non-wind power).

At the same time, owing to the expensive installation cost of wind power the total cost would increase by 1.8 to 3 times taking into consideration the 50% and 75% wind penetration scenarios, respectively. Considering the predicted 2050 year fuel prices the total cost of electricity supply in Western Denmark region would be 37% higher compared to the baseline scenario in which case the 2010 year fuel prices and the actual (2010) electricity supply were taken into account.

The cost of reducing CO2 by one ton during the electricity production is increasing owing to the growing cost of electricity supply and the decreasing CO2 emission (Table 11). The marginal cost of one megawatt hour electricity increases by 76 to 175 percent in the 50%, 75% wind penetration scenarios compared to the 35% wind penetration scenario. The cost of reducing the emitted CO2 by one ton would increase to more than 765 Danish kroner depending on the share of wind power penetration.

Table 11 Cost of reducing CO_2 emission

Reducing emission per tCO2 (in DKK)		Increase in per MWh costs (in %)	
50%	75%	50%	75%
765	860	76.16%	175.29%

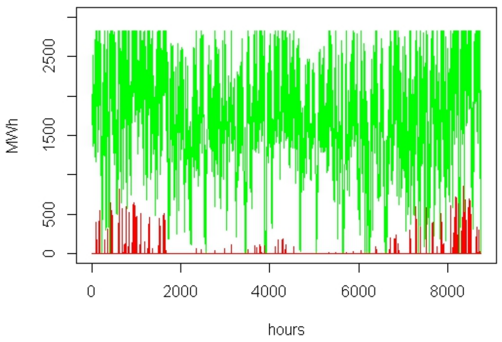

Figure 13 Hourly adjustment by based load coal (green line) and natural gas (red line) for 35% wind penetration

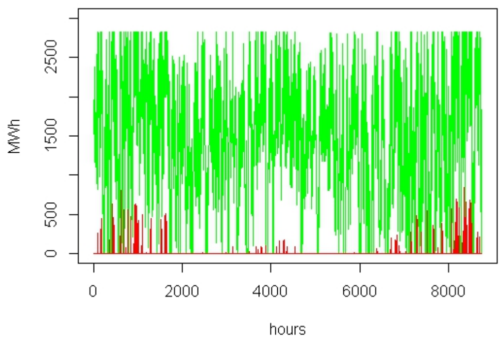

Figure 14 Hourly adjustment by based load coal (green line) and natural gas (red line) for 50% wind penetration

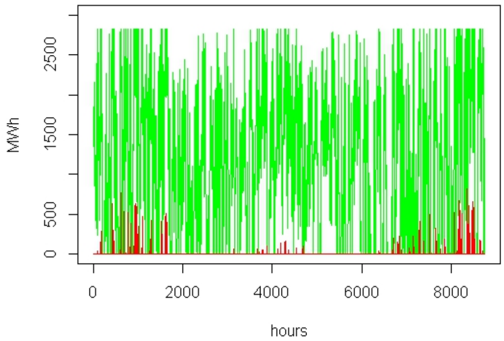

Figure 12 Hourly adjustment by based load coal (green line) and natural gas (red line) for 75% wind penetration

The hourly adjustment by coal and natural gas generating sources for different wind penetration scenarios are depicted in Figures 12-14. As it was mentioned previously the main backup generating source is coal while natural gas is used when more adjustment is needed than the capacity of the coal fired power plants or when the coal power plant cannot ramp up as quickly as electricity is needed. From the figure above it can also be found that the higher the wind penetration is the higher the fluctuation of the backup systems will be.

7.3.3 Discussion

Concluding the results of the simulation by adapting van Kooten's (2009) grid management model in the Western Denmark region we find that economically the most optimal solution is to run coal and natural gas fired power plants as backup systems in a power system with high wind penetration. Although a more diverse power production would result in less CO_2 emitting electricity supply, thus there is a trade-off between the cost efficient power production and the electricity supply when the CO_2 emission is minimized. It was also found that the increasing wind penetration would decrease the CO_2 emission but at the same time the production would be less efficient due to the higher amount of excess electricity supplied by wind power.

Focusing on the cost results we can conclude that owing to the high operation and maintenance and the high installation costs of wind power and to the increasing fuel prices the cost of the electricity supply would grow in direct ratio to the increasing wind penetration level. These higher fuel prices would result in an increasing cost of reducing CO_2 emission.

Conclusion

Through various policies and energy plan Denmark has shown a shift towards a more diverse energy supply, since 1976 with the replacement of oil imports, leading to higher imports of coal and gas. However, with advent of time the approach bent more towards environmentally desirable energy supply with a long-term declaration of fossil fuel independency, triggering an increase in natural gas consumption and a significant growth in wind energy sector, resulting in reduction of coal consumption. This study examined the economic impacts of increasing integration of large-scale wind power to the existing Danish electrical grid. Our survey of literature and data analysis shows the significant changes in the wind energy capacities and production through 10 years (2000-2010).

Triggered by the change in policies and government support, the wind production in Denmark increased rapidly with increase in capacity, resulting in a high share of wind in the electricity production. It is evident from the residual load duration curve that with higher penetration of wind into the grid lowers the need for base load, which is covered by the conventional power plants. However, it can be seen in standard deviation calculation that with an increase in the wind capacity there is higher fluctuation in the wind energy output. Through the regression calculations for price determinacy, it can be noticed that there is a negative and weak correlation between wind power production and electricity prices, therefore, with an increase in wind penetration the price of electricity decreases.

The effects of the increasing wind penetration level on the electricity output, on the CO_2 emission and on the cost of electricity production were simulated applying van Kooten's (2009) grid management model for the Western Denmark Region. The results show that when the total cost of electricity production is minimized, only the coal and natural gas fired power plants would generate base load owing to its low O&M and fuel costs. Furthermore, the increasing marginal cost of reducing CO_2 emission occurs due to the increasing marginal cost of electricity production and the decreasing level of CO2 emission.

Finally, we can conclude that the increasing level of wind penetration in Western Denmark results in lower needs for base load as it was shown by the RLDC and also by the cost minimization calculations. On the other hand due to the high installation cost of wind energy the electricity production costs would increase significantly.

References

Albadi, M.H., E. E.-S. (2010) Overview of wind power intermittency impacts of power systems. *Electric Power Systems Research 80* , 627-632.

Asmus, P. (2003) How California Hopes to Manage the Intermittency of Wind Power. *The Electricity Journal* , 48-53.

Brendan Fox, D. F.-L. (2007) Wind Power Integration- Connection and system operational aspects. *IET Power and Energy Series 50* , 1-269.

C.K. Woo, I. H. (2011) The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. *Energy Policy 39* , 3939-3944.

Danish Commission on Climate Change Policy (2010) Grøn Energi, *Danish Commission on Climate Change Policy*

Danish Energy Agency (2011) *Energy in Denmark.* Copenhagen: Danish energy agency.

Danish Energy agency (2010) *Technology Data for Energy Plants.* Copenhagen: Danish Energy Agency.

Energinet.dk (2000) Retrieved September 01, 2011, from Energinet.dk: http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

Energinet.dk (2005) Retrieved September 01, 2011, from Energinet.dk: http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

Energinet.dk (2010) Retrieved September 01, 2011, from Energinet.dk: http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx

Energi Styrelsen (2010) *Denmark's Oil and Gas Production - and Subsoil Use.* Copenhagen: Energi Styrelsen.

Energi Styrelsen (2011) Retrieved december 21 , 2011, from Energi Styrelsen : http://www.ens.dk/da-DK/Info/TalOgKort/Statistik_og_noegletal/Energipriser_og_afgifter/Oliepriser/Sider/Forside.aspx

Frans Van Hulle, N. F.-F. (2010) *Powering Europe: wind energy and the electricity grid.* Brussels: European Wind Energy Association.

Fred Espen Benth, R. K. (2012) Acritical empirical study of three electricity spot price models. *Energy Economics* .

Ger Klaassen, A. M. (2005) The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. *Ecological Economics 54 (2005)* , 227 – 240.

Goran S., A. S. (2007) Impact of wind generation on the operation and development of the UK electricity systems. *Electric Power Systems Research.* , 1214-1227.

Henderson, C. (2007) *Fossil Fuel-Fired Power Generation.* Paris: International Energy Agency.

Hermann-Josef Wagner, J. M. (2009) *Introduction to Wind Energy Systems- Basics,Technology and Operation.* Heidelberg: Springer.

Houmøller, A. P. (2004) Retrieved September 2011, 10, from Nord Pool Spot: http://www.nordpoolspot.com/Global/Download%20Center/Rules-and-regulations/The-Nordic-Electricity-Exchange-and-the-Nordic-model-for-a-liberalized-electricity-market.pdf

International Energy Agency (2001) *Energy Prices and Taxes.* International energy Agency.

International Energy Agency (2006) *Energy Prices and Taxes, Volume 2006 Issue 1.* International Energy Agency.

International Energy Agency (2011) *Energy Prices and Taxes, Volume 2011 Issue 1.* International energy Agency.

Jesse D. Maddaloni, A. M. (2008) Network constrained wind integration on Vancouver Island. *Energy Policy 36* , 591–602.

Joos, D. G. (2005) *Wind Energy Delivery and Reliability.* Toronto: Canadian Wind Energy Association.

Joseph F. DeCarolis, D. W. (2004) The Costs of Wind's Variability: Is There a Threshold? *The Electricity Journal* , 69-77.

Kennedy, S. (2005) Wind power planning: assessing long-term costs and benefits. *Energy Policy 33* , 1661–1675.

Kooten, G. C. (2009) Wind Power: the economic impact of intermittency. *Lett Spat Resource Science 3, 1-17*

Kris R. Voorspools, W. D. (2006) An analytical formula for the capacity credit of wind power. *Renewable Energy 31* , 45–54.

Lightfoot, H. D. (2006) A Strategy for Adequate Future World Energy Supply & Carbon Emission Control. *IEEE* , 1-10.

Lund, H. (2006) Large-scale integration of optimal combinations of PV, wind and wave power into the electricity supply. *Renewable Energy 31* , 503-515.

Lund H., B. M. (May 2008) Energy system analysis of 100% renewable energy systems- The case of Denmark in years 2030 and 2050. *Energy* , 524-531.

Mathew, S. (2006) *Wind Energy- Fundamentals, Resource Analysis and Economics.* Malapuram: Springer.

Meyer, N. I. (March 2004) Renewable energy policy in Denmark. *Energy for Sustainable Development, Volume VIII No.1* , 25-34.

Monique Hoogwijk, D. v. (2007) Exploring the impact on cost and electricity production of high penetration levels of intermittent electricity in OECD Europe and the USA, results for wind energy. *Energy 32* , 1381-1402.

Paul Twomey, K. N. (2010) Wind power and market power in competitive markets. *Energy Policy* , 3198-3210.

Pedro S. Moura, A. T. (2010) The role of demand-side management in the grid integration of wind power. *Applied Energy 87* , 2581-2588.

Poul Erik Grohnheit, F. M. (2011) Area price and demand response in a market with 25% wind power. *Energy Policy, Volume 39, Issue 12* , 8051–8061.

Rácz, V. J. (2012) *An Economic Analysis of Compressed Air Energy Storage System: A Danish Case Study.* M.Sc diss. Syddansk Universitet.

Robert Gross, P. H. (2006) *The Costs and Impacts of Intermittency.* London: UK Energy Research Centre's Technology and Policy Assessment.

Robert Gross, P. H. (2008) The costs and impacts of intermittency: An ongoing debate "East is East, and West is West, and never the twain shall meet.". *Energy Policy 36* , 4005– 4007.

Søren Krohn, P.-E. M. (2009) *The Economics of Wind Energy.* Brussels: European Wind Energy Association.

Weisser, D. (2007) A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies, *Energy*, Volume 32, Issue 9, PP. 1543-1559

Appendix

APPENDIX I

Table 12 Primary capacity in the given years (2000, 2005, and 2010)

	Primary Capacity (MW)		
	Initial Value	Change between the years	Change in capacity through the years (compared to 2000)
2000	4220.7	-531	
2005	3689.7	-52.1	- 12,6%
2010	3637.6		-13,8%

Table 13 Local capacity in the given years (2000, 2005, and 2010)

	Local Capacity (MW)		
	Initial Value	Changes between the years	Change in capacity through the years (compared to 2000)
2000	1438.8	89.8	
2005	1545.6	213.3	7,4%
2010	1834.5		27,5%

Table 14 Wind capacity in the given years (2000, 2005, and 2010)

	Wind Capacity (MW)		
	Initial Value	Changes between the years	Change in capacity through the years (compared to 2000)
2000	1121.1	635.0	
2005	2236.7	383.4	99,5%
2010	2642.3		135,7%

Appendix II

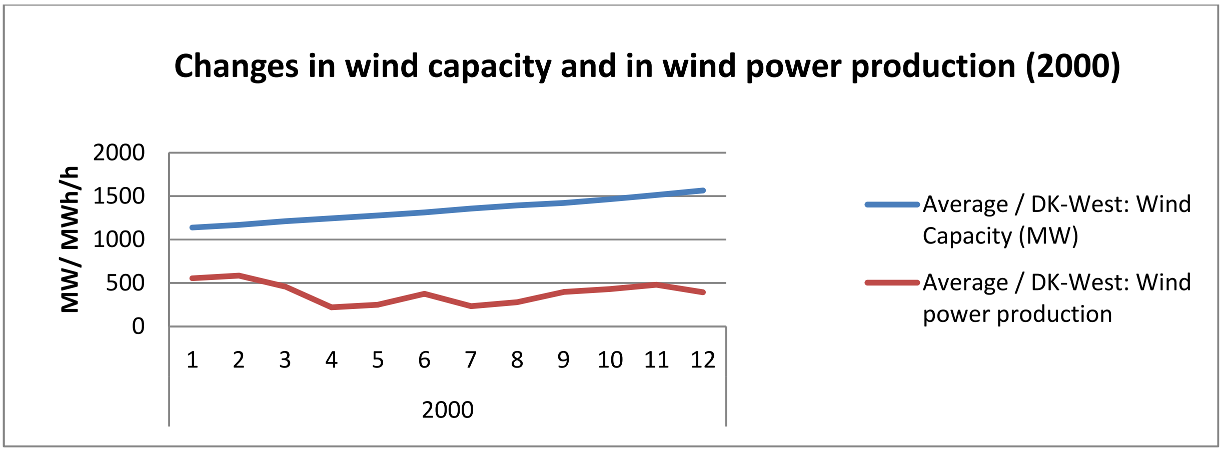

Figure 15 Changes in wind capacity and WPP (2000)

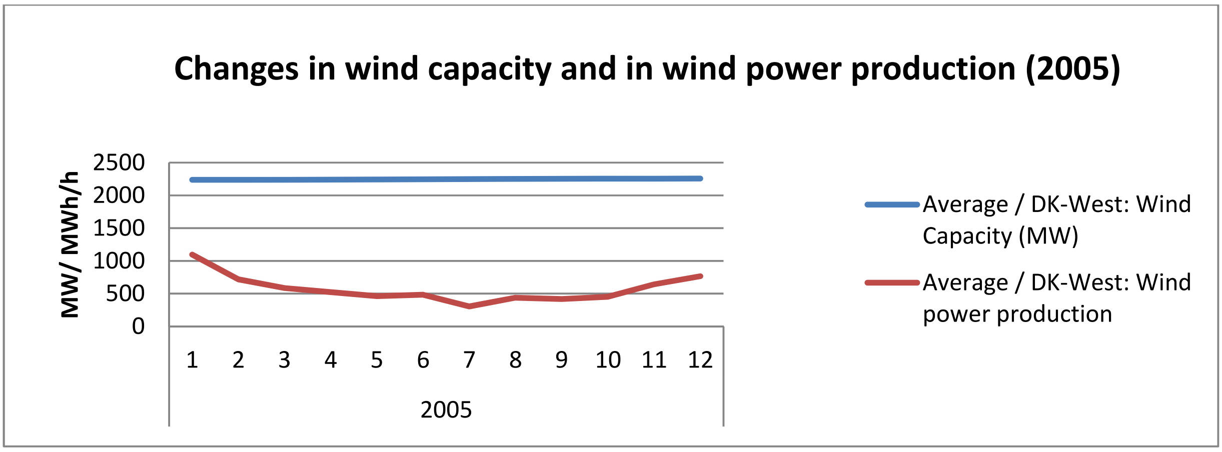

Figure 16 Changes in wind capacity and WPP (2005)

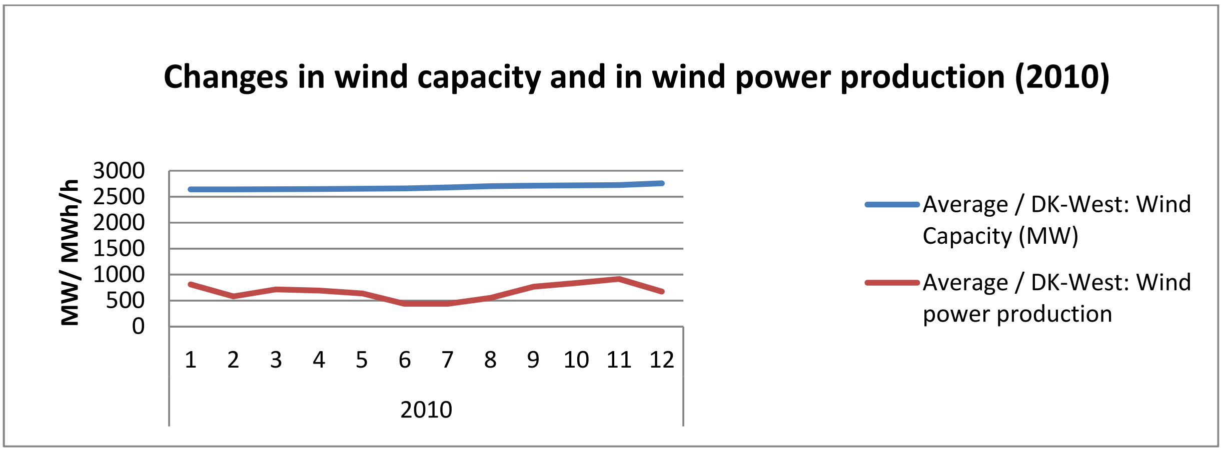

Figure 17 Changes in wind capacity and WPP (2010)

Appendix III

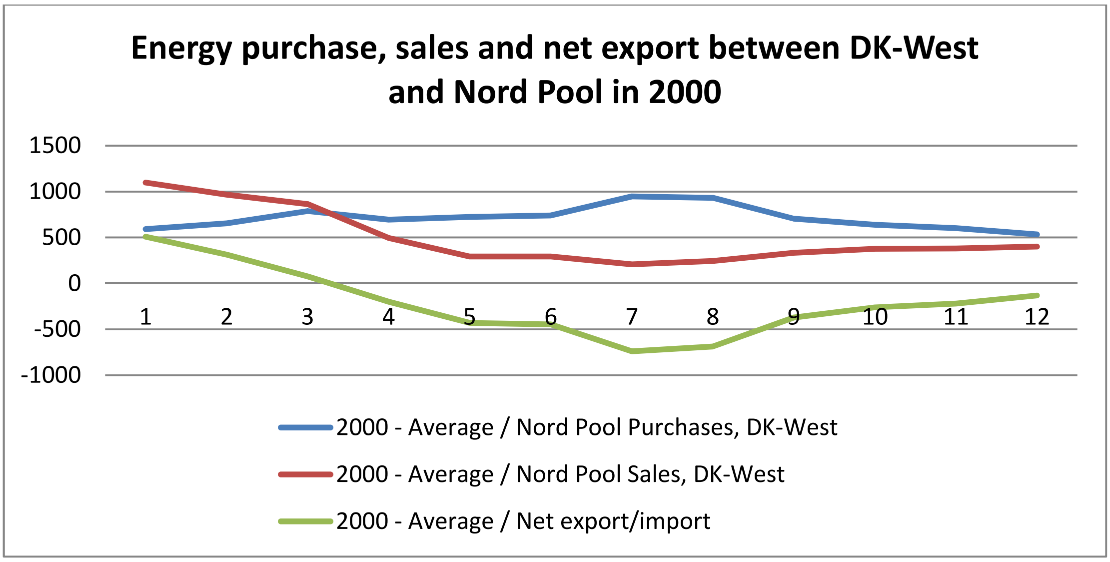

Figure 18 Energy purchase, sales and net export between DK-West and Nord Pool in 2000

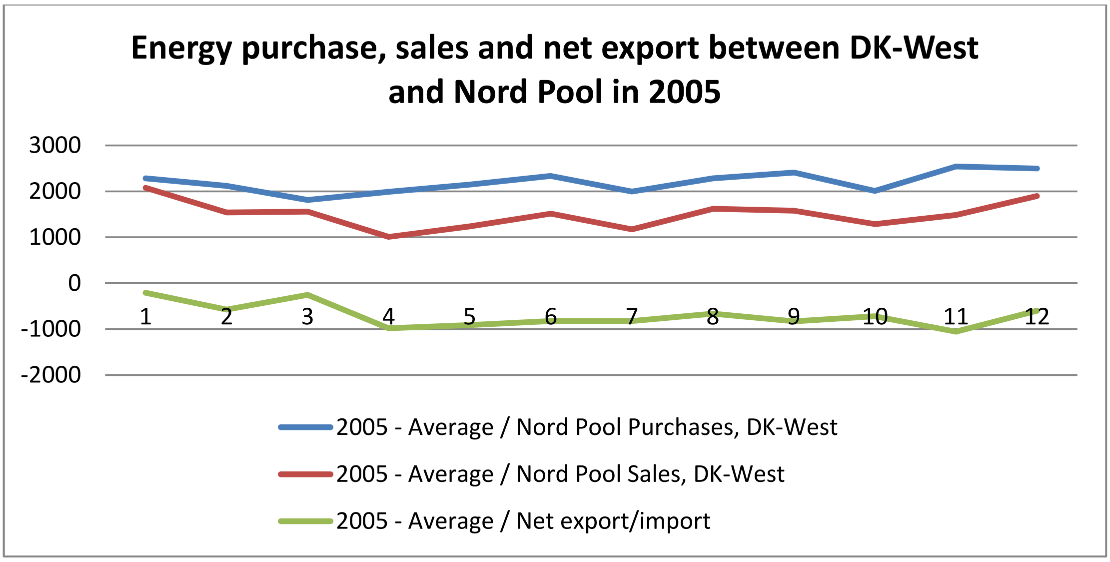

Figure 19 Energy purchase, sales and net export between DK-West and Nord Pool in 2005

You may find the figure for the year 2010 about the energy purchase, sales and net export between DK-West and the other bidding area in Nord Pool market in the text, on the page 16 (Figure 8).

Appendix IV

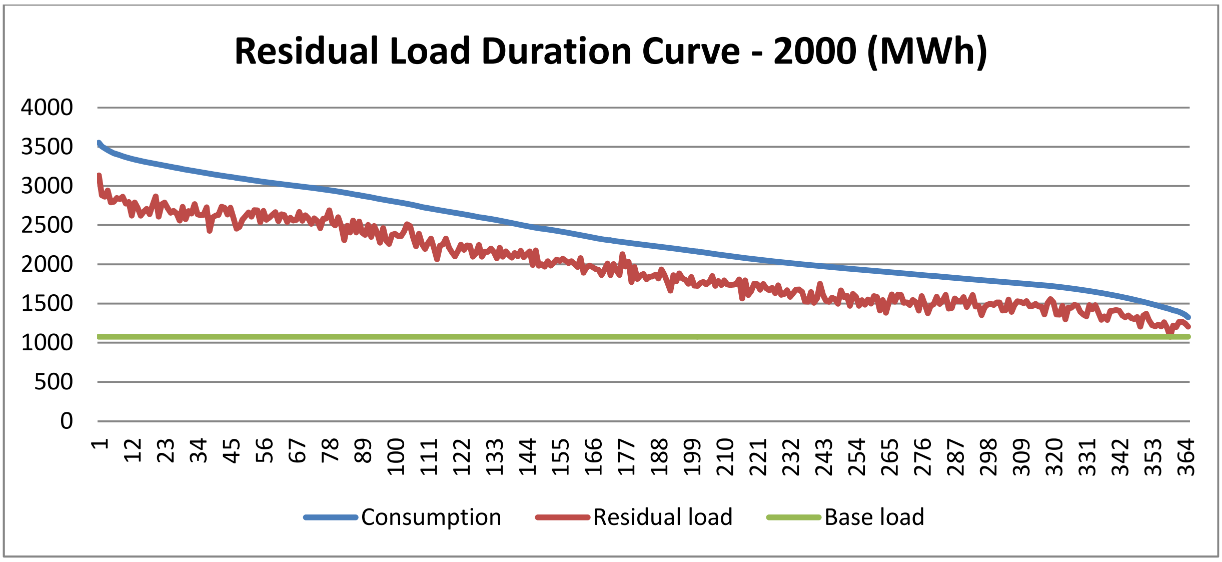

Figure 20 Residual Load Duration Curve for the year 2000

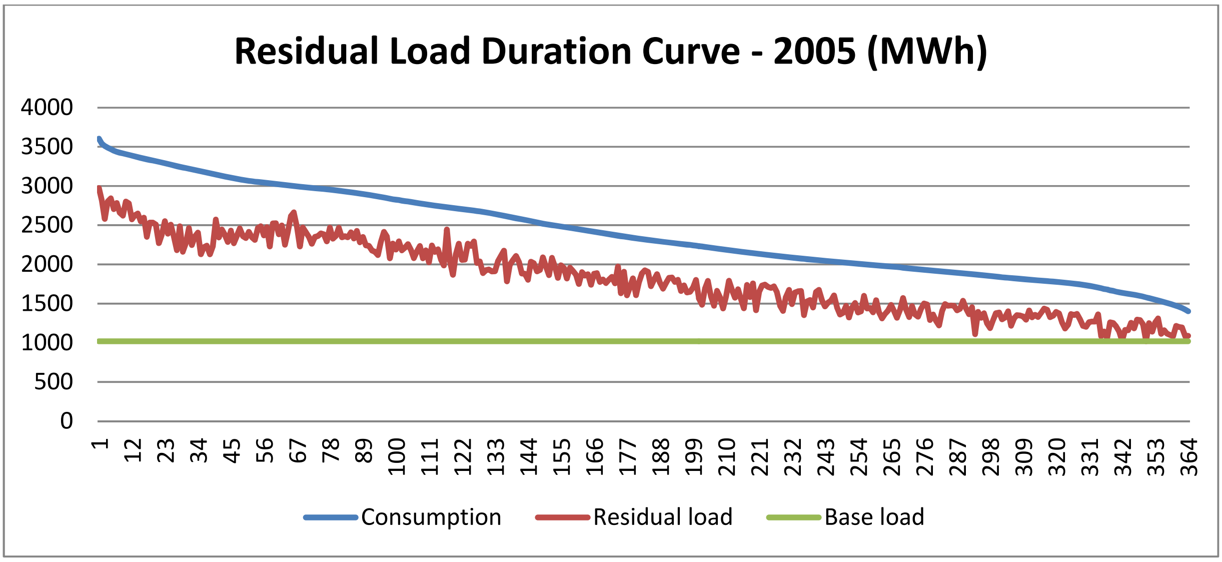

Figure 21 Residual Load Duration Curve for the year 2005

You may find the figure for the year 2010 about the Residual load duration curve in the text, on the page 17 (Figure 9).

Appendix V

Table 15 The influence of the Pff and Demand on the electricity price

FF components	Coeff.	R-squared	Root MSE	t	[95% Conf. Interval]	
Price of coal	-2.193176	0.6188	86.564	-19.21	-2.416995	-1.969356
Price of oil	.7148102			34.49	.6741927	.7554276
Price of natural gas	1.956644			25.12	1.803952	2.109337
Demand	.0960871			98.59	.0941768	.0979974
Constant	-325.4255			-23.32	-352.772	-298.079

Department of Environmental and Business Economics
Institut for Miljø- og Erhvervsøkonomi (IME)

IME REPORTS

ISSN: 1399-3232

Issued reports from IME
Udgivne rapporter fra IME
No.

1/99	Niels Kold Olesen Eva Roth	*Det danske dambrugserhverv – en strukturanalyse*
2/00	Pernille Eskerod (red.)	*Projektstyring og -ledelse - de bedste cand.merc. bidrag fra 1998-99*
3/00	Hanne W. Tanvig Chris Kjeldsen	*Aktuel forskning om danske landdistrikter*
4/00	Birgit Nahrstedt Finn Olesen	*EU, ØMU'en og den europæiske beskæftigelse*
5/02	Frank Jensen Henning Peter Jørgensen Eva Roth (koordinator)	*En diskussion af hvorledes fiskerireguleringer påvirker biodiversitet, økonomi og social tilpasning*
6/02	Helge Tetzschner Henrik Herlau	*Turismeudvikling ved innovation og entreprenurskab. Et potentiale for lokal erhvervsudvikling*
7/04	Bodil Stilling Blichfeldt	*Why do some Tourists choose to spend their Vacation Close to home*
8/06	Bodil Stilling Blichfeldt	*A Nice Vacation*
9/07	Helge Tetzschner	*Eksplorativ analyse af virksomheders bløde aktiver – metoder og værktøjer*
10/07	Svend Ole Madsen	*Analyse af den danske offshoresektor – Virksomhedsudvikling og klyngeperspektiver*
11/07	Lone Grønbæk Kronbak (Redaktør) Niels Vestergaard m.fl.	*IMPSEL - Implementering af mere selektive og skånsomme fiskerier. Konsekvenser for ressource, fiskere og samfund*
12/07	Lars Ravn-Jonsen Niels Vestergaard et al.	*Comparative Evaluation of the Fisheries Policies in Denmark, Iceland and Norway: Multispecies and Stochastic issues*
13/12	Malene Damsted Hans Stubbe Solgaard	*Dialogbaseret Miljøsamarbejde*
14/13	Viktor J. Rácz Priyadarshini Yadav Niels Vestergaard	*Integration of Wind Power into the Danish Power System*