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Large scale introduction of wind power in an electricity production system

Estimated effects on the carbon dioxide emissions

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Abstract

Large scale introduction of wind power in an electricity production system - Estimated effects on the carbon dioxide emissions

Kajsa Ehrengren

This thesis considers the effect of a large scale wind power introduction into an electricity system and the focus has been on the carbon dioxide emissions. Two different systems were studied, the Swedish and the Danish electricity system. When studying the Swedish electricity system different scenarios were created to see what might happen with the CO2 emissions with an introduction of a large amount of wind power. The model that was used is based on parameters such as regulating power, transmission capacity, export possibility, and the electricity generation mixes in the Nordic countries. Given that the transmission capacity is good enough, the conclusion is that the carbon dioxide emissions will be reduced with a large scale introduction of wind power. In the Danish electricity system wind power is already introduced to a large extent. The main purpose here was to investigate the development of the CO2 emissions and if it is possible to decide the actual change in carbon dioxide emissions due to the large scale introduction of wind power. The conclusions to this part are that the CO2 emissions per kWh produced electricity have decreased since the electricity generation mix has changed but the total amount of CO2 emissions fluctuates depending on weather, in a dry year less hydro power from Norway and Sweden can be used and more electricity from the fossil fuelled CHPs are generated. It has not been possible to determine the influence of the wind power on the CO2 emissions.

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Uppsala, April 2010

Kajsa Ehrengren

Sammanfattning

Det svenska elproduktionssystemet består idag till största delen av vattenkraft och kärnkraft medan vindkraften endast står för drygt 1 % av elproduktionen. Energimyndigheten har lagt fram ett planeringsmål på 30 TWh årlig vindkraftsproduktion till år 2020. Detta motsvarar cirka 12 000 MW installerad vindkraftseffekt. I Danmark har utvecklingen av vindkraft kommit längre och cirka 20 % av deras elproduktion är vindkraftsbaserad. En annan skillnad mellan Danmark och Sverige är att Danmarks el till största delen produceras med hjälp av fossila bränslen. En ökad andel vindkraft i elproduktionssystemet gör att variationerna från elproduktionen kommer att variera i högre utsträckning än tidigare. Detta i sin tur resulterar i ökade krav på reglerkapaciteten för att kunna balansera variationerna. Beroende på var vindkraften lokaliseras kan även kraven på transmissionskapaciteten i elnätet komma att öka.

Huvudsyftet med denna rapport var att försöka ta reda på hur Sveriges elproduktionssystem skulle påverkas av en storskalig introduktion av vindkraft med fokus på hur detta skulle kunna komma att påverka koldioxidutsläppen från elproduktionen. Vidare har även det danska elproduktionssystemet studerats. Eftersom de redan har en stor andel vindkraft i systemet har målet här varit att försöka avgöra om det har blivit några faktiska förändringar tack vare införandet av vindkraft. Även här har fokus legat på hur koldioxidutsläppen har förändrats.

För att kunna analysera hur det svenska elproduktionssystemet skulle kunna komma att påverkas har en modell över systemet tagits fram. I modellen tas faktorer som reglerkraft, transmissionskapacitet, export och de nordiska ländernas elproduktionsmixer upp. Elproduktionssystemet är mycket komplext och det har inte varit möjligt att inom ramen för detta examensarbete utveckla en tillräckligt detaljerad modell. En hel del förenklingar har alltså varit nödvändiga att göra vilket gör att resultaten måste värderas därefter. Till exempel har det antagits att elanvändningen håller ett konstant värde och att elproduktionsmixen inte förändras på annat sätt än att vindkraften ersätter lika stor andel annan produktion. För att kunna jämföra olika utvecklingsmöjligheter har ett antal olika scenarier tagits fram.

Under arbetets gång har det visat sig i denna del av arbetet att det är oerhört svårt att modellera en rättvisande bild av ett framtida elproduktionssystem och framtida koldioxidutsläpp. En slutsats som kan dras är dock att under förutsättning att det finns tillräckligt mycket transmissionskapacitet att exportera den storskaliga vindkraftsproduktionen så kommer koldioxidutsläppen från den svenska elproduktionen att minska. Skulle det däremot uppstå en ”worst case”-situation där ingen vindkraftsproduktion kan exporteras och kärnkraft skulle bli ersatt av vindkraft så skulle utsläppen istället få en liten ökning. Detta är dock ett mycket osannolikt scenario då marknaden styr vilken el som kommer att produceras.

I studien av det danska elproduktionssystemet har statistik från den danska energimyndigheten använts. Här har dels utvecklingen av den totala elproduktionsmixen samt vindkraften studerats liksom utvecklingen av koldioxidutsläppen från elproduktionen. Vidare har även elverkningsgraden i de danska centrala värmekraftverken studerats eftersom denna påverkas negativt vid reglering av variationerna i vindkraftsproduktionen. I denna studie kan man tydligt se att den danska elproduktionsmixen har förändrats sedan 1994, från en mix där kol stod för drygt 80 % av elproduktionen (1994) till en mix där de förnyelsebara kraftslagen tillsammans med naturgas står för cirka 50 % av elproduktionen (2008). Koldioxidutsläppen per kWh elproduktion har tydligt minskat medan de totala koldioxidutsläppen från elkraftsproduktionen fluktuerar mer beroende på väderförhållanden. När det till exempel är torrår i Sverige och Norge så importeras mindre vattenkrafts-el från dessa länder och istället måste

Danmark öka sin fossilbaserade elproduktion vilket leder till att den totala mängden koldioxidutsläpp ökar. När det gäller el-verkningsgraden i de centrala värmekraftverken så stagnerade ökningen runt mitten av 90-talet, ungefär samtidigt som vindkraften introducerades i stor skala. Om detta beror på ökningen av vindkraften eller inte är dock svårt att säga med den information som har använts i detta arbete. Andra anledningar kan vara att det även infördes fler mindre kraftvärmeverk eller att förändringar i värmeproduktionen har gjorts.

Ämnet som har studerats i detta examensarbete är väldigt stort och många forskningsprojekt pågår inom området. Mycket mer forskning och mer noggranna modeller behöver utvecklas för att göra det möjligt att dra mer exakta slutsatser än de som varit möjliga att dra i detta arbete. Hur som helst indikerar resultaten från den här rapporten på minskade koldioxidutsläpp med en storskalig introduktion av vindkraft i elsystemet.

Index

1 Introduction

Wind power is a renewable energy source, the solar radiation creates a difference in pressure and temperature between different layers in the air which creates wind and no fuel is needed. [1] Energy from wind has been utilized by humans for thousands of years and windmills were already introduced in the thirteenth century. The wind power plant includes a rotor which is turned by the force of the wind and is connected to a generator. The generator transforms the rotation energy into electricity. Wind power plants normally generate electricity when the wind speed is between 4 and 25 m/s. [2]

Since the middle of the 1980s, wind power has developed very fast. (Figure 1) Different sizes of the plants have been tested but today the most common size for new plants in Sweden is 2 MW. In Europe there are already plants that can generate 6 MW and there are plans for plants generating between 10-20 MW. [2] The largest plant operational in Sweden is 108 meters high and has a rotor diameter of 100 meters. The capacity of this plant is 3 MW and it generates in average about 8 000 MWh of electricity every year. [3] With a more continuous energy source than wind power (not being limited by only generate electricity in the right wind spand), about three times as much electricity can be generated over time. This means a necessity of more regulating power when introducing wind power.

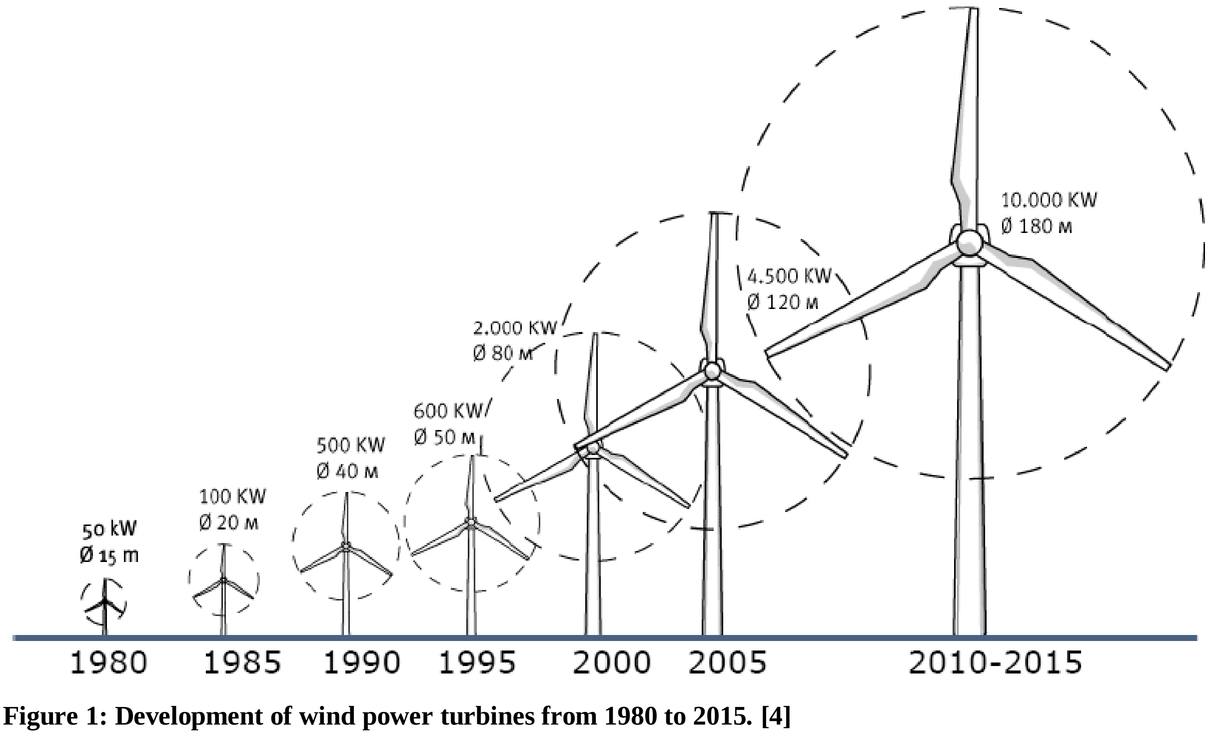

Figure 1: Development of wind power turbines from 1980 to 2015. [4]

Wind power production in Sweden was about 1.4 TWh in 2007 and about 2 TWh in 2008. [2] Sweden has a relatively small amount of wind power compared to countries such as Denmark and Germany. The annual wind power production in Denmark is about 7 TWh and in Germany about 38 TWh. However, in Sweden wind power is about to increase and there is a proposal from the Swedish Energy Agency to introduce 30 TWh into the Swedish electricity system until 2020. 10 TWh is planned to be offshore and 20 TWh onshore. [5]

1.1 Purpose

The main subject studied in this thesis is how the carbon dioxide (CO_2) emissions would be affected with a large scale introduction of wind power in the Swedish electricity system. Furthermore a smaller investigation of the Danish electricity system has been made to see if there are any indications on how the introduction of wind power has affected the system.

When looking at the Swedish electricity system, two parallel cases will be studied, one with 10 TWh and one with 30 TWh wind power production introduced into the system. A number of different scenarios have been created in order to analyze and to answer the following questions:

- How is the Swedish electricity system influenced by a large scale introduction of wind power?
  - What are the main problems?
- What happens to the CO_2 emissions when introducing 10 or 30 TWh wind power in the electricity system?
  - How much regulating power is needed and how much does the regulating power contribute to the CO_2 emissions?
  - What are the best and worst case scenarios?
  - How does the actual substitution of different energy sources affect the change of emissions?

As stated above, a smaller investigation of the Danish system has been made as well. The main focus has been to see if it is possible to find any trends in how the electricity generation mix has changed during the introduction of wind power. The questions asked are:

- How has the electricity generation mix changed since the introduction of wind power?
  - How has the CO_2 emissions been affected during this time?
  - What are the connections between wind power and CO_2 emissions?
- Has the operation and hence the electrical efficiencies in the coal fuelled combined heat and power plants (CHPs) been affected with more wind power in the electricity system?

2 Theory

Wind power differs from most other energy sources in the way that it is very difficult to predict the generation due to wind speed varying over time. The progress of research makes the forecasts more and more reliable, but still there is a challenge to encounter difficulties from fluctuating wind speeds. Introducing wind power affects the entire electricity system and to find out the change in CO_2 emissions many different areas need to be considered. The aim of this chapter is to give a picture of the electricity generation mix in the Nordic countries (chapter 2.1), explain how the electricity system and the electricity market are constructed (chapter 2.2) and describe the function of the reserves (chapter 2.3).

2.1 The electricity generation mix

In 2008, the Nordic[1] electricity production system consisted of more than 50 % hydro power, about 21 % nuclear power, about 13 % fossil fuels and about 10 % renewable sources. [6] (Figure 2)

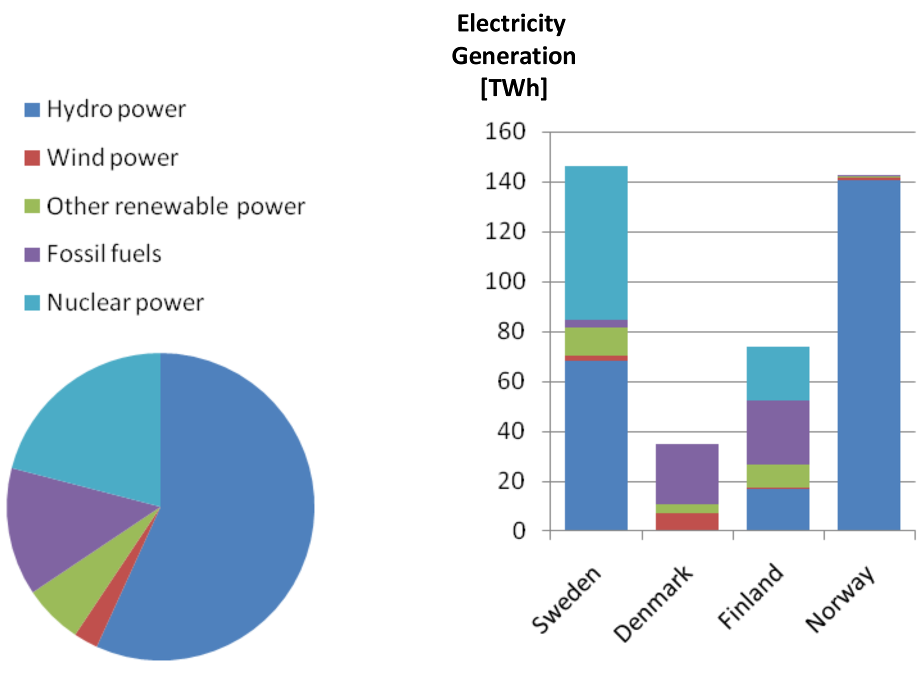

Figure 2: The electricity generation in the Nordic countries in 2008. [6]

As shown in Figure 2, the electricity generation in Sweden is dominated by nuclear power and hydro power. Denmark has mainly fossil fuels and renewable power (not including hydro power)[2]. The production in Finland is split into about one third nuclear power, one third fossil fuels and the last third is hydro power and other kinds of renewable power. The production in Norway is dominated by hydro power.

The electrical grids in the different countries are connected and Figure 3 shows the total amount of electricity exchanged across the borders in 2008.

[1] Nordic countries in this context mean Norway, Denmark, Sweden and Finland.
[2] Renewable power in this context consists of: wind power, biomass and waste.

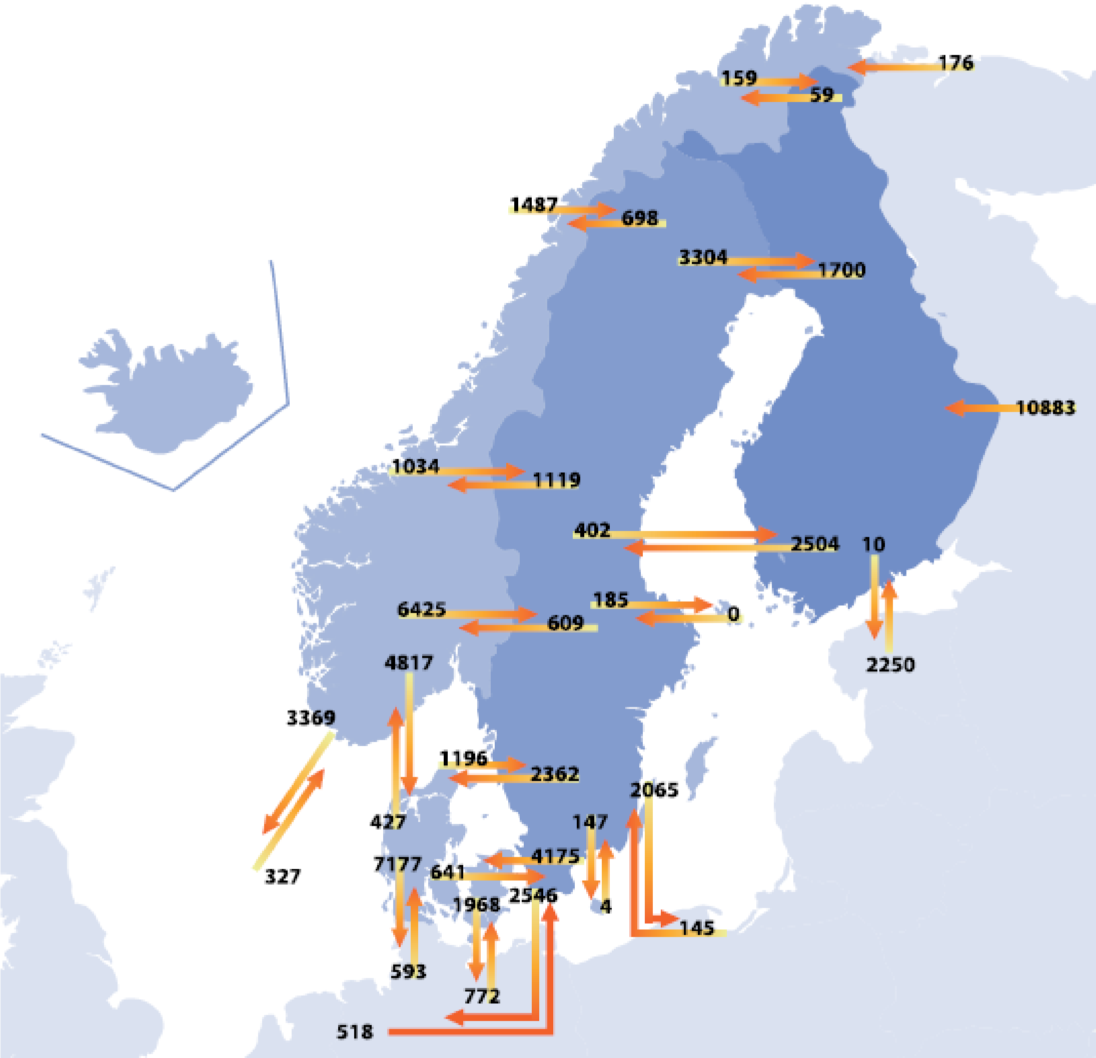

Figure 3: Electricity exchange to and from the Nordic countries in 2008, GWh. [6]

2.1.1 The Swedish electricity generation mix

In 2008 the total amount of supplied energy in Sweden was 613 TWh [7], the total electricity generation was 146.1 TWh and the net export of electricity was 2 TWh [6]. Between 1970 and 1987 the electricity consumption in Sweden was increasing almost 5 % every year. From 1987 until 2005 the annual increase has, in average, been about 0.3 %. The relatively high level of electricity consumption in Sweden is explained by heavy industry that uses a lot of electricity, a cold climate, electric heating and historically low electricity prices. Prognoses for future electricity consumption show that the demand will increase. It is believed that the increase will rise with about 0.3 % per year until 2025. The total electricity consumption is expected to rise to 152 TWh in 2015 and 157 TWh in 2025. [8]

In the beginning of the 1970s the main electricity generation sources were hydro power and oil condensing power. At the same time as Sweden expanded nuclear power in the 1970s, the oil crisis appeared [8] and today there is almost no oil condensing power in the system. Today the Swedish electricity production system consists of relatively few power plants with a very high capacity. It is large scale hydro power (mainly in the north) and three nuclear power plants at the west and east coast in the southern half of Sweden. They are complemented by a number of smaller hydro power plants in different parts of Sweden, combined heat and power plants (CHPs) that are producing both heat and electricity, a few condensing power plants and gas turbines that are used when the consumption is peaking. [1] The mix of 2008 can be seen in Figure 2 in chapter 2.1.

2.1.2 The Danish electricity generation mix

Until the middle of the 1980s, the electricity production in Denmark was dominated by coal and the remainder was essentially oil. In the beginning of the 1990s sources such as natural gas and renewable energy started to increase and consequently the mix changed. [9]

In 2008, the total electricity generation in Denmark was 34.6 TWh and this mainly consisted of fossil fuels where production from coal was 16.1 TWh, natural gas 7.0 TWh and oil 0.9 TWh. The rest of the production came from renewable power sources where wind power had 7.0 TWh which is about 20 % of the total electricity generation. The net import in Denmark was 1.5 TWh in 2008 [6], but this number is varying from year to year. The mix from 2008 is shown in Figure 2 in chapter 2.1.

2.2 Electrical grid and electricity market

The electricity market can be divided into three parts. (Figure 4) To be able to transfer electricity, an electricity system with infrastructure including transmission and distribution networks between producers and consumers is needed. The operation- and investment costs are covered by both producers and consumers in form of network fees. The electricity is then traded on a market. [10] In the following sections the concepts will be more thoroughly described.

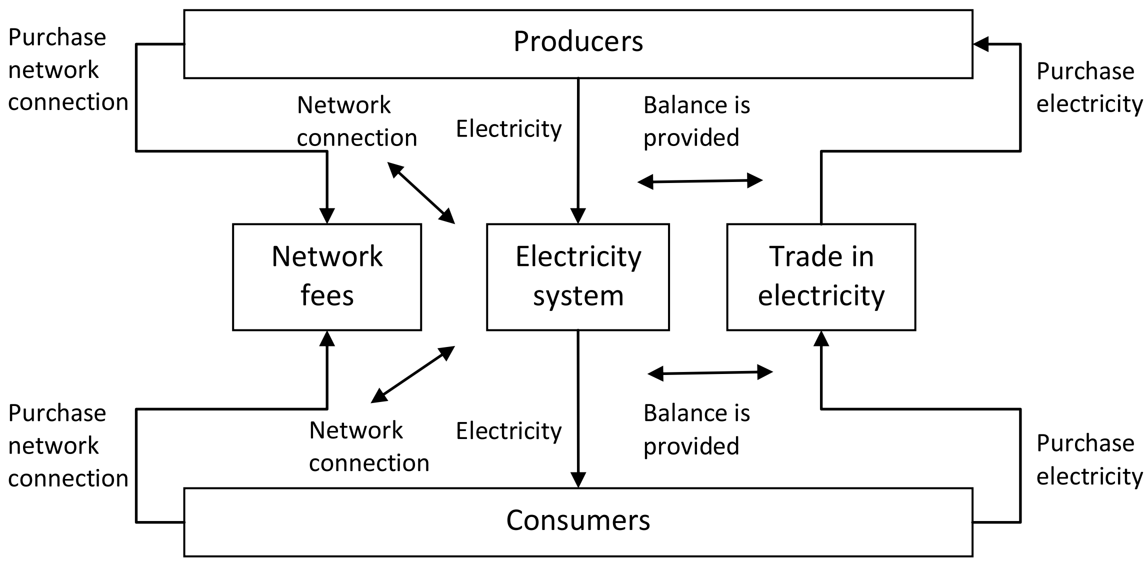

Figure 4: The physical flow of electricity and the relationships between the players on the electricity market. [10]

2.2.1 The electricity system

The electricity system in Sweden consists of the national electrical grid, regional networks and local networks. The frequency is a global quantity kept at 50 Hz everywhere in the grid while the voltage is kept at different levels in different parts of the system. [1]

The national grid in Sweden is owned by Svenska Kraftnät (SvK) and has voltages of 400 or 230 kV. It has been constructed in order to transmit large volumes of electricity over great distances. The voltage in the electricity system is then lowered step by step until it reaches the final consumers. The national power grid is connected to regional networks that have voltages of 130 or 70 kV. The regional networks are owned and managed by larger energy utility companies like Vattenfall, Eon and Fortum and are used for transmission of electricity from the national grid to local networks. The local networks have voltages of 10-40 kV and are used for distributing electricity to households, factories and other consumers. They are managed by local operators which most commonly are subsidiary companies to municipal energy companies. Before the electricity reaches the final customers the voltage is transformed to low voltages of 690 V (for industries) or 400 V (for households). [1]

To be able to produce as low cost electricity as possible it is important to minimize the transmission losses in an electricity system, the losses can be calculated from

$$P_{loss} = |I|^2 R \quad \text{and} \quad Q_{loss} = |I|^2 X \qquad (1)$$

where P_{loss} and Q_{loss} are the active and reactive losses, I is the current and R and X are the resistance and reactance. [11] From equation 1 it can be seen that the losses depend on the current. To minimize losses the current in the power lines must be minimized. This is done by transforming the voltage to a higher level which indirectly increases the current by using the formula

$$P = UI\cos\varphi \qquad (2)$$

where P is the power, U is the voltage, I is the current and $\cos\varphi$ is the power factor which is the cosine of the phase shift between the voltage and current. [11] It is impossible to avoid losses in form of heat but the amount depends on distance, voltage and load. Even if the losses are greater when the voltage is lowered it has the advantage of requiring cheaper equipment and electricity lines. Every year several TWh are lost in transmission and these are compensated for through purchase by Svenska Kraftnät. [1]

The national grids in Sweden, Norway, Finland and east Denmark (DK 2) are synchronically connected which means that the grids are connected via AC lines. West Denmark (DK 1) is connected to Sweden and Norway with high voltage direct current (HVDC) cables in the north. These networks together are called Interconnected Nordic Power System (INPS). The south of West Denmark is also synchronically connected to the continental European power system (UCTE). [12] In Figure 5 the power transmission network in northwestern Europe can be seen.

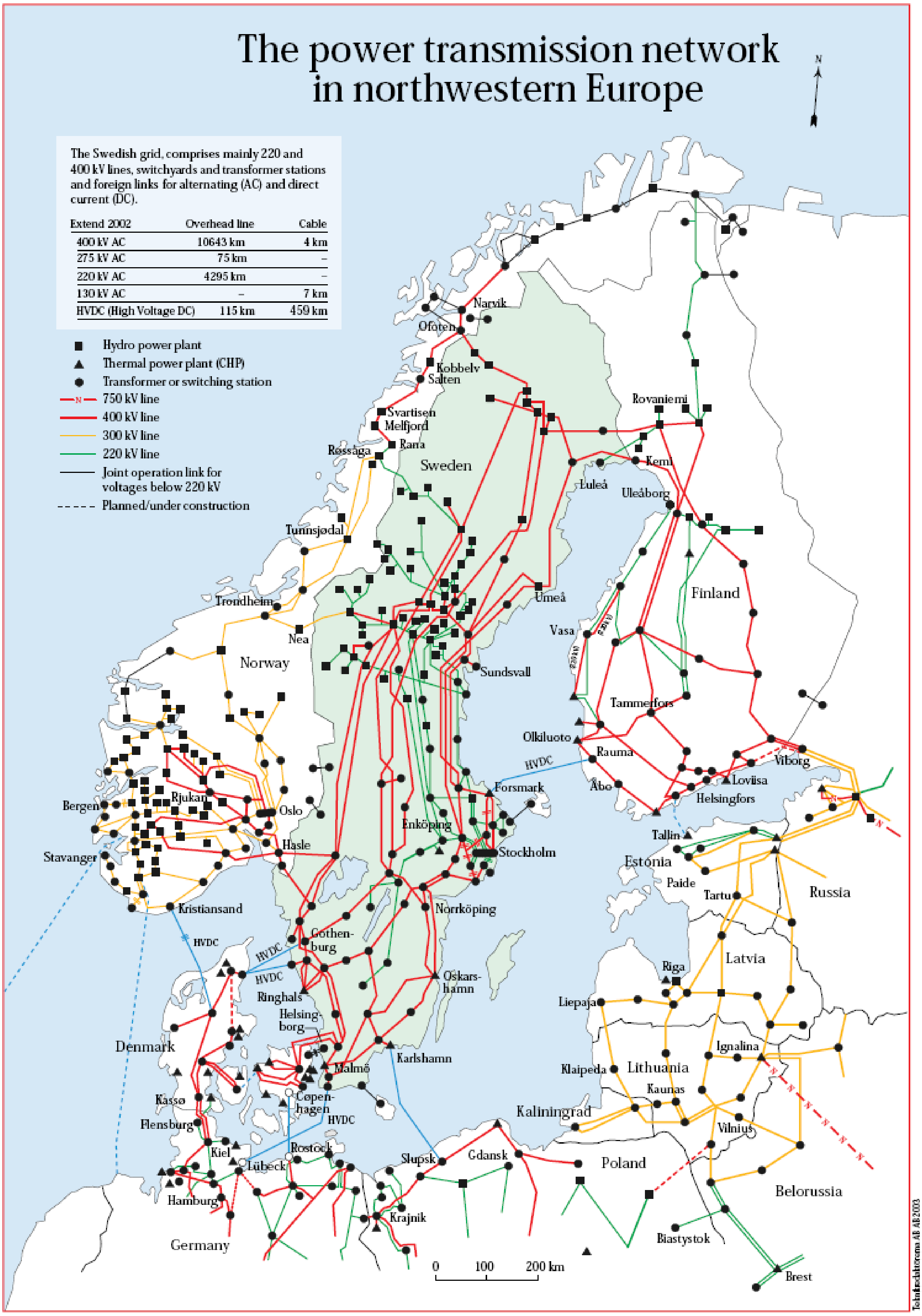

Figure 5: The power transmission network in northwestern Europe. [13]

2.2.2 Players on the electricity market

The electricity market consists of the following independent players: electricity producers, electricity consumers, network owners, the Transmission System Operator (TSO), electricity traders in the role of electricity suppliers and/or balance providers.

The producers are the players that own and operate the power plants on the electricity market and the consumer are the ones that consume the electricity. Both producers and consumers are connected to the electricity system and have to pay for using the network in form of network fees to the network owners. The role of the network owners is to operate and maintain the power network together with securing the quality of the electricity. Their responsibility is also to measure the production and consumption of the connected producers and consumers. Furthermore, the network owner has to buy electricity to cover the losses in the network. [10]

The main high voltage electric transmission networks are managed by the TSOs. Their obligation is to provide grid access to the players of the electricity market according to regulations that make sure that no one is discriminated. The TSOs also have to make sure that the supply is secured and that the operations and maintenance of the national system are safe. Furthermore they are responsible for the development of grid infrastructure in many countries. In the internal electricity market of the European Union, the TSOs are operating independently from the other electricity market players. [14] The TSOs in the Nordic power system are Svenska Kraftnät (SvK) in Sweden, Fingrid in Finland, Statnett in Norway and Energinet.dk in Denmark. [12] The Nordic TSOs have been cooperating in the Nordel organization since 1963, but from the first of July in 2009 Nordel became a part of the new organization ENTSO-E (European Network of Transmission System Operators for Electricity), which consists of 42 TSOs from 34 countries in Europe. [15]

Electricity traders in the role of electricity suppliers are companies that buy electricity from producers or the power exchange and sell to the consumers. They are working as a link between producers and consumers. In Figure 4 in chapter 2.2 the electricity traders only operate in the electricity trade sector. [10] Electricity traders can also have the role of balance providers which means that they are financially responsible that the electricity the trader sells is kept in balance at all times with the electricity purchased to cover consumption. [16]

2.2.3 The electricity market and Svenska Kraftnät

Until 15-20 years ago, the electricity production was mostly state-owned and not exposed to competition in an open market. In recent years, this has rapidly changed and in large parts of Europe, electricity markets have opened up. In Sweden, the electricity market was reformed in 1996 and it meant that the responsibility of electricity production and sale was separated from transmission. This was done to expose electricity generation and trading to competition while network operation would still be monopolized. [16]

Svenska Kraftnät (SvK) is a public utility which is responsible for managing and operating the national electrical transmission grid in Sweden as well as the overseas links. The electricity shall be transferred in a safe, reliable, efficient and environmentally-adapted way and the electricity market shall be open, effective and competitive. SvK are supposed to organize the trade in electricity with physical transmission and the economical and physical balancing of electricity in Sweden. This is done by using point-of-connection tariff, power exchange, balance service, and market-adapted methods to prevent bottlenecks in the system. [16]

2.2.3.1 Point-of-connection tariff

The different players on the market have to pay for the right to generate and consume electricity at a single connection point. The charges are paid to the owner of the concerned network. From the connection point, access is given to the whole network system and the whole electricity market. This means that the player can trade in electricity with everyone in the entire network system. The owners of the local networks pay their network fees to regional network owners and the regional network owners pay their network fees to Svenska Kraftnät. Most of the electricity is transferred from the north to the south of Sweden and therefore the charges for input in the north of Sweden are higher than the charges for output. In the south of Sweden the situation is the opposite. [16]

2.2.3.2 The power exchange

The electricity system has many different types of power plants and the costs of operation and capital vary. The aim is to generate power with as low cost as possible and those sources that can keep the lowest costs are the ones that will be running almost all the time (base load demand). The sources with higher costs are only used when the load is so high that electricity from the cheaper sources does not cover the demand. The power plants are sorted with respect to the marginal costs (second order costs such as start-up, shutdown and reserves are ignored) and wind power plants are on the top of that list since the marginal cost is usually assumed to be zero. [17] This means that wind power is used whenever available. Theoretically the electricity market works in a similar way. The producers need to receive at least the same price as their variable costs which regulate their bids on the market. The purpose of trading in electricity is that the producers will get paid for the electricity they generate. Since the electricity system partly operates by automatic control systems the payment cannot be done in real time. Instead one-hour contracts are used. The trade in electricity is divided into several steps; the prior market, real time market and the after-market. [10]

In the prior market trade is made before delivery. The power exchange Nord Pool is a prior market and consists of a spot market (Nord Pool Spot) and an adjustment intraday market (Elbas) for physical trading. It also consists of a financial market where the trade is made for the present and the next following five years. The Nordic spot-market is part-owned by the Nordic TSOs. On the spot-market physical hourly contracts for every hour of the following 24-hour period (midnight to midnight) are traded. The countries that are trading in Nord Pool Spot are Sweden, Norway, Finland and Denmark. [18] Nord Pool Spot is connected to the German market EEX. In 2010, France, Holland and Belgium will also be connected to the German market which means that the spot markets of the whole Northwestern Europe will be connected to each other. [19] The TSOs decide the amount of cross border capacity that is given to the spot market and then the trading companies have to bid before 12.00 am the day before delivery. When the spot market close at 12.00 am, an auction is held and [20] selling and purchasing curves are constructed. This is done by arranging selling bids in a supply curve where the bids are sorted in growing order according the lowest requested bid. In the same way the purchase bids are arranged in a demand curve by sorting the bids in a decreasing order. The electricity price is then determined by the point where the curves cross each other. All bids to the left of the cross are taken. [10] (Figure 6) The players are then informed about the amount of electricity they have been apportioned and to what price. Svenska Kraftnät's balance service then receives the information about the trade in Nord Pool and plans of production and forecasts of consumption are made. Finally, the planning and operation of the electricity system can be presented. [16] In 2007, 69 % of the electricity was traded on Nord Pool Spot. [20]

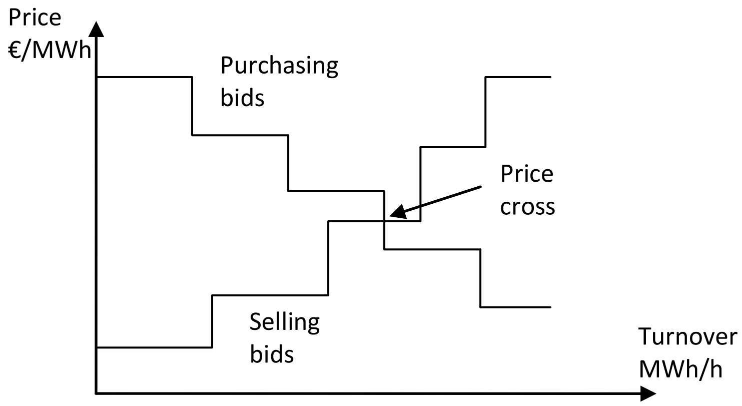

Figure 6: The electricity price is determined by where the curves of selling and purchasing cross each other. [10]

When the spot market has closed at 12.00 am, the remaining capacity is available at the adjustment intraday market, Elbas. Elbas opens at 2.00 pm and Sweden, Finland, Denmark, Norway and Germany start trading [20]. In 2010, Holland and Belgium will join Elbas as well. EEX and Nord Pool work in a project on connecting the platforms of the two intraday markets so that trade can be made from both. When this is achieved France, Switzerland, and Austria will be connected to Elbas as well. The plan is to finish the project during 2010. [19] In the intraday market the players get the chance to compensate for unexpected events that happened after the spot market was closed. In Elbas the trading is done continuously until one-hour before delivery. [16] Closer to the delivery hour the TSO may give more cross border capacity to the intraday market. The last hour before delivery the remaining capacity from Elbas is used in the regulating market. [20] In Figure 7, the time table for trading and balance is shown.

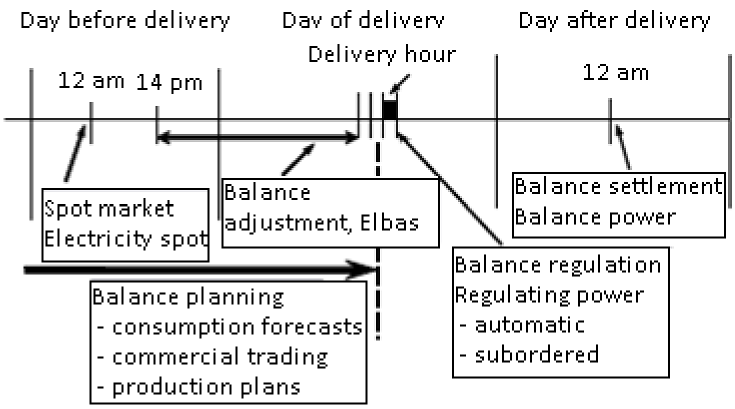

Figure 7: Time table for trading and balance. [16]

There is also a financial market with a different kind of price insurances. A financial derivative is a bilateral agreement between two players in the market. The trade with financial derivatives is not reported to the TSO and is not counted in the balance on the after-market. [10]

2.2.3.3 Balance service

Svenska Kraftnät has the responsibility of the physical and economical balance in the electricity system. When the frequency differs from the nominal value of 50 Hz (+/-0.1 Hz) they order regulating power from balance providers. [16]

There are three levels of responsibilities within the Swedish electricity market. On the national level, the whole system has to be in balance and this is the responsibility of Svenska Kraftnät. To achieve this, a balance, between production and consumption on an instantaneous basis (minute-by-minute), has to be maintained. The whole Nordic system needs to be in balance and the different TSOs are cooperating to maintain this. On the second level the balance providers need to maintain their company balances on an hourly basis. The responsibility on the third level rests with the electricity suppliers. Instead of signing a Balance Obligation Agreement with Svenska Kraftnät, they can make an agreement with a balance provider who manages the balance on their behalf. [16]

Physical balance maintained by trade and balance regulation

It is important that the physical balance is maintained, which means that production and purchasing are in balance with consumption and sale. To be able to sustain the physical balance, the balance providers have the possibility to trade in electricity just before the delivery hour. The balance is traded on Nord Pool’s spot- and intraday adjustment market, but bilateral agreements are also used. [16]

When the delivery hour starts, the balance is managed by the balance service. Svenska Kraftnät receives bids from balance providers who are ready to increase or decrease their production or consumption within 10 minutes. For every hour of operation the bids are set up in order of price and form a “staircase”. Sweden forms the staircase together with Norway, Finland and Denmark. When the system is unbalanced and it is necessary to regulate the frequency, the most favorable bid is accepted. Beside this manually regulation, an automatic frequency controlled regulation of the generators of some power stations is accessible. This kind of regulation is bought from balance providers, by Svenska Kraftnät. [16]

Economical balance maintained by balance settlement

It is not only the physical balance that must be maintained, so must the economical balance. The economical balance is maintained by balance settlement, which means that the costs of regulation and unbalance between balance providers are divided by Svenska Kraftnät. All balance providers are paid or have to pay for the balance power that deviates from the plan. The price is set depending on if it was upward or downward regulation the hour in question. [16]

2.2.3.4 Bottlenecks – market division and counter-trade

When transmission to meet the market's demand is limited by the capacity of the power lines, the consequence is a bottleneck in the system. There are some sectors, so called cross-sections, where the risk of bottlenecks is larger. [21] Where the cross-sections within Sweden are located can be seen in Figure 8.

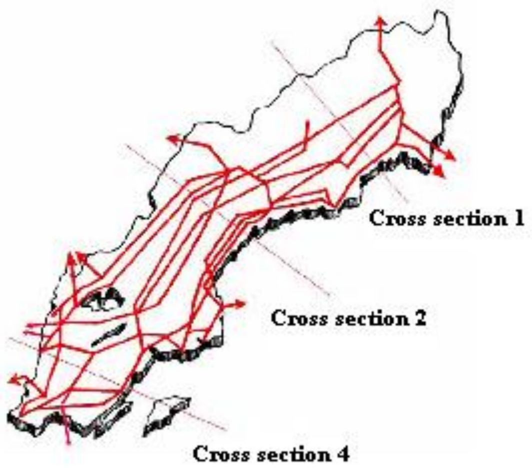

Figure 8: Cross-sections in the Swedish national grid. [22]

The fundamental reason for the appearance of bottlenecks in the Swedish power grid is that a large part of the production capacity is situated in the north and the center of consumption is located in the south. This means that most of the electricity transmission occurs in direction north to south. The transmission capacity in the Swedish grid is enough to meet the Swedish demand, but not for unlimited trade with the neighboring countries. The limitations vary from year to year depending on if it is a wet or a dry year. In a wet year there is more production in the north than in a dry year and consequently the risk of bottlenecks in cross-section 1 is greater in a wet-year. During most time of the year, the capacity in the cross sections is more than enough and therefore it is not economical justifiable to expand the network to the extent that no bottlenecks will ever appear. [21] Instead the problem is solved by market division and counter-trade; both methods are used in the Nordic system. In Sweden the problems with bottlenecks are not solved during the planning phase, instead counter-trading is used in the operational phase. An example of when counter-trading is used is when the transmission between the North and South of Sweden needs to be reduced. Then more production can be ordered in an area with low production, and a decreased production is ordered in an area with too much production. Svenska Kraftnät manages the counter-trade by the balance service. [18] However, in the end of 2011 SvK is expected to divide Sweden into four potential price areas which mean that a market division can take place instead. [23] Market division is, unlike counter-trade, performed in the planning phase for each hour of trade. In the planning phase the potential bottlenecks can be identified by analyzing the supply and demand and geographical location of bids. In the areas where the capacity is lower than the expected transmission, the market is divided into two geographical areas with different prices. The electricity produced in the area where the supply is greater than the demand, obtains a higher price than the electricity in the area with shortage of supply. In this way the market solves problems with bottlenecks by itself since the electricity with the lowest price will become sold first. [12]

2.3 Reserves

It is important to keep the electricity system running at all times since the consequences of a failure could be very serious and costly. A problem with electricity is that there is no satisfactory way to store it and the balance between production and consumption in the electricity system has to be maintained all the time. Hence the reliability of the system is kept at a very high level. The supply needs to be secured and it is necessary that the system is flexible and guarantees the function all the time, including peak load situations. To achieve this, the system needs to contain reserves. Situations that can appear are plant outages (managed by disturbance reserve) as well as predictable and non-predictable variations in load and in primary generation resources, including wind (managed by operational reserves). [17]

Both consumption and production of electricity vary with time and historically it has mostly been the consumption that is varying. [24] Prognoses are made to determine the demand for electricity. The consumption of electricity varies both during the day and season. For example, the electricity consumption is much higher in winter than in summer, due to heating. The peak of the year normally appears in January or February when it is cold and windy in the whole country. [1] With more wind power in the system the production is varying to a larger extent. [24] When the consumption or production is changing, regulating power has to be activated and in these cases the operational reserves are used. If there on the other hand is an unplanned interruption in a power plant the disturbance reserve is used. [17] In the Nordel system, it is specified that the disturbance reserve for each country has to be larger than the largest production unit dropping off instantaneously. Wind power has no influence on the disturbance reserve as long as wind farms are less than the largest production unit in the system. The Swedish disturbance reserve is about 2000 MW [25].

However, in this project the focus is on a large scale introduction of wind power in the electricity system. One of the problems with wind power is that it is difficult to make 100 % reliable forecasts of the weather. Since the wind varies with time the electricity production from wind power varies as well. Wind power does not need to be matched one-for-one by having another power plant generating electricity when the wind power is out. Instead the entire system has to be balanced in order to prevent production and consumption to deviate from each other. There are different kinds of variations in the wind, firstly there are fast variations from wind gusts and secondly there are slow variations from weather front systems that pass the power stations. [26] This means that if the wind turbines are spread out the variations are smoothed out since the wind speed is diverse at different places and consequently less regulating power is needed.

The variations are managed in different ways. The fast variations are mainly handled by the automatic primary reserves, which maintain the momentary balance between the electricity production and consumption. The slow variations are handled on the prior market (Elspot, Elbas and bilateral agreements). Based on available wind prognoses, producers of wind power are bidding on the prior market. If for an hour a lot of wind power production is predicted, fewer bids for other power sources will be accepted during that hour. If low wind power production is prognosticated on the other hand it is compensated by more trade in other power sources. If a prognosis does not agree with the reality, the system operator compensates for this by activating bids in the real time market. The bids are based on hourly contracts and therefore the real time market may be used even if the total amount of wind power in the prognoses is correct. Since the wind is uneven, it might blow a lot in the beginning of the hour and less in the end of the hour. As a consequence the TSO has to regulate down in the beginning of the hour and regulate up in the end. [26]

However, a distinction is made between primary and secondary reserve. The division is made depending on the time-scale in which they are operating. The primary reserve is automatically activated by frequency fluctuations within a few seconds. Secondary reserve is active or reactive power activated manually or automatically within 10-15 minutes after the occurrence of frequency deviation from nominal frequency. [17]

2.3.1 Primary reserve

If the production or the load is varying, the frequency in the system is changed and then the primary reserve (also called instantaneous or automatic reserve) is activated automatically within seconds or a few minutes. On this time scale a great number of turbines in the electricity system smooth out the variations from gusts and furthermore the inertia of the large rotors as well as variable speed turbines absorb the variations. [17] The primary reserve is divided into frequency reserve and momentary disturbance reserve. The first should keep the frequency at 50 Hz and the second should restore the system if a large frequency drop occurs. [27]

The primary regulation is managed separately for every synchronous power system. The function can shortly be described in the following way: [27]

1. Assume that the frequency in the system is 50 Hz and the production drops at a certain point of time. The consumption is constant at that moment.
2. Since production and consumption have to be balanced the electricity has to be generated somewhere else. Rotation energy is stored in the system; more specifically in the rotors (of all synchronous machines[3]) and the connected turbine shafts. The balance in the system is maintained by using the stored energy thereby decreasing the rotation speed. In synchronous machines the rotational speed is proportional to the electrical frequency which means that the electrical frequency is decreasing with the rotation speed.
3. In some power plants there is equipment that recognizes frequency changes. When the frequency is decreasing the regulating power is activated and the production is increasing according to the frequency decrease.
4. The production in these power plants keeps increasing as long as the frequency is decreasing. When the frequency is stabilized the balance is fulfilled but on a lower level than the nominal frequency.

In this case, decrease of production is the reason for activating the primary reserve, rise of the load could evoke the same result. Furthermore, a decrease in load or an increase in production has the same effect, but then the frequency is increasing instead and consequently the regulating power is decreasing. [27]

Some important consequences of the primary regulating power functions are [27]:

- If, for example, a reactor in the south of Sweden makes a fast stop the frequency in the whole Nordic system will become influenced. This means that the regulating power starts in Swedish, Finish, Norwegian and Danish power plants. Since the production is moved, the flows of currents through the transmission network are automatically changed.

[3] All larger power plants (> 3 MW) are using synchronous machines.

- If no other production is turned on, except for the one activated by the regulating power the nominal frequency will not be achieved. The primary reserve is used in the frequency interval of 49.9 to 50.1 Hz. At a larger deviation other measures are taken such as reducing the export on the HVDC-lines abroad.

It is essential to have enough power plants with regulating power opportunity and that the marginal is wide enough to meet changed consumption and production. Another important matter is that the location of the regulating power is planned in an appropriate way so that the transmission from the primary regulating power can be handled. [27]

2.3.2 Secondary reserve

As stated in chapter 2.2.1, the primary reserve is activated if production and consumption are unbalanced. This makes the frequency stable, but it differs from the nominal frequency, which is 50.0 Hz (+/- 0.1 Hz). As long as no other disturbances arise this is not a problem, but if another disturbance occurs there are not enough primary reserves to restore the system. Instead the secondary reserve (also called fast reserve) is activated within 15 minutes to return the frequency to 50 Hz and to replace the primary reserve if unforeseen load and production changes would occur again. [27] The secondary reserve consists of spinning reserve (hydro and thermal plants in part load operation) and standing reserve (rapidly starting gas turbines and load shedding). [17]

An example of how the secondary reserve operates is when a bigger production unit suddenly has to be disconnected from the system. First primary reserves compensate for this with a new stable production but with a lower frequency. This means that the primary reserves have been used and another kind of reserve is needed, the secondary reserve. The task of the secondary reserve is to increase the frequency to the nominal value of 50 Hz and to make sure that the integrated time deviation is not too large. The time deviation is the deviation between the correct time and the time of a clock driven by the electrical frequency. Because of this, it is important that the amount of secondary reserve is enough to bring the system back to normal. Too little primary reserves is more critical than too little secondary reserves, but the secondary reserves work as a safety marginal if another disturbance would occur. [27]

The secondary reserve is divided into two parts: the operating reserve and the production/transmission reserve. They work in the same way, but are used in different situations. The unforeseen variations induced from wind power are handled by the operating reserve. [17] In the Nordic electricity system all secondary regulating power is handled manually from the control room of the TSOs. [10] All the TSOs are responsible for activating secondary reserves in their own areas and ensuring that the physical constraints of the transmission grid are observed. [17]

When the penetration of wind power in the system increases, an increasing amount needs to be allocated for secondary reserve. When the penetration of wind power is 10 % the requirements for reserves is about 2 % of the installed wind power capacity and at a 20 % penetration the requirement is about 4 % of the installed wind power capacity. [17]

To sum up, the secondary reserve is used for [27]:

- Restore the momentary disturbance reserve
- Regulate prognoses deviations, for example when the real consumption differs from the bidding on Nord Pool Spot.
- TSOs counter trade
- Making trade between different TSOs possible.
- Lower the risk of power shortage.

After the secondary reserve the long-term reserve (also called slow or tertiary reserve) is activated and is in operation within a few hours. [17] To regulate the variations raised from wind power the primary and secondary reserves are used. [24]

2.3.3 Voltage control

Besides the frequency control, there is voltage control in the system. The equipment connected to different parts of the grid is dimensioned for certain interval of voltages and therefore it is necessary to keep the voltage in this interval since the equipment could otherwise be destroyed. [27] While frequency is a global quantity and can be taken care of wherever there is enough transmission capacity, voltage is a local quantity and voltage management should be taken care of in the nearby area. [17] A deviation in voltage is caused by unbalance in reactive power. In contrast to balance in active power, where the production and consumption must be the same in the whole system, the reactive power has to be balanced in certain limited geographical areas. This is because reactive power can not be transported very far. When the input of reactive power is low the voltage is decreasing and with a high input the voltage is increasing. [28] To manage the voltage level during disturbances reactive reserves are used. These reserves are mainly used as primary reserves in order to guarantee that the voltage level of the power system remains stable during disturbances. [17] Some different reactive regulating options that could be used are: synchronous machines, capacitors, reactors, SVC (Static Var Compensation), VSC (Voltage Source Converter) and adjustable transformers. [27]

2.3.4 Hydro power as regulating power

According to Amelin et al [26], 80 % of the capacity of the Swedish hydro power could compensate for more or less all wind power variations even with an introduction of 12 000 MW[4] in the north of Sweden. The challenge would be to export the electricity that is produced. Since there is no feasible way to store energy from wind power production it is necessary to share the hydro power energy in a way so that the available export capacity is utilized at most. Effective tools for both short time and season planning are a necessity and it is important that the market is designed in a way making it profitable for the hydro power producers to provide as much regulating power as possible. [26]

[4] This corresponds to about 30 TWh wind power.

3 Methodology: Sweden

The aim of this chapter is to describe the model and the equations that were used to find out how the carbon dioxide emissions might be influenced with an introduction of a large scale wind power production within the Swedish electricity system.

3.1 Model used to estimate CO2 emissions

To be able to study the carbon dioxide emissions with an introduction of large scale wind power production within the Swedish electricity system a model has been created. The following parameters have been considered when calculating the emissions:

- Penetration of wind power production in the electricity system
- Transmission capacity between the national grids in the Nordic countries
- Export
- The electricity generation mixtures of Sweden, Denmark, Norway and Finland
- Regulating power and carbon dioxide emissions from different sources of power

The model is visualized in a flowchart in Figure 9.

The changes of CO_2 emissions are then calculated by subtracting the replaced energy emissions from the emissions generated by the extra need of regulating power and the increased wind power production. The regulating power is composed of the extra primary and secondary reserve that are prognosticated to be used because of the increased amount of wind power. The replaced energy sources are determined by the conditions proclaimed by the different scenarios created within the project and to achieve this, the electricity generation mixture of Sweden, Denmark, Norway and Finland are used. Finally the values of the CO_2 emissions from the different energy sources are used as input data in primary reserve, secondary reserve, wind power production and replaced energy sources.

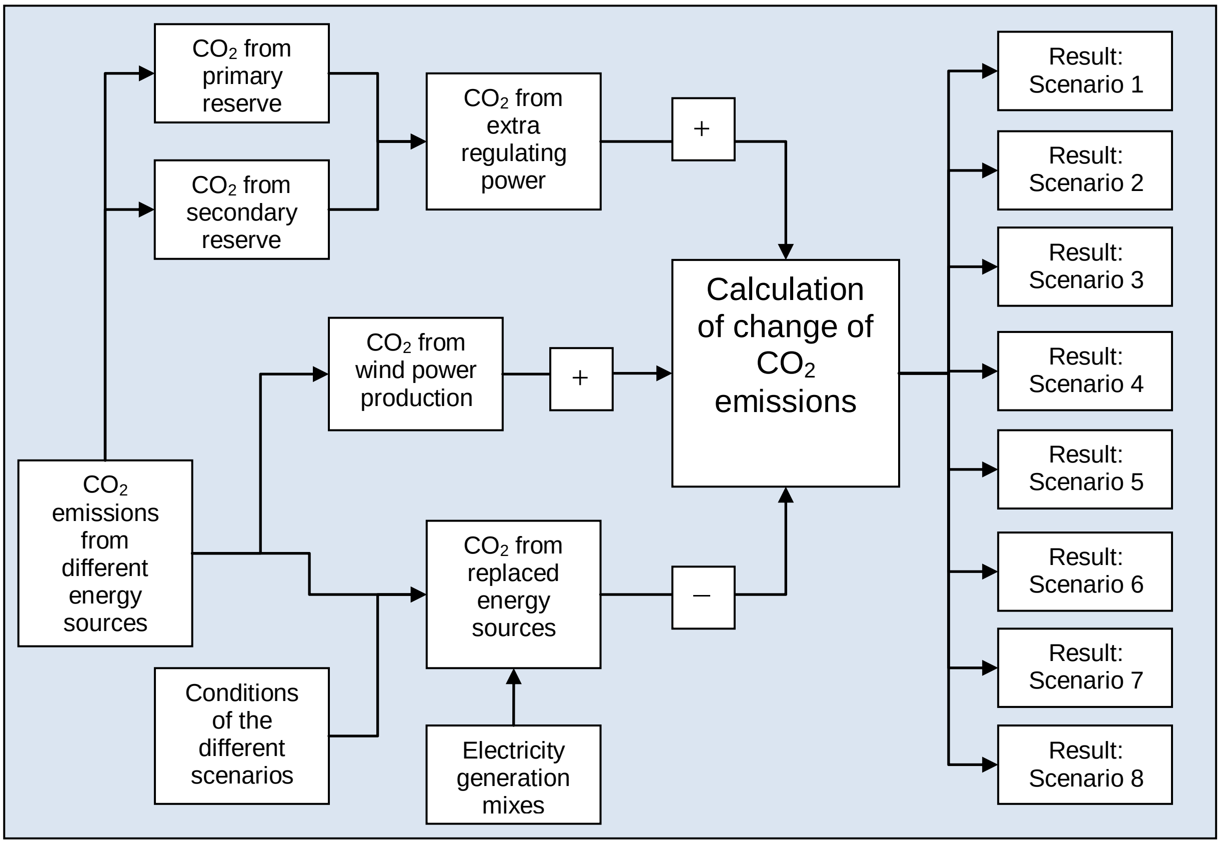

Figure 9: Flowchart showing how the parameters interact to estimate the change of the carbon dioxide emissions with an introduction of large scale wind power production in the Swedish energy system.

In the project, 8 different scenarios with different conditions are investigated. A short description of the scenarios follows (a more detailed description can be found in chapter 4.2).

- Scenario 1 (best case scenario): Hydro power is used for all regulation and the replaced energy sources are the ones with the highest CO_2 emissions. This scenario will result in the largest reduction of CO_2 emissions.
- Scenario 2 (worst case scenario): Gas turbines are used for all regulation and the replaced energy sources are the ones with the lowest CO_2 emissions. This scenario will result in the lowest reduction or the largest increase of CO_2 emissions.

In the following scenarios (scenario 3-8), the regulating power consists of a mixture of hydro power, thermal power (coal, oil and natural gas) and gas turbines.

- Scenario 3: 100 % of the replaced energy sources is in the same proportion as the Swedish electricity generation mix.
- Scenario 4: 50 % of the replaced energy sources is in the same proportion as the Swedish electricity generation mix and 50 % is in the same proportion as the electricity generation mix of Denmark, Norway and Finland.
- Scenario 5: 100 % of the replaced energy sources is in the same proportion the electricity generation mix of Denmark, Norway and Finland.
- Scenario 6: The replaced energy sources consist of the Swedish electricity sources with the highest CO_2 emissions.
- Scenario 7: The replaced energy sources consist of nuclear power.
- Scenario 8: 100 % of the replaced energy sources is in the same proportion as the Danish electricity generation mixture.

3.2 Carbon dioxide emissions

When looking at the change of CO_2 emissions, the values of CO_2 emissions from the replaced energy sources together with the sources used as regulating power are used. The Nordic[5] electricity generation mix contains the following energy sources: nuclear power, coal, oil, peat, natural gas, hydro power, wind power, biomass and waste. At Vattenfall, life cycle assessments (LCA), for the different electricity production techniques, are made. The LCAs consist of detailed information about the environmental impacts that are caused or necessitated by the existence of the electricity production technique. The LCAs are used as basis for the Environmental Product Declarations (EPD) made by Vattenfall. In the EPDs information about the environmental performance of different products and services are presented from a life cycle perspective [29]. In this thesis the values of the CO_2 emissions estimated by Vattenfall, are used. Both values regarding power plant operation only and the whole life cycle (LCA) are used.

3.3 Conditions and assumptions

The amount of annual wind power that is studied has been set to 10 and 30 TWh. These two cases have been investigated parallel to each other and correspond to about 7 % and 21 % wind power production in the Swedish electricity system. An estimation is that a capacity of about 4 000 MW wind power must be installed to receive 10 TWh wind power and a capacity of about 12 000 MW is needed to receive 30 TWh wind power [30].

The capacity of transmission has to be large enough to make it possible to transfer electricity without bottlenecks in the power grid. In the model it is assumed that the transmission capacity is sufficient and that no bottlenecks will appear. Furthermore it is assumed that the consumption of electricity is constant at the level of 2008. When wind power is introduced in the system another source of power can be reduced, where usually the most expensive electricity production is replaced. [31]

In the model it is assumed that 1 kWh wind power means a reduction of 1 kWh from another energy source. The kind of source that is replaced by wind power is decided by the conditions in the different scenarios. How the substitution is made in the different scenarios is shown in Table 1.

[5] Nordic means Sweden, Denmark, Norway and Finland.

Table 1: The conditions in the 8 different scenarios.

Scenario	Substituted energy sources	Export of wind power electricity
1	Energy sources with highest CO_2 emissions in the Nordic countries.	Infinite exportation.
2	Hydro power.	No electricity is exported.
3	Energy sources that are corresponding to the Swedish electricity mix.	No electricity is exported.
4	50% corresponding to the Swedish mix and 50 % corresponding to the mix of Denmark, Norway and Finland.	50 % of the electricity is exported.
5	100 % corresponding to the mix of Denmark, Norway and Finland.	All electricity is exported.
6	Energy sources with highest CO_2 emissions in Sweden.	No electricity is exported.
7	Nuclear power.	No electricity is exported.
8	100 % corresponding to the Danish mix.	All electricity is exported.

3.4 Estimation of change of CO_2 emissions

Since the wind is not blowing everywhere at every moment and generation needs to be the same as consumption there is a need of regulating power. In the model it is expected that all regulating power is produced within the Swedish borders.

In the model a distinction between primary reserve and secondary reserve is made. The reserves give different contributions to the carbon dioxide emissions depending on what energy source that is used.

The primary reserve is activated automatically within second or a few minutes. A production of 10 TWh wind power requires a 20 MW installed primary reserve [32] and this is scaled up to a 60 MW installed primary reserve for 30 TWh wind power production.

The increase in wind power capacity is proportional to the increase of wind power production. One consequence of increasing wind power capacity and production is that more primary reserve capacity and production are needed and in the thesis it assumed that the amount of reserves that is installed is adjusted to the amount of wind power production in an average year. In the model the following assumption regarding the annual production from primary reserves due to wind power is made: The ratio between the installed capacity for the primary reserve and the wind power is the same as the ratio between the annual productions for the primary reserve and the wind power. This is a simplification and cannot be applied in all situations. If the capacity is adjusted to a mean value of wind power it is more reliable than if it is adjusted to all possible extreme situations that happen very seldom. In this thesis it is assumed to be adjusted to a mean value. These assumptions result in the following equation

$$\frac{C_{prim}}{C_{wind}} = \frac{G_{prim}}{G_{wind}} \qquad (3)$$

where C_{prim} is the installed primary reserve capacity, C_{wind} is the installed wind power capacity, G_{prim} is the annual electricity production from the primary reserve and G_{wind} is the annual amount of electricity produced by wind power.

The annual production of the primary reserve is then calculated from

$$G_{prim} = G_{wind} \cdot \frac{C_{prim}}{C_{wind}} \tag{4}$$

In all scenarios except for the worst case scenario hydro power is used as primary reserve. In the worst case scenario gas turbines are assumed to be used instead.

On a fifteen minutes to one hour time scale, the secondary reserve is activated. The secondary reserve production is assumed to be about 2 % of the wind power production (10 % wind power production in the system) [32]. The same is assumed for a penetration of 7 % which corresponds to 10 TWh. With a penetration of about 21 % which corresponds to 30 TWh, the secondary reserve is assumed to be 4 %. This assumption is made in view of a simulation of the Nordic electricity system made by Holtinnen [17] where the reserve requirements would increase from 2 to 4 % of wind power capacity at 10 and 20 % wind power penetration of gross demand [17]. The secondary reserve is calculated from

$$G_{\sec} = n \cdot G_{wind} \tag{5}$$

where n is the percentage of reserve power needed and G_{wind} is the annual amount of electricity produced by wind power.

The secondary reserve mostly consists of gas turbines, hydro power, thermal plants and load shedding. In scenario 1 (best case) the secondary reserve consists of hydro power and in scenario 2 (worst case) it consists of gas turbines. In the other scenarios the secondary reserve consists of the same proportion of hydro power, thermal plants and gas turbines.

The total amount of CO_2 emissions from the regulating power is calculated from

$$CO2_{reserve} = G_{prim} \cdot \sum_{i=1}^{n} x_i y_i + G_{\sec} \cdot \sum_{i=1}^{n} x_i y_i \tag{6}$$

where G_{prim} is the production from primary reserves, G_{sec} is the production from secondary reserves, x_i is the percentage of the reserve for a certain energy source and y_i is the amount of CO_2 emissions from this source.

The change of CO_2 emissions from wind power substituting another energy source are calculated according to the conditions in the different scenarios. The change of CO_2 emissions from the substitution is calculated from

$$CO2_{substitution} = G_{wind} \left(y_{wp} - \sum_{i=1}^{n} x_i y_i \right) \tag{7}$$

where y_{wp} is the CO_2 emissions per kWh from wind power production, x_i is the percentage of the replaced energy source and y_i is the CO_2 emissions from the specific energy source per kWh.

The total change of CO_2 emissions is then calculated from

$$CO2_{tot} = CO2_{reserve} + CO2_{substitution} \qquad (8)$$

where $CO2_{reserve}$ is the CO_2 emissions from the reserves and $CO2_{substitution}$ is the CO_2 emissions from wind power substituting another energy source.

4 Data used in the thesis

The aim of this chapter is to give an account of the data that is used in the thesis. When prognosticating the change of carbon dioxide emissions after an introduction of 10 and 30 TWh in Sweden, the electricity generation mixes in all the Nordic countries have been taken into account. In Table 2 the electricity generation by energy source in the Nordic countries in 2008 [6] is shown.

Table 2: Total electricity generation by energy source and net exchange of electricity 2008 (TWh) [6].

	Sweden	**Denmark**	**Finland**	**Norway**	**Nordel**[6]
Total generation	**146.1**	**34.6**	**74.1**	**142.7**	**397.5**
Total thermal power	**64.7**	**24.1**	**47.6**	**0.4**	**136.8**
Nuclear power	61.3	0.0	22.0	0.0	83.3
Other thermal power	**3.4**	**24.1**	**25.6**	**0.4**	**53.5**
Coal	0.6	16.1	8.5	0.0	25.2
Oil	0.6	0.9	0.3	0.0	1.8
Peat	0.1	0.0	5.8	0.0	5.9
Natural gas	1.1	7.0	11.0	0.4	19.5
Others	1.0	0.0	0.0	0.0	1.0
Total renewable power	**81.4**	**10.6**	**26.5**	**142.3**	**260.8**
Hydro Power	68.4	0.0	16.9	140.7	226.0
Other renewable power	**13.0**	**10.6**	**9.6**	**1.6**	**34.8**
Wind power	2.0	7.0	0.3	0.9	10.2
Biomass	9.6	1.9	8.7	0.0	20.2
Waste	1.4	1.7	0.6	0.7	4.4
Net imports	**-2.0**	**1.5**	**12.9**	**-13.9**	**-1.5**

4.1 Carbon dioxide emissions from different energy sources

The values of the carbon dioxide emissions from the different energy sources used in the project are shown in Figure 10. [34][35][36][37][38] The blue parts of the bars show the emissions from the operation and the red parts the emissions from other activities in the life cycle such as mining, transports, processing of the fuel, recycle of the plant etc. In the figure it can be seen that gas turbines has the highest value of CO_2 emissions of about 1300 g/kWh, while hydro power and nuclear power is very low, almost no emissions. (See appendix 1 for exact input values and references.)

[6] Nordel means Sweden, Denmark, Finland and Norway.

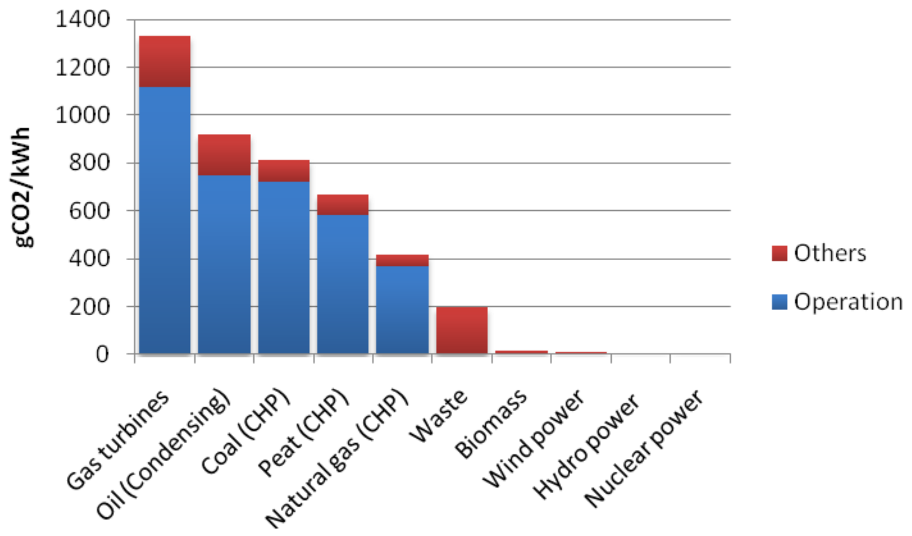

Figure 10: CO_2 emissions from the different energy sources.

The emissions from biomass, wind power, hydro power and nuclear power are shown more closely in Figure 11 and here it can be seen that these sources do not contribute with any emissions in the operation, just in the other activities in the life cycle.

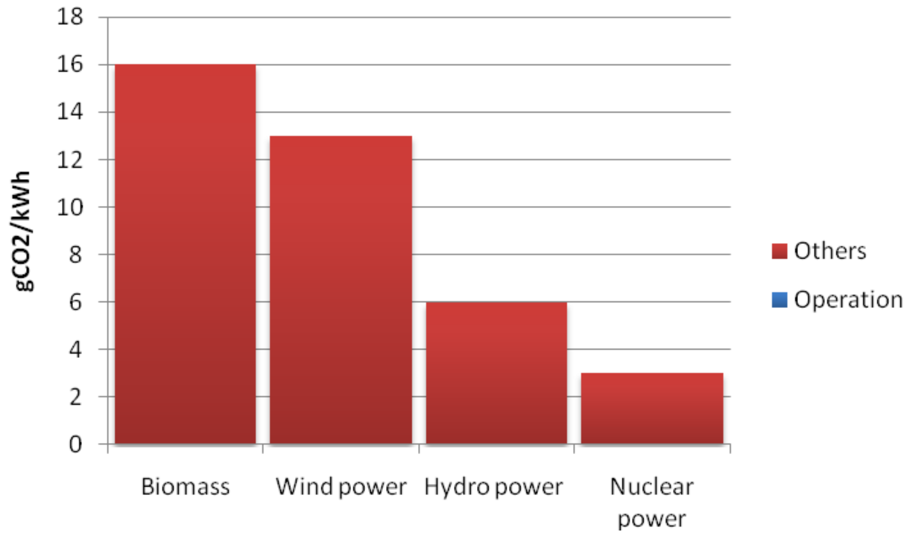

Figure 11: A closer look at the CO_2 emissions from biomass, wind power, hydro power and nuclear power.

4.2 Data in the scenarios

Eight different scenarios have been created to see what would happen with the carbon dioxide emissions in specific situations with certain conditions. The best and worst case scenarios are investigated first to get a rough estimate of the changes that could appear. Furthermore, six other scenarios with other conditions are analyzed. In all scenarios both a production of 10 and 30 TWh wind power have been investigated. Furthermore all scenarios have been investigated in view of operation only and of the whole life cycle.

Scenario 1 (best case scenario)
Best case scenario means that the greatest decrease of carbon dioxide emissions that theoretically could appear when introducing 10 and 30 TWh wind power in the system is calculated. In this scenario all regulating power is managed by hydro power. The energy sources which have the highest carbon dioxide emissions in the Nordic countries are being replaced by wind power. The CO_2 emissions in the case of 30 TWh is not proportional to the case of 10 TWh. This is because wind power will replace different energy sources and also because of a non-proportional demand of secondary reserves. (Table 3)

Table 3: Amount of regulating power managed by different energy sources and amount of replaced energy sources in the best case scenario.

	10 TWh	**30 TWh**
Primary reserve		
Hydro power (TWh)	0.050	0.150
Secondary reserve		
Hydro power (TWh)	0.200	1.200
Replaced by wind power		
Coal (TWh)	10	25.2
Oil + others (TWh)		2.8
Peat (TWh)		2

Scenario 2 (worst case scenario)
Worst case scenario means that the greatest increase of carbon dioxide emissions that theoretically could appear when introducing 10 and 30 TWh wind power in the system is calculated. In this scenario all regulating power is managed by gas turbines. (Table 4)

Table 4: Amount of regulating power managed by different energy sources and amount of replaced energy sources in the worst case scenario.

	10 TWh	**30 TWh**
Primary reserve		
Gas turbine (TWh)	0.050	0.150
Secondary reserve		
Gas turbine (TWh)	0.200	1.200
Replaced by wind power		
Nuclear power (TWh)	10	30

In the following six scenarios the regulating power is managed by the same energy sources. The primary reserve is managed by hydro power, the secondary reserve by hydro power, thermal power (coal, oil and natural gas) and gas turbines. (Table 5) A complete account of the energy sources that are replaced in scenario 3-8 can be seen in appendix 2.

Table 5: Regulating power in scenario 3-8.

	10 TWh WPP	30 TWh WPP
Primary reserve		
Hydro power (TWh)	0.050	0.150
Secondary reserve		
Hydro power (TWh)	0.067	0.400
Thermal power (TWh)	0.067	0.400
Coal (TWh)	*0.036*	*0.217*
Oil (TWh)	*0.003*	*0.015*
Natural gas (TWh)	*0.028*	*0.168*
Gas turbine (TWh)	0.067	0.400

Scenario 3

In scenario 3, the wind power is used within Sweden and it is replacing energy sources according to the Swedish electricity generation mix[7]. The Swedish mixture can be seen in Table 2 in chapter 4.

Scenario 4

In scenario 4, 50 % of the wind power is exported to the other Nordic countries and 50 % is used within Sweden. The exported wind power is replacing energy sources according to the electricity generation mixes[8] in Denmark, Finland and Norway and the electricity not exported replaces energy sources according to the Swedish mixture[9]. See Table 2 in chapter 4 for the mixtures.

Scenario 5

In scenario 5, 100 % of the wind power is exported to the other Nordic countries and are replaced according to the electricity generation mix[10] in Denmark, Norway and Finland.

Scenario 6

In scenario 6, no wind power is exported and it is replacing the energy sources with the largest amount of CO_2 emissions in Sweden. See Table 6 for the substituted energy sources. The energy sources are substituted in different ways when looking at operation and the whole life cycle. In the operation, waste, biomass and nuclear power do not have any or very low fossil CO_2 emissions, but in the whole life cycle waste and biomass have larger CO_2 emissions than nuclear power.

[7] Wind power is excluded from the mix of the substituted electricity.
[8] Wind power is excluded from the mix of the substituted electricity.
[9] Wind power is excluded from the mix of the substituted electricity.
[10] Wind power is excluded from the mix of the substituted electricity

Table 6: The energy sources that are replaced in scenario 6 in the core process and the whole life cycle.

Scenario 6	Operation		LCA	
	10 TWh	30 TWh	10 TWh	30 TWh
Coal	0.6	0.6	0.6	0.6
Oil + others	1.6	1.6	1.6	1.6
Peat	0.1	0.1	0.1	0.1
Natural gas	1.1	1.1	1.1	1.1
Waste			1.4	1.4
Biomass			5.2	9.6
Nuclear power	6.6	26.6		15.6

Scenario 7
In scenario 7, no wind power is exported and it replaces nuclear power.

Scenario 8
In scenario 8, 100 % of the wind power is exported to Denmark and replaces energy sources according to the Danish electricity generation mix[11]. (Table 2 in chapter 4)

[11] Wind power is excluded from the mix of the substituted electricity.

5 Results Sweden

The aim of this chapter is to present the results from the calculations of change in carbon dioxide emissions when introducing a large scale of wind power in the Swedish electricity system. First the extra CO_2 emissions due to regulating power is presented (chapter 5.1) and then the total change of CO_2 emissions (chapter 5.2).

5.1 Regulating power

In the best case scenario (highest reduction of CO_2 emissions) it is assumed that hydro power can be used for regulating all the new wind power production. This means that the regulation of wind power does not contribute with any CO_2 emissions in the operation and almost nothing in the whole life cycle. In the worst case scenario (lowest reduction or highest increase of CO_2 emissions) it is instead assumed that gas turbines are used to regulate all wind power since it is the reserve with the highest emissions. The reserves are divided into primary and secondary reserves and the amount of reserves is calculated according to equation 4 and 5 in chapter 3.4. The contribution of CO_2 emissions in the operation is about 30 grams per kWh wind power production when introducing 10 TWh wind power and about 50 grams when introducing 30 TWh. The secondary reserve contributes with the greater part of the emissions. Figure 12 shows the emissions from the regulating power in the operation, the blue part of the bars is the emissions from the primary reserves and the red part from the secondary reserve. In the whole life cycle the contribution is a few grams more than just in the operation.

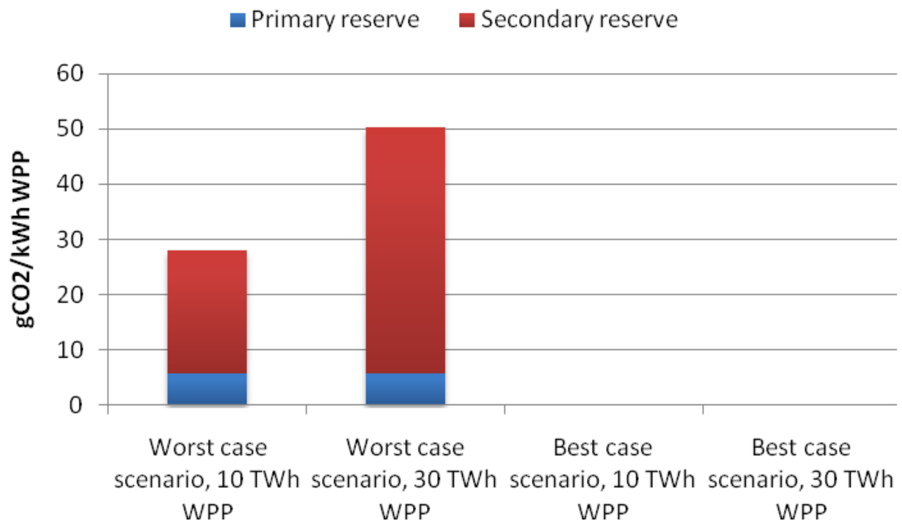

Figure 12: Diagram of CO_2 emissions caused by regulating power when introducing 10 and 30 TWh annual wind power production in Sweden. The bars show the contribution from primary and secondary reserves in the worst and best case scenario.

In scenario 3-8, the primary reserve is assumed to be managed by hydro power and the secondary reserve by one third hydro power, one third thermal power (coal, oil, and natural gas in proportion to the Nordic mix) and one third gas turbines. The CO_2 emissions are then calculated to be about 10 and 20 grams per kWh wind power production in the case of 10 and 30 TWh wind power respectively. All results can be found in appendix 2.

5.2 Total change of CO_2 emissions

In this section, the results from the estimated total change of CO_2 emissions are presented.

In Figure 13 the best and worst case (scenario 1 and 2) are shown. The figure shows the estimations both from 10 TWh and 30 TWh annual wind power productions, in the Swedish electricity system. Furthermore a distinction has been made between the operation and the whole life cycle perspective. The results are measured in grams CO_2 per kWh wind power production (WPP).

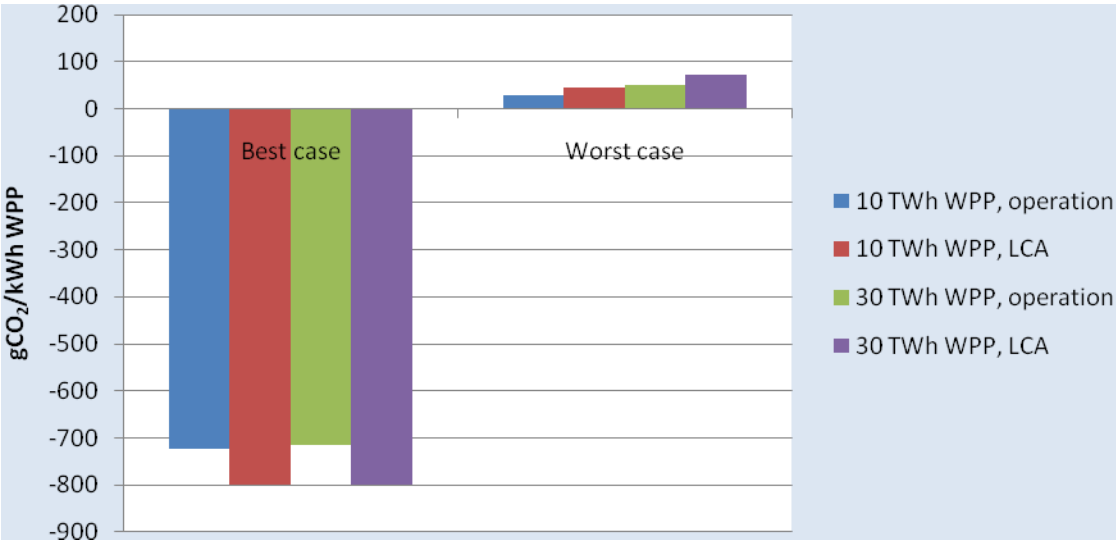

Figure 13: Diagram of best and worst case scenarios according to the change of CO_2 emissions at 10 and 30 TWh annual wind power production (WPP) in Sweden, the data used is from both in operation and the whole life cycle. The results are measured in grams CO_2 per kWh WPP.

In the best case scenario all the regulating power is assumed to be managed by hydro power and coal, oil and peat are the sources that are assumed to be replaced by wind power. In the best case scenario the results point at a reduction of CO_2 with about 700 grams CO_2 per produced kWh wind power electricity in operation and when looking at the whole life cycle the results point at a reduction of 800 grams CO_2 per produced kWh wind power electricity.

In the worst case scenario all the regulating power is assumed to be managed by gas turbines and the substituted sources of power is nuclear power. Opposite to the best case scenario the results point at an increase of CO_2 emissions with at most 60 grams CO_2 per produced kWh wind power electricity.[12] 30 TWh wind power results in a larger increase of CO_2 emissions than 10 TWh wind power since a larger amount of wind power in the system requires a larger percentage of regulating power.

In Figure 14 the results of the remaining scenarios (scenario 3-8 in chapter 4.2) are shown. A comparison is made between the operations of 10 and 30 TWh wind power production. The blue bars show the estimated results of 10 TWh wind power production and the red bars show the estimated results of 30 TWh wind power production. The results are measured in grams CO_2 per kWh wind power production (WPP).

[12] 60 grams CO_2 is the result when looking at the worst case scenario in the whole life cycle with an introduction of 30 TWh annual wind power production in the system.

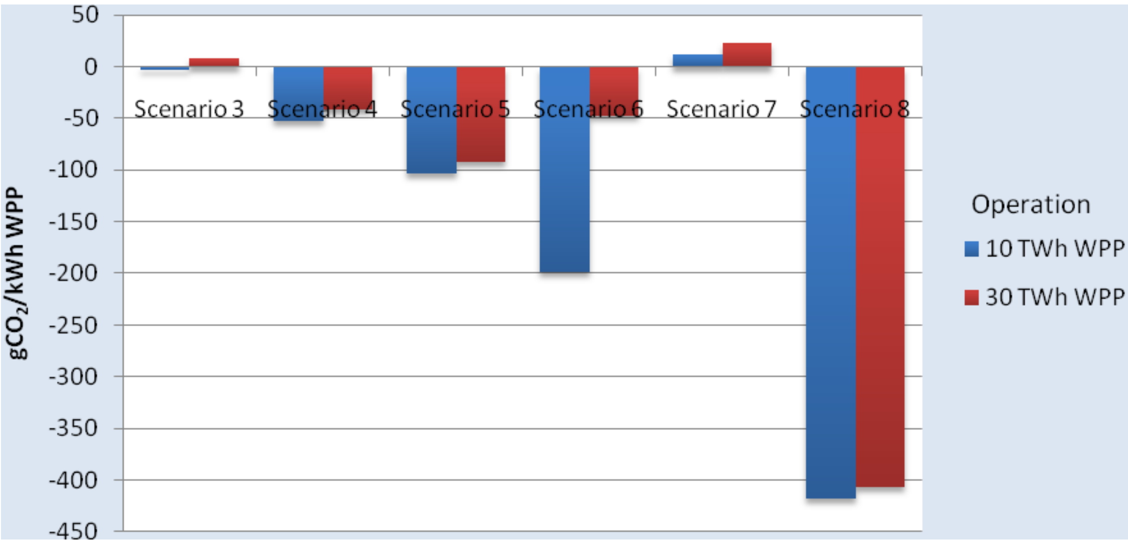

Figure 14: Diagram of the change of CO_2 emissions with an introduction of 10 and 30 TWh annual wind power production in Sweden, in scenario 3-8 in chapter 4.2. The results are measured in grams CO_2 per kWh WPP and the operation is concerned.

In scenario 3, where all wind power substitutes electricity sources according to the Swedish electricity mix, the results point at almost no change in CO_2 emissions.

In scenario 4, where half of the wind production is replaced by electricity sources according to the Swedish mix and half of it is replaced according to the mix of Norway, Finland and Denmark. The results point at a decrease of about 40-60 grams CO_2 per produced kWh wind power.

In scenario 5, where all wind power replaces production forms according to the mixture of Norway, Finland and Denmark, the CO_2 emissions are decreasing with about 95-110 grams per produced kWh wind power.

In scenario 6, where the energy sources with the highest CO_2 emissions per produced kWh in Sweden are replaced first. Here the results show a large difference in decrease of CO_2 emissions per kWh wind production depending on how much wind power that is introduced in the system. When introducing 10 TWh wind power in the system the decrease is about 200 grams per kWh and with 30 TWh wind power in the system the decrease is about 50 grams. This scenario differs from the others since 30 TWh wind power indicates a much smaller decrease in CO_2 emissions than 10 TWh wind power. Since the Swedish electricity system has a very low part of fossil fuels (3.4 TWh), wind power also substitutes sources with very low values of CO_2 emissions. Consequently an introduction of 30 TWh means a lower reduction per kWh as well as total.

In scenario 7, where all wind power replaces nuclear power, the CO_2 emissions are increasing with about 10-20 grams per produced kWh wind power.

In scenario 8, where all wind power replaces electricity sources according to the Danish mix, the emissions are decreasing with about 420-430 grams CO_2 per kWh wind power production.

The results from all of the scenarios indicate a larger gain per kWh wind power with 10 TWh compared to 30 TWh wind power production in the system. Given that a larger penetration of wind power in the system needs a larger part of regulating power.

The results that have been presented so far have been measured per kWh wind power production. In Figure 15 the change of emissions are compared to the emissions caused by the total electricity production in Sweden in the operation.

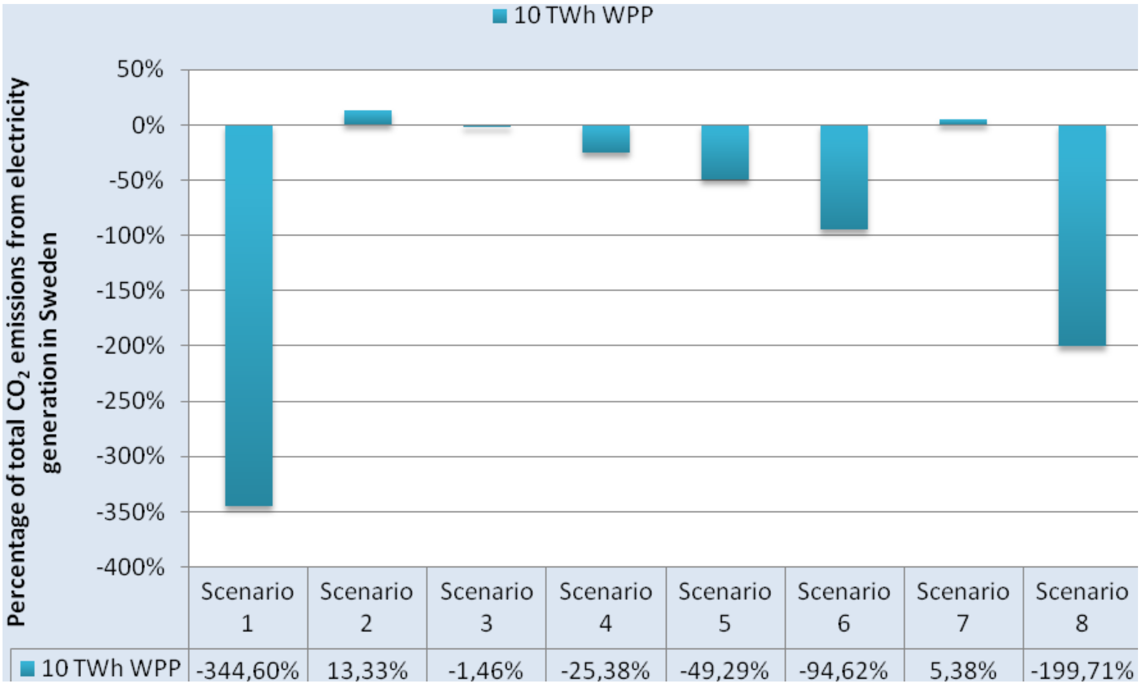

Figure 15: Diagram of the change of the total CO_2 emissions compared to the Swedish total CO_2 emissions from the electricity production. The bars show the change when introducing 10 TWh annual wind power production.

When introducing 10 TWh wind power generation the estimated decrease of the global CO_2 emissions in the best case scenario corresponds to 341 % of the emissions from the total electricity productions in Sweden. The reason for this is that the emissions are reduced abroad and the total amount of emissions from the Swedish electricity production is very low since the main sources are hydro- and nuclear power with almost no emissions. In the worst case scenario the estimated increase corresponds to 13 % of the emissions from the total electricity productions in Sweden. In appendix 2 all results can be found.

6 Denmark

The situation in Denmark is different from the one in Sweden since about 7 TWh (about 20 % penetration of gross demand) is already introduced and instead of hydro and nuclear power there is a lot of thermal power in the system. The aim of this chapter is to see if it is possible to find out any trends regarding the CO_2 emissions and the introduction of wind power in the system with help of statistics from the Danish Energy Agency (appendix 3). In chapter 6.1 the change in the Danish electricity generation mix and CO_2 emissions is investigated and in chapter 6.2, the change of efficiency in the central CHPs is studied.

6.1 Change of electricity mix in Denmark between 1990 and 2008

As stated, the situation in Denmark is different compared to Sweden since they already have introduced a large amount of wind power in their system. Figure 16 shows the development of wind power in the Danish electricity system from 1980 to 2008. The wind power in Denmark has increased from 610 GWh wind power in 1990 to 6 928 GWh in 2008. The real increase started in the middle of the 1990s.

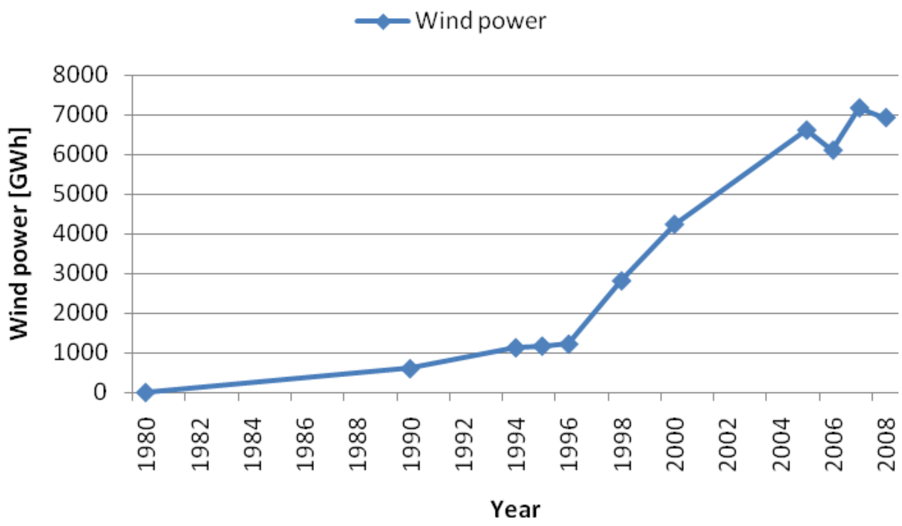

Figure 16: The development of wind power in Denmark from 1990 to 2008.

According to statistics from the Danish Energy Agency the total amount of CO_2 emissions per kWh from the electricity generation in Denmark has clearly decreased while the total amount of CO_2 emissions are varying from year to year depending on the amount of production. (Figure 17) In 1996 and 2006 the total production was higher which meant a larger total amount of CO_2 emissions in contrast to the amount per kWh.

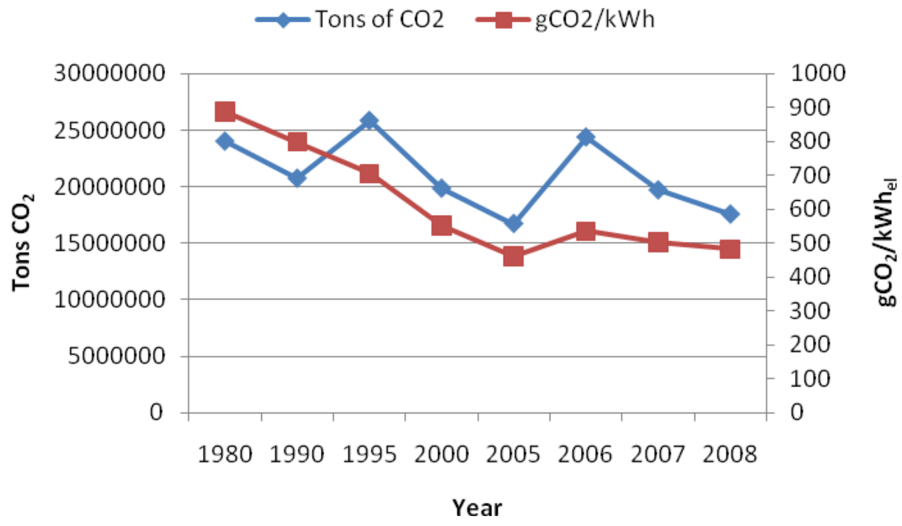

Figure 17: CO_2 emissions from the electricity generation in Denmark. The blue line shows the total amount in tons and the red line shows the amount per generated kWh electricity. Observe that the horizontal axis is nonlinear.

In Figure 18 the proportion of the energy sources can be seen. Wind power, natural gas and biomass have clearly increased their part of the total amount while coal and oil has decreased.

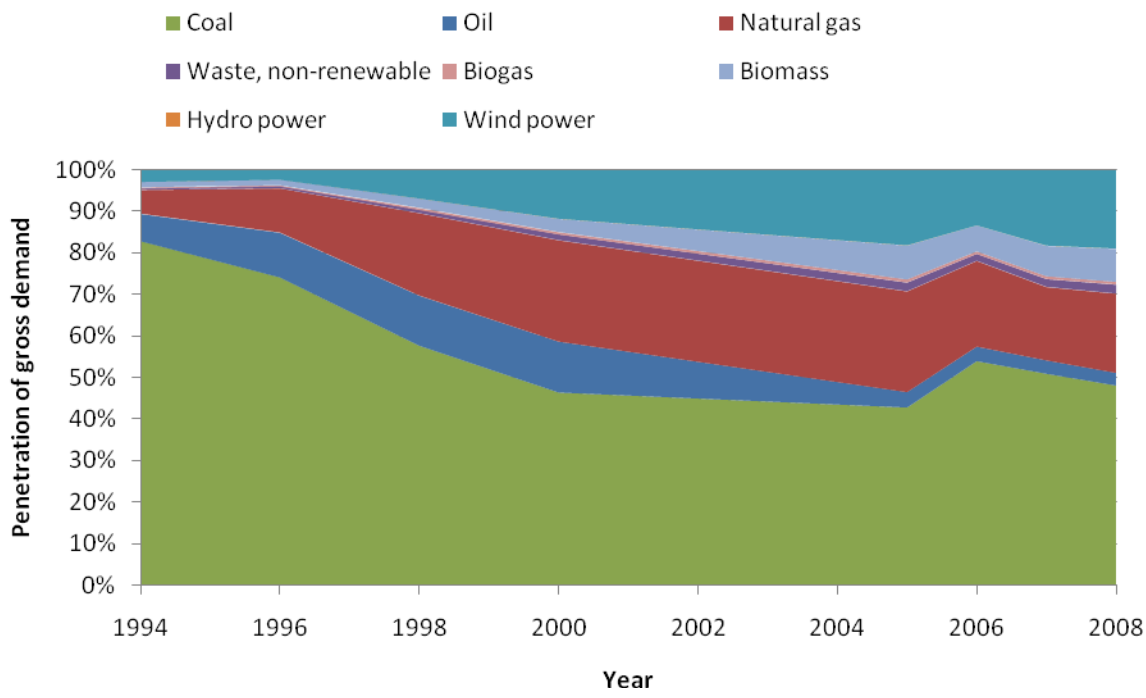

Figure 18: The electricity generation mix in Denmark from 1994 to 2008.

As can be seen in Figure 19, the total generated electricity was peaking in 1996 and 2006 and because of this the total amount of fossil fuels was in a higher level in those years. From the two black lines in the diagram it can be seen that the level of fossil fuels has decreased since 1994 and is at its lowest level in 2008.

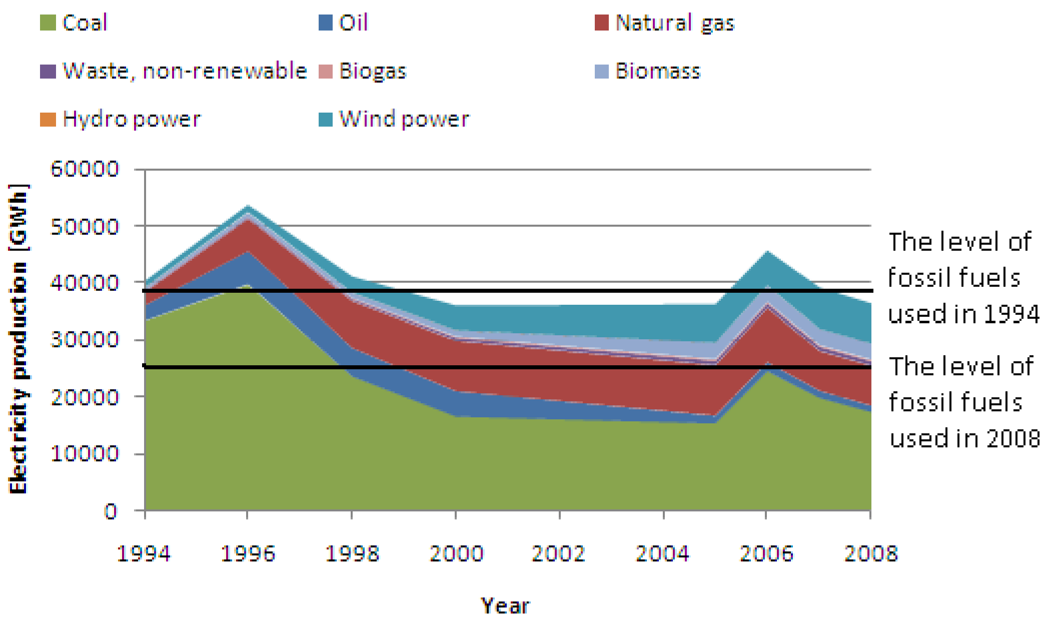

Figure 19: The different energy sources in GWh between 1994 and 2008.

In Figure 20 both the CO_2 emissions and the wind power production is plotted. As shown in the figure the CO_2 emissions are getting lower when the amount of wind power increases, but as stated above the mix has changed in other ways than the increased wind power production. This makes it difficult to evaluate what changed the CO_2 emissions.

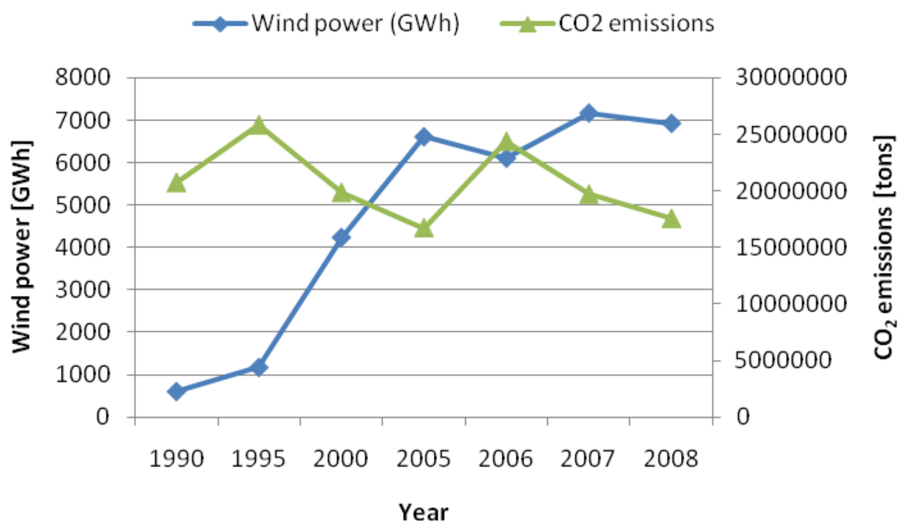

Figure 20: Shows how the CO_2 emissions from the electricity production in Denmark have changed compared to the development of wind power in the country. Observe that the time scale is non-linear.

6.2 Efficiencies in the coal-fuelled CHP units

From the beginning the central coal-fuelled CHPs were condensing units that were supposed to generate electricity and assure stability. Later on, they were changed to units that except from being electricity suppliers also became heat suppliers. In the early/mid 1990s more wind and local CHPs were introduced in the system and this changed the function of the CHPs. From then the CHPs, rather than solely supply electricity, are used to assure grid stability and regulation as well as supply heat. [33] The intention in this part is to make an effort to investigate if the different way of operating the CHPs has changed the efficiency of the power plants. To see how the electrical efficiency has changed, a plot was made (Figure 21), showing the efficiencies in the central CHPs in Denmark from year 1980 to 2008. The efficiency is varying and quite a lot from year to year depending on amount of production. The peaks can be explained by dry years since less hydro power from Norway and Sweden is imported then and consequently there is more production in the central CHP units which make the efficiency higher. A trend line (a polynomial of order 6) is plotted in the chart to see the trend.

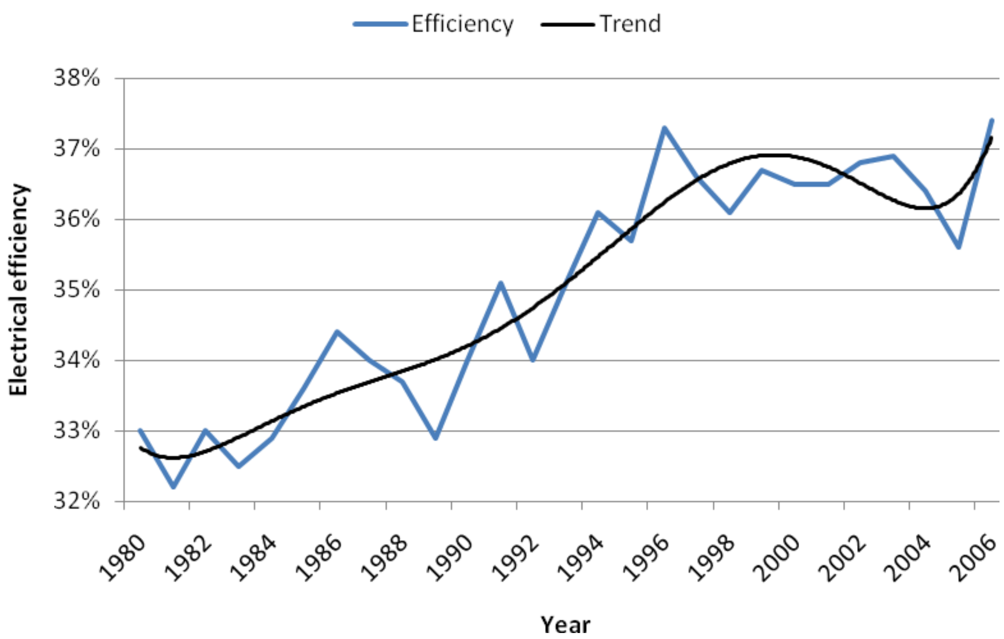

Figure 21: The electrical efficiency in coal fuelled power plants from 1990 to 2008. The trend line is a polynomial of order 6.

As can be seen in Figure 21 the rise in efficiency flattened in the middle/end of the 1990s. This was when the wind power production started to increase a lot. Assuming that these two things are connected the following scenario is created: The efficiency of the central CHPs would have increased at the same rate all the time from 1980 (the black line in Figure 22). This scenario has been chosen to show what would happen with a linear development of the increasing electrical efficiency.

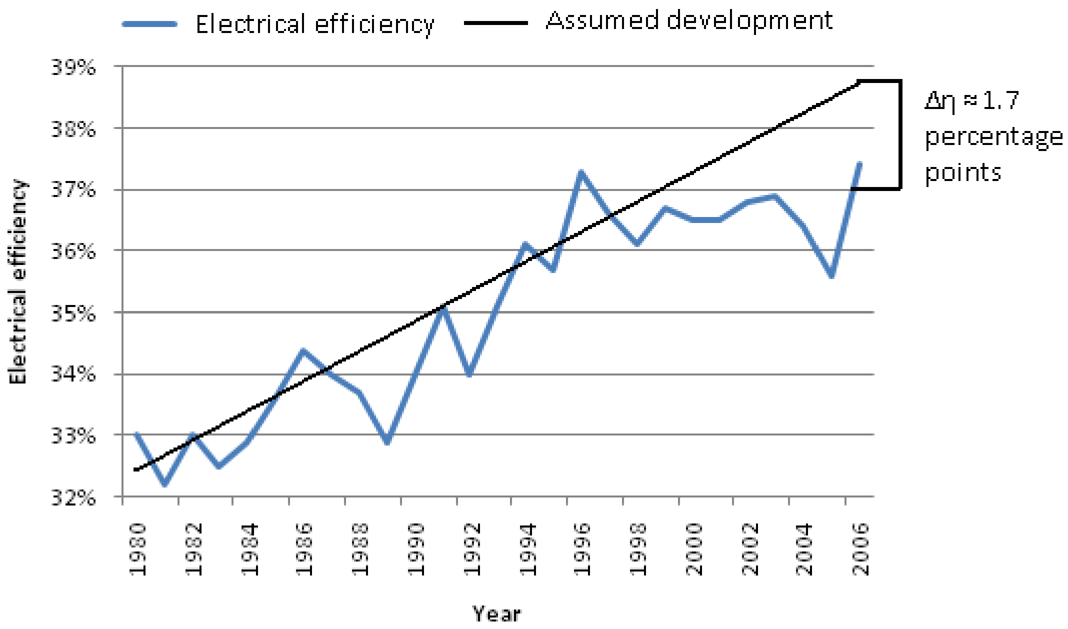

Figure 22: The efficiency in central CHPs compared to the assumed development in the scenario.

If the electrical efficiency would have continued to develop it would have become about 38.7 % instead of 37 %. This means that the efficiency would have increased with 1.7 percentage points without wind power introduced in the system compared to the system of today. The consequence of a lower efficiency is higher amount of carbon dioxide emissions.

The value of CO_2 emissions from a coal-fuelled power plant is calculated from

$$CO2_{coal} = \frac{S_{coal}}{\eta_{coal}} \cdot G_{coal} \qquad (9)$$

where S_{coal} is CO_2 content of the combustion from coal, η_{coal} is the efficiency with a separate production of electricity from coal and G_{coal} is the amount of electricity generated from coal.

A difference in efficiency changes the carbon dioxide emissions and Figure 23 shows the increase of carbon dioxide emissions per kWh in a coal fuelled CHP in full condensing mode when the efficiency is decreasing by 1 percentage point. For example, if the efficiency is decreasing from 37 to 36 % the CO_2 emissions are increasing with about 25 grams per kWh generated electricity in a coal fuelled CHP in full condensing mode.

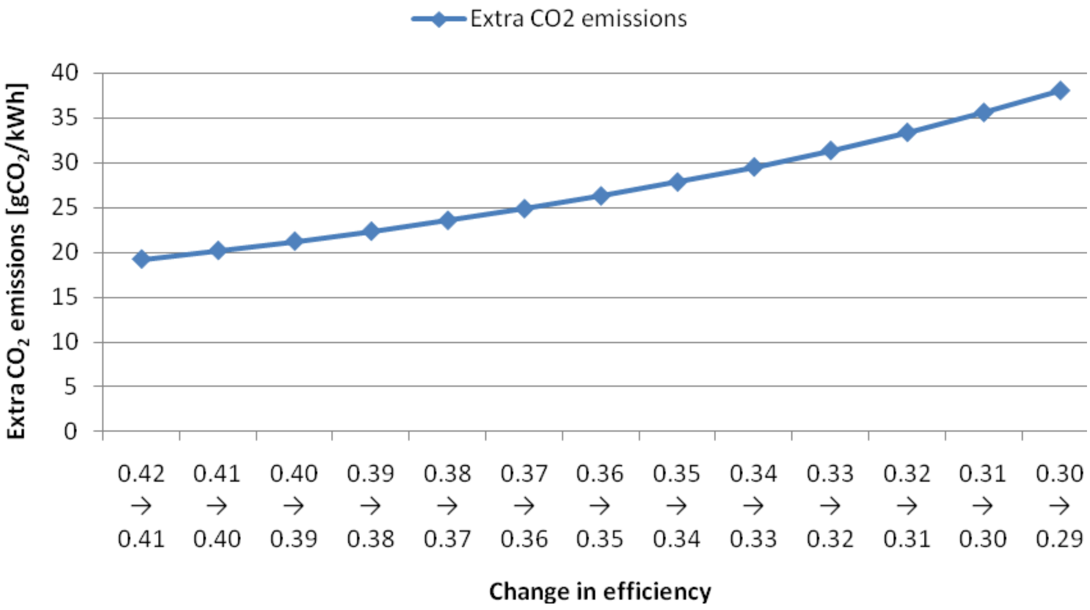

Figure 23: The diagram shows the extra CO_2 emissions per kWh electricity when the efficiency is lowered 1 percentage point.

In the scenario shown in Figure 22, the decrease in emissions would have been 39 gCO_2/kWh in a coal fuelled CHP in full condensing mode. In 2008, the total amount of electricity coal-fuelled power plants was 16.1 TWh and with a higher efficiency according to the above scenario[13] this would have reduced the CO_2 emissions with about 627 900 tons. However, wind power in the system has decreased the electricity generated from coal-fuelled power plants. If assuming that 1 kWh wind power has reduced the electricity from coal-fuelled power plants with 1 kWh at an efficiency of 37 % the total reduction of CO_2 emissions would be 5 634 262 tons even if the extra emissions arisen from a lower efficiency are added. There is an increase of CO_2 emissions from the CHPs because they are used to compensate for varying electricity production from wind power. However, according to the estimations above, this increase is very small as compared to the total reduction of CO_2 due to wind power.

[13] The coal-fulled power plants are expected to be operated in full condensing mode.

7 Discussion

The CO_2 emissions are in focus and most researchers agree on that the emissions need to be reduced. Different goals are set regarding reduction of CO_2 emissions and therefore it is important to investigate the effects that different tools results in. To be able to reduce the emissions globally it is important that all countries take their responsibility and do what they can, both within their boarders and globally.

7.1 Sweden

The aim of this part of the project was not to find out an exact prognosis of the future but to analyze some different scenarios. To see how a large scale introduction of wind power in Sweden could affect the electricity system and consequently the carbon dioxide emissions. The aim was to investigate if there were any trends rather than to give the absolute truth regarding the future. Since the electricity system is very complex with variables like weather, development and politics, a much more thorough investigation needs to be done to achieve more reliable results.

Even if the model is very simplified and many parameters are not considered the results give information about trends in different development directions. Furthermore a worst and best case scenario has been analyzed to set an upper and lower limit for the emissions of CO_2. In the project data from both the operation alone and the whole life cycle perspective was used. The reason for this was to see if the trends were different depending on what data that was used. When looking at the results, the same trends are found, both with the data from operation only and the whole life cycle.

7.1.1 Regulating power

According to Amelin [26] up to 12 000 MW wind power (corresponding to 30 TWh wind power per year) in the north of Sweden could be balanced by the already installed hydro power in Sweden. This information is used in the best case scenario (scenario 1) in this thesis when it is assumed that hydro power is managing all regulating power. However, in the other scenarios other conditions are set which leads to higher emissions than in scenario 1. In the worst case scenario (scenario 2) the regulating power is managed by gas turbines alone, but a development like this is not very likely since Sweden has a lot of hydro power. Furthermore gas turbines would not work as primary reserve since they take too long to start producing electricity. The reason for using gas turbines in scenario 2 is that together with the best case scenario they set a limit of the change in CO_2 emissions. However, in the remaining 6 scenarios (scenario 3-8) a combination of hydro power, thermal power and gas turbines are assumed as regulating power. This assumption is made since the most likely scenario is that the regulating power is managed by a range of different power sources due to limitations in the power distribution networks. Current limitation will however probably be reduced through investments in the distribution networks.

The amount of regulating power, estimated for 10 and 30 TWh wind power production (Table 7), and the total amount of electricity production will be compared.

Table 7: Amount of regulating power with 10 and 30 TWh wind power production.

	10 TWh WPP	30 TWh WPP
Primary reserve (TWh)	0.05	0.15
Secondary reserve (TWh)	0.2	1.2

The amount of predicted reserves to be used is no more than 1.5 TWh and the total electricity production is about 150 TWh (hydro power generates about 70 TWh of this amount). As can be seen the extra regulating power is a very small quantity compared to the total amount. The question is how much impact the regulating power would have on the entire system. It may not be the amount of regulating power that is actually used that is the problem, but the capacity needed in a worst case scenario. However, the amount of capacity needed has not been studied in this thesis.

7.1.2 Discussion of the results

In Table 8 the results from the 8 different scenarios are shown. The results show the change of carbon dioxide emissions per kWh wind power production if introducing 10 and 30 TWh wind power in the Swedish electricity system.

Table 8: Change of CO_2 emissions with 10 and 30 TWh wind power (gCO_2/kWh WPP). The results that are shown are from the operation only.

	10 TWh WPP	30 TWh WPP
Scenario 1	-722	-715
Scenario 2	28	50
Scenario 3	-3	8
Scenario 4	-53	-42
Scenario 5	-103	-92
Scenario 6	-198	-47
Scenario 7	11	23
Scenario 8	-418	-407

The results above only concern the operation but the same trends can be seen when looking at the whole life cycle. The difference is that the CO_2 values are a bit higher in the life cycle perspective. The substitution of energy sources is made by looking at the electricity generation mixes in the Nordic countries in 2008. The mixes are changing from year to year but in this project the newest data available were used even though it may have been interesting to use a mean value for a number of years. All scenarios will be analyzed more carefully in the following text.

The first scenario is the best case scenario where wind power replaces coal, oil and peat. The total amount of coal in the Nordic system was 25.2 TWh in 2008, which made the substitution to differ between the introduction of 10 and 30 TWh wind power. When introducing 30 TWh wind power, the residual 4.8 TWh not replacing coal-fuelled power plants, replaced oil and peat power production. The reduction of CO_2 emissions are about 700 gCO_2/kWh wind power production and this is the very best result with the stated conditions.

The second scenario is the worst case scenario; this scenario is used to get an upper limit of how much the wind power could increase the emissions. In this case nuclear power is replaced and this is because nuclear power has the lowest amount of CO_2 emissions. This scenario points at an increase of CO_2 emissions with about 30-50 gCO_2/kWh. Scenario 7 can be compared with this scenario since it also replaces nuclear power but the regulating power is managed by hydro power, thermal power and gas turbines. In scenario 7 the increase would become a little bit lower; 10-20 gCO_2/kWh.

In scenario 3, the substitution would be according to the Swedish electricity generation mix. Since the Swedish mix mostly consists of hydro power and nuclear power the change of CO_2 emissions is about zero. This scenario is not very likely since electricity will be exported and since the price of hydro and nuclear power are too cheap to be replaced.

In scenario 4, wind power replaces 50 % according to the Swedish electricity generation mix and 50 % according to the mixes of Denmark, Finland and Norway and in scenario 5, all wind power would be exported and substituted according to the mix of Denmark, Finland and Norway. Again, scenario 4 and 5 are far away from the reality since the price decides how the substitution will be made.

In scenario 6, it is assumed that there is no export and the sources that are substituted are the ones with the highest values of CO_2 emissions. Since the amount of fossil energy sources in Sweden is very low (totally 3.4 TWh) the result shows on a much larger reduction of CO_2 emissions when introducing 10 TWh than 30 TWh wind power production in the system. With 10 TWh wind power production the gain is about 200 gCO_2/kWh wind power production while the gain with 30 TWh is only about 50 gCO_2/kWh wind power production. This shows on a possible problem when introducing a large amount of wind power, the gain decreases since the already existing energy sources in Sweden contribute with a very low amount of CO_2 emissions. When looking at the operation the CO_2 emissions from a mean kWh electricity generated are about 14 g/kWh and from wind power it is zero. In the whole life cycle on the other hand the mean value is 24 gCO_2/kWh wind power production while wind power contributes with about 15 gCO_2/kWh. Even if the exact values in this thesis are uncertain it exist a limit where the positive effect on the CO_2 emissions of wind power subsides. According to the results in this thesis that limit when looking at the operation is lower than 10 TWh since we do not have more than 6.6 TWh fossil fuels. In the whole life cycle the limit is somewhat higher (about 15 TWh) since waste and biomass contributes with more CO_2 than wind power does.

In scenario 8, the wind power substitutes electricity production according to the Danish mix. This scenario results in a decrease of about 420 gCO_2/kWh wind power production. The large reduction of CO_2 emissions in this scenario is due to the large amount of fossil fuels in Denmark.

A more explicit investigation of the impact of large scale wind power production on the Nordic electricity system has been made by Hannele Holttinen [17]. Her results show on a reduction of 700 gCO_2/kWh wind power production with a low penetration and 620 gCO_2/kWh wind power production at a penetration higher than 10 %. When comparing Holttinen’s results with those of this thesis only the best case scenario reaches her values. There are many reasons for reaching different results. First of all, Holttinen makes a much more explicit investigation where she simulates the whole Nordic system together with the electricity market. She makes simulations that depend on time while this theses look at mean values. She is more focused on finding the very best value while the aim of this thesis is to get an idea of a value and to look at the difference of different scenarios. Furthermore Holtinnen's values of CO_2 emissions values from the fossil fuelled energy sources are a little bit higher compared to the values used in this thesis.

7.1.3 Weaknesses

The most important weakness of the model in this thesis is that no careful simulation over time has been made; instead mean values are being used. If doing a proper simulation many more parameters need to be taken into account. First of all the location of the wind power turbines is needed. It is not possible to know the exact location since no decisions have been taken where all turbines are going to be built. Furthermore the historical wind speed at the different areas needs to be considered to know how much electricity that can be generated at different places and how the transmission will be changed. Since the wind is varying from time to time, data sets from all the different places are needed and the best way is to take data from a number of years to be able to find out a reliable mean value. The electricity system is very complex and the electricity generated is depending on the electricity market, which set prices according to demand and supply. Demand and supply on the other hand depend on for example weather and political decisions. In addition the consequences for the existing power plants need to be investigated because efficiency and wear may change the conditions for operation. Much more time and knowledge are needed to make a model that takes all these issues into account. Therefore the aim of this thesis has been to find some trends with just a simpler model and to see what difference there is between different scenarios.

One thing that would have improved the model would have been to make a more careful investigation of the costs of different sources and from this decide the energy sources to replace. The problem is that prices are differing from time to time and varying charges for CO_2 emissions and similar things are a part of the price. Furthermore demand, weather and temperature govern the prices and it is hard to foresee.

A great problem with a large scale introduction of wind power is the transmission since bottlenecks can appear when new generation is connected to the grid. The capacity is adjusted to the conditions of today and depending on where the turbines are placed it could be necessary to strengthen the grid. In some places bottlenecks may appear in the grid certain times of the year while the capacity is more than enough at other times. This is another reason why mean values are not the best way to look at the problem. Since there could be enough capacity looking at the total amount of electricity to be transmitted, there may be peaks that creates bottlenecks many times during the year. As long as it is free capacity, the transmission could be affordable without any problems and the electricity reaches the place where the demand is. The capacity could be enough most time of the year but too small when it is needed because of the electricity flow changing, depending on parameters such as weather, demand and supply. How much more electricity is possible to export? In 2008 it was about 17 TWh [6], would it be possible to export 30 TWh more? This depends on when it is blowing and how the transmission capacity is developed.

In a wet year the flow from north to the south is much larger than in a dry year and with a lot of wind power in the north bottlenecks could appear in the section between the north and the south. If the grid is not strengthened it may be necessary to turn off the wind turbines or spill water. Rain and wind often occur at the same time.

When doing a true representation of the reality, it is really important to have the market in mind. To set the price on the market in reality, one has to take in account that all different producers act on the electricity market. The cheapest way of producing electricity decides how the plants will be operated. To create a model of the market is very complicated and demands a huge amount of data.

Finally there is one aspect that has not been considered in this model and that is whether the consumption will increase in the future. If the consumption increases, the wind power will not replace any other source just become an extra power source. In a prognosis from the Swedish Energy Agency the electricity consumption may increase from 146.2 TWh in 2007 to 157 TWh in 2025 [8] and with these 10 extra TWh the situation would change. With that in mind there would not be a change comparing to the emissions of today. However, the consumption will probably increase regardless of the development of wind power but with wind power covering the increase at least the CO_2 emissions will not increase.

7.2 Denmark

7.2.1 Change of electricity mix and CO_2 emissions

It is very difficult to say how much of the changes in the CO_2 emissions in Denmark are caused by the increased use of wind power. First of all there is the same problem as in the Swedish model, the complexity of the electricity system. Because of the interaction between the Nordic countries, a change in Denmark leads to a change in the surrounding countries as well. Most of the wind power is located in west Denmark, which is connected to Sweden, Norway and Europe but not east Denmark. The surrounding countries will very likely have to consider the Danish wind power production when operating the electricity system. In this part only the Danish electricity system has been considered, the gain of wind power may very well be larger looking at a larger system. However, it is a fact that the electricity generation mix in Denmark has changed since wind power was introduced, but at the same time other energy sources have been introduced as well. Biomass, waste and natural gas are other new energy sources in the Danish electricity system. Therefore it is hard to know the exact reasons for the emission reduction that can be observed.

The emissions per kWh generated electricity have an explicit negative curve while the total emissions are changing up and down depending on the consumption and production. The more electricity that is consumed the more generation is needed and therefore the total emissions are getting higher. When looking at the mix of electricity generated, the percentage of renewable sources are increasing which results in a decrease of emissions per kWh as well. The total amount of CO_2 emissions on the other hand has a greater variation from year to year. To be able to reduce CO_2, more than just changing to renewable sources is needed, the consumption also needs to decrease. An additional problem with wind power is the need of a certain amount of power to cover the base load. Since wind is varying it can be hard to foresee wind power electricity generation. Covering the base load must be secured and there is a risk that wind power to some extent is just added on the top of the already existing generation.

7.2.2 Efficiencies in CHP units

One problem with wind power production not being predictable is the need of using other types of power plants as regulating power. In Denmark, the central CHPs are used for this purpose together with hydro power in Norway and Sweden. However, the problem with CHPs is that the wear on the units becomes greater and the efficiency is lowered as a consequence of it being regulated up and down. Sometimes it is better to pay for other regulating power than operating the power plants in that mode [40].

In this project, an investigation of what has happened to the efficiency of the central CHPs during a 26 year period has been made. (Figure 22, chapter 6.2) The result points at a decrease of the development of the electrical efficiency at the same time as wind power was introduced in a larger scale in the system. A scenario with a continuing development such as the one from 1980 to 2000 was studied. The expected development without wind power in the system shows that the efficiency could have become 1.7 percentage points higher resulting in a decrease of 39 gCO_2/kWh electricity produced by a coal-fuelled CHP in full condensing mode.

The estimated efficiency in the scenario was 38.7 %. Comparing to three of Vattenfall's CHP units with 41-47 % possible electrical efficiency, in full condensing mode (Table 9), the estimated efficiency in the scenario would not have been impossible to reach. However, it is not very likely that the CHPs are operated in full condensing mode very often and therefore the number to compare the result to should be a bit lower. However, this is an area that has to be investigated much more thoroughly; this thesis is just scratching the surface.

Table 9: Three of Vattenfall's CHP units in Denmark and the highest possible efficiency (in full condensing mode). [33]

Unit	AMV 3	FYV 7	NJV 3
Possible electrical efficiency (full condensing mode)	42 %	41 %	47 %

7.3 Comparison

This thesis consists of two parts; the first part investigates the future effects on the CO_2 emissions with an introduction of a large scale wind power production in Sweden. In the second part the actual change of CO_2 emissions in Denmark, after an introduction of wind power in a larger scale, has been studied. The aim of this chapter is to bring the results from the two parts together and also to compare them.

In scenario 8 in the Swedish part (chapter 5), wind power substitutes electricity production according to the Danish mix. This scenario results in a decrease of about 420 gCO_2/kWh wind power production. 420 gCO_2/kWh wind power production corresponds to 120 gCO_2/kWh generated electricity in Denmark in the case of 10 TWh wind power production and to 350 gCO_2/kWh generated electricity in Denmark in the case of 30 TWh wind power production. This can be compared to the results in chapter 6.1 where the total amount of CO_2 emissions per kWh from the electricity generation has been plotted. The amount of CO_2 emissions per kWh generated electricity in 2008 was 482 g/kWh. In other words, if introducing 10 TWh wind power production in Sweden, Denmark will decrease their emissions with about 25 % and with 30 TWh wind power production the reduction will be about 73 %.

The investigation in the Swedish part resulted in a reduction of CO_2 emissions in all scenarios except from scenario 2 (worst case scenario), scenario 3 and scenario 7. In scenario 2 and 7 all wind power substituted nuclear power and then the emissions increased a little bit. In scenario 3 all wind power substituted electricity sources according to the Swedish electricity generation mix and there were almost no change in emissions. In the Danish part of the thesis it can be seen that the CO_2 emissions per kWh generated electricity have decreased after the wind power was introduced. It is hard to say how much change comes from wind power and how much comes from other changes in the system. However, wind power is contributing to some change in emissions even if it increases the emissions in the central CHPs because of regulating of the wind power. The two parts of the thesis points in the same direction; a reduction of CO_2 emissions with a large scale introduction of wind power and the more fossil fuels in the electricity system that can be substituted, the larger is the reduction of CO_2.

8 Conclusions

When introducing a large amount of wind power into an electricity system, technical problems will occur. The main technical problems are the transmission and regulating power capacity. Transmission capacity needs to be large enough to deliver electricity both to the consumers within the national power grid and abroad. Furthermore the wind power production is varying over time, which means that it has to be balanced in some way. This is done by regulating power and the electricity market and the more variations the more regulating power is needed.

As the work of this thesis progressed, it turned out to be a very complex and difficult work to make a reliable model of the future electricity system in Sweden. Since the electricity system is connected to the Nordic systems as well as Northwestern Europe, the system borders in this project may have to be widened. There are too many variables that have to be taken into account to get a reliable result, and the results in this thesis should be looked upon with this in mind. However, one conclusion can be made. The CO_2 emissions from the Swedish electricity production would decrease if the transmission capacity would be high enough to export electricity. The more coal-fuelled power that is substituted, the larger the decrease of CO_2 emissions becomes. In the worst case scenario no electricity production can be exported and the wind power replaces nuclear power. In this case there would not be any decrease in emissions; there would more likely be an increase. This is a very unlikely scenario though since the market rules what power that will be produced by selecting the cheapest way to produce electricity.

In Denmark the development of the electricity production mix shows a change from a lot of coal (a bit more than 80 % in 1994) to a mix with a larger amount of natural gas and renewable sources (natural gas together with renewable power was about 50 % in 2008). When looking at the CO_2 emissions from the electricity production it has decreased per kWh produced electricity while the total amount is more dependent on weather conditions. In a dry year in Sweden and Norway for example less electricity is produced from hydro power and Denmark cannot import as much hydro power as they usually do. Electricity produced from fossil fuels is exported instead, which influence the total CO_2 emissions in a negative way.

The development of the electrical efficiency in the central CHPs stagnated in the middle of the 1990s (as the wind power was increasingly introduced). The reason could be that they were needed to regulate the variations from wind power. Another reason could be that more heat was produced i.e. that the central CHPs have also been used to regulate the district heating systems. The subject studied in this thesis heeds more investigation and more detailed models including more information in order to draw more solid conclusions.

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Appendix 1 – Carbon dioxide emissions

Input values on CO_2 emissions (and sources) used in the thesis can be found in Table 10.

Table 10: Input values CO_2 emissions.

	Operation	**LCA**
Gas turbines [34]	1117	1333
Oil (Condensing) [34]	750	917
Coal (CHP) [35]	722	814
Peat (CHP) [34]	583	667
Natural gas (CHP) [34]	367	417
Waste [34]	0	196
Biofuel [34]	0	16
Wind power [36]	0	15
Hydro power [37]	0	6
Nuclear power [38]	0	3

Appendix 2 – Input data and results in the Swedish model

Regulating power

Installed wind power capacity [MW]	**4000**	**12000**
Wind power production [TWh]	**10 TWh**	**30 TWh**
Penetration of wind power in the Swedish electricity system	**6.84 %**	**20.53 %**
Primary reserve		
Installed capacity primary reserve [MW]	20	60
Production primary reserve [TWh]	0.05	0.15
Secondary reserve		
% of wind power production	2 %	4 %
Production secondary reserve (TWh)	0.2	1.2

Change of carbon dioxide emissions in the core process

CO_2 emissions from the regulating power

CO_2 emissions from regulating power scenario 1-2	**10 TWh WPP**	**30 TWh WPP**
Scenario 1: Best case		
Primary reserve		
Hydro power [TWh]	0.05	0.15
CO_2 emissions from primary reserve [tons]	0	0
Secondary reserve		
Hydro power [TWh]	0.2	1.2
CO_2 emissions from secondary reserve [tons]	0	0
Total amount of CO_2 emissions from regulating power in scenario 1 [tons]	0	0
Scenario 2: Worst case	**10 TWh WPP**	**30 TWh WPP**
Primary reserve		
Gas turbine [TWh]	0.05	0.15
CO_2 emissions [tons]	55 850	167 550
Secondary reserve		
Gas turbine [TWh]	0.2	1.2
CO_2 emissions [tons]	223 400	1 340 400
Total amount of CO_2 emissions from regulating power in scenario 2 [tons]	279 250	1 507 950

CO_2 emissions from regulating power scenario 3-8	10 TWh WWP		30 TWh WWP	
	Amount of reserve [TWh]	CO_2 emissions [tons]	Amount of reserve [TWh]	CO_2 emissions [tons]
Primary reserve				
Hydro power	0.050	0	0.150	0
Secondary reserve				
Hydro power	0.067	0	0.400	0
Coal	0.036	26085	0.217	156511
Oil	0.003	1935	0.015	11613
Natural gas	0.028	10260	0.168	61561
Gas turbine	0.067	74467	0.400	446800
Total amount of CO_2 emissions from regulating power in scenario 3-8 [tons]		112 748		676 485

Total change of CO_2 emissions in the different scenarios (operation)

Scenario 1: Best case	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Coal [TWh]	10	25.2
Oil + others [TWh]		2.8
Peat [TWh]		2
CO_2 emissions [tons]	7 220 000	21 460 400
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-7 220 000	-21 460 400
CO_2 emissions from wind power [tons]	0	0
CO_2 emissions from regulating power [tons]	0	0
Total change [tons]	-7 220 000	-21 460 400
Total change [g/kWh wind power production]	-722	-715
Change compared to total CO_2 emissions from electricity production in Sweden	-344.6 %	-1024.3 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-23.4 %	-69.5 %

Scenario 2: Worst case	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Nuclear power [TWh]	10	30
CO_2 emissions [tons]	0	0
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	0	0
CO_2 emissions from wind power [tons]	0	0
CO_2 emissions from regulating power [tons]	279 250	1 507 950

Total change [tons]	279 250	1 507 950
Total change [g/kWh wind power]	27.93	50.27
Change compared to total CO_2 emissions from electricity production in Sweden	13.3 %	72.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	0.9 %	4.9 %

Scenario 3: 100 % Swedish electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Swedish mix [TWh]	10	30
CO_2 emissions [tons]	143 409	430 226
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-143 409	-430 226
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	-30 661	246 259
Total change [g/kWh wind power]	-3.07	8.21
Change compared to total CO_2 emissions from electricity production in Sweden	-1.5 %	11.8 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-0.1%	-0.8 %

Scenario 4: 50 % Swedish electricity mix, 50 % Nordel-Sweden electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
50 % Swedish mix [TWh]	5	15
50 % Nordel mix [TWh]	5	15
CO_2 emissions [tons]	644 405	1 933 216
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-644 405	-1 933 216
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	-531 658	-1 256 730
Total change [g/kWh wind power]	-53.17	-41.89
Change compared to total CO_2 emissions from electricity production in Sweden	-25.4 %	-60.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	1.7 %	-4.1 %

Scenario 5: 100 % Nordel electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Nordel mix [TWh]	10	30

CO_2 emissions [tons]	1 145 402	3 436 205
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-1 145 402	-3 436 205
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	-1 032 654	-2 759 720
Total change [g/kWh wind power]	-103.27	-91.99
Change compared to total CO_2 emissions from electricity production in Sweden	-49.3 %	-131.7 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-3.3 %	-8.9 %

Scenario 6: Power with highest CO2-emissions first in Sweden	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Coal [TWh]	0.6	0.6
Oil + others [TWh]	1.6	1.6
Peat [TWh]	0.1	0.1
Natural gas [TWh]	1.1	1.1
Nuclear power [TWh]	6.6	26.6
CO_2 emissions [tons]	2 095 200	2 095 200
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-2 095 200	-2 095 200
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	-1 982 452	-1 418 715
Total change [g/kWh wind power]	-198.25	-47.29
Change compared to total CO_2 emissions from electricity production in Sweden	-94.6 %	-67.7 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-6.4 %	-4.6 %

Scenario 7: Nuclear power	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Nuclear power [TWh]	10	30
CO_2 emissions [tons]	0	0
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	0	0
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	112 748	676 485
Total change [g/kWh wind power]	11.27	22.55
Change compared to total CO_2 emissions from electricity production in Sweden	5.4 %	32.3 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	0.4 %	2.2 %

Scenario 8: 100 % Danish electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Danish mix [TWh]	10	30
CO_2 emissions [tons]	4 297 168	12 891 503
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	4 297 168	12 891 503
CO_2 emissions wind power [tons]	0	0
CO_2 emissions regulating power [tons]	112 748	676 485
Total change [tons]	-4 184 420	-12 215 018
Total change [g/kWh wind power]	-418.44	-407.17
Change compared to total CO_2 emissions from electricity production in Sweden	-200 %	-583.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-13.6 %	-39.5 %

Change of carbon dioxide emissions in the whole life cycle (LCA)

CO_2 emissions from the regulating power

CO_2 emissions from regulating power scenario 1-2	**10 TWh WPP**	**30 TWh WPP**
Scenario 1: Best case		
Primary reserve		
Hydro power [TWh]	0.05	0.15
CO_2 emissions from primary reserve [tons]	280	840
Secondary reserve		
Hydro power [TWh]	0.2	1.2
CO_2 emissions from secondary reserve [tons]	1 120	6 720
Total amount of CO_2 emissions from regulating power in scenario 1 [tons]	1 400	7 560

Scenario 2: Worst case	**10 TWh WPP**	**30 TWh WPP**
Primary reserve		
Gas turbine [TWh]	0.05	0.15
CO_2 emissions [tons]	66 650	199 950
Secondary reserve		
Gas turbine [TWh]	0.2	1.2
CO_2 emissions [tons]	266 600	1 599 600
Total amount of CO_2 emissions from regulating power in scenario 2 [tons]	333 250	1 799 550

CO_2 emissions from regulating power scenario 3-8	**10 TWh WWP**		**30 TWh WWP**	
	Amount of reserve [TWh]	CO_2 emissions [tons]	Amount of reserve [TWh]	CO_2 emissions [tons]
Primary reserve				
Hydro power	0.050	0	0.150	0
Secondary reserve				
Hydro power	0.067	373	0.400	2 240
Coal	0.036	29 409	0.217	176 454
Oil	0.003	2 366	0.015	14 199
Natural gas	0.028	11 658	0.168	69 948
Gas turbine	0.067	88 867	0.400	533 200
Total amount of CO_2 emissions from regulating power in scenario 3-8 [tons]		132 954		796 881

Total change of CO_2 emissions in the different scenarios (LCA)

Scenario 1: Best case	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Coal [TWh]	10	25.2
Oil + others [TWh]		2.8
Peat [TWh]		2
CO_2 emissions [tons]	8 140 000	24 414 400
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-8 140 000	-24 414 400
CO_2 emissions from wind power [tons]	150 000	450 000
CO_2 emissions from regulating power [tons]	1400	7560
Total change [tons]	-7 988 600	-23 956 840
Total change [g/kWh wind power production]	-798.86	-798.56
Change compared to total CO_2 emissions from electricity production in Sweden	-226.7 %	-680.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-21.0 %	-63.0 %

Scenario 2: Worst case	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Nuclear power [TWh]	10	30
CO_2 emissions [tons]	33 000	99 000
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-33 000	-99 000
CO_2 emissions from wind power [tons]	150 000	450 000
CO_2 emissions from regulating power [tons]	333 250	1 799 550
Total change [tons]	450 250	2 150 550
Total change [g/kWh wind power]	45.03	71.69
Change compared to total CO_2 emissions from electricity production in Sweden	12.8 %	61.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	1.2 %	5.7 %

Scenario 3: 100 % Swedish electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Swedish mix [TWh]	10	30
CO_2 emissions [tons]	241 246	723 739
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-241 246	-723 739
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881

Total change [tons]	41 707	523 142
Total change [g/kWh wind power]	4.17	17.44
Change compared to total CO_2 emissions from electricity production in Sweden	1.2 %	14.8 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	0.1 %	1.4 %

Scenario 4: 50 % Swedish electricity mix, 50 % Nordel-Sweden electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
50 % Swedish mix [TWh]	5	15
50 % Nordel mix [TWh]	5	15
CO_2 emissions [tons]	806 835	2 420 505
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-806 835	-2 420 505
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881
Total change [tons]	-523 881	-1 173 624
Total change [g/kWh wind power]	-52.39	-39.12
Change compared to total CO_2 emissions from electricity production in Sweden	-14.9 %	-33.3 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-1.4 %	-3.1 %

Scenario 5: 100 % Nordel electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Nordel mix [TWh]	10	30
CO_2 emissions [tons]	1 372 424	4 117 271
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-1 372 424	-4 117 271
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881
Total change [tons]	-1 089 470	-2 870 389
Total change [g/kWh wind power]	-108.95	-95.68
Change compared to total CO_2 emissions from electricity production in Sweden	-31.0 %	-81.4 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-2.9 %	-7.6 %

Scenario 6: Power with highest CO2-emissions first in Sweden	**10 TWh WPP**	**30 TWh WPP**

Energy sources replaced by wind power		
Coal [TWh]	0.6	0.6
Oil + others [TWh]	1.6	1.6
Peat [TWh]	0.1	0.1
Natural gas [TWh]	1.1	1.1
Waste [TWh]	1.4	1.4
Biofuel [TWh]	5.2	5.2
Nuclear power [TWh]		15.6
CO_2 emissions [tons]	2 568 820	2 690 700
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-2 568 820	-2 690 700
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881
Total change [tons]	-2 285 866	-1 443 819
Total change [g/kWh wind power]	-228.59	-48.13
Change compared to total CO_2 emissions from electricity production in Sweden	-64.9 %	-41.0 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-6.0 %	-3.8 %
Scenario 7: Nuclear power	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
Nuclear power [TWh]	10	30
CO_2 emissions [tons]	33 000	99 000
Change of CO_2 emissions		
CO_2 emissions nuclear power [tons]	-33 000	-99 000
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881
Total change [tons]	249 954	1 147 881
Total change [g/kWh wind power]	25.00	38.26
Change compared to total CO_2 emissions from electricity production in Sweden	7.1 %	32.6 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	0.7 %	3.0 %

Scenario 8: 100 % Danish electricity mix	**10 TWh WPP**	**30 TWh WPP**
Energy sources replaced by wind power		
100 % Danish mix [TWh]	10	30
CO_2 emissions [tons]	5 005 436	15 016 308
Change of CO_2 emissions		
CO_2 emissions from replaced sources [tons]	-5 005 436	-15 016 308
CO_2 emissions wind power [tons]	150 000	450 000
CO_2 emissions regulating power [tons]	132 954	796 881
Total change [tons]	-4 722 482	-13 769 426
Total change [g/kWh wind power]	-472.25	-458.98
Change compared to total CO_2 emissions from electricity production in Sweden	-134.0 %	-390.7 %
Change compared to total CO_2 emissions from electricity production in the Nordic countries	-12.4 %	-36.2 %

Appendix 3 – Danish statistics

Statistics of electricity production by fuel, observed CO_2 emissions from energy consumption and the electricity efficiency in central CHPs from 1980 to 2006 can be found in Table 11, Table 12 and Table 13.

Table 11: Electricity production by fuel [GWh] [9]

Production	1994	1996	1998	2000	2005	2006	2007	2008
Oil	2652	5780	4974	4434	1370	1614	1282	1128
Natural gas	2279	5678	8128	8775	8779	9401	6909	6928
Coal	33290	39665	23653	16673	15463	24566	19898	17463
Waste, non-re-newable	190	313	359	509	747	754	728	769
Wind power	1137	1227	2820	4241	6614	6108	7171	6928
Hydro power	33	19	27	30	23	23	28	26
Biomass	526	748	922	1138	2960	2854	2868	2900
Biogas	89	113	189	209	283	285	272	249
Total	42190	55539	43069	38009	38244	47613	41163	38397

Table 12 shows the CO2 emissions from electricity production in Denmark and in Table 13 the electrical efficiency in the central CHPs from 1980 to 2006 can be found.

Table 12: CO_2 emissions. [9]

CO_2 emissions	1980	1990	1995	2000	2005	2006	2007	2008
1000 tons	24038	20741	25867	19855	16724	24401	19711	17558
(gCO_2/kWh_{el})	887.5	798.4	705.5	550.8	461.5	535.0	503.4	482.5

Table 13: Electrical efficiency in the central CHP from 1980 to 2006. [39]

Year	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**
Efficiency	33.0 %	32.2 %	33.0 %	32.5 %	32.9 %	33.6 %	34.4 %	34.0 %
Year	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
Efficiency	33.7 %	32.9 %	34.0 %	35.1 %	34.0 %	35.1 %	36.1 %	35.7 %
Year	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Efficiency	37.3 %	36.6 %	36.1 %	36.7 %	36.5 %	36.5 %	36.8 %	36.9 %
Year	**2004**	**2005**	**2006**					
Efficiency	36.4 %	35.6 %	37.4 %					