Final report

Integrating Wind Power into the Dutch System

(non confidential version)

22 November 2005

TenneT

Summary

The total wind power capacity currently installed in the Netherlands comes to around 1200 MW. The wind power capacity installed in the Dutch electricity system is expected to increase sharply over the next decade, both onshore and offshore. Operating electricity systems in which a high percentage of the power is obtained from wind energy imposes additional requirements on the rest of the connected system. The requirements are concerned with the grid (transmission capacity) as well as the rest of the generating equipment (installed capacity and controllability) in the system. The project has investigated the extent to which wind power can be further integrated into the Dutch system on a large scale.

This study provides an initial estimate of the technical possibilities available in the Dutch generating units for the large-scale integration of wind power in the Dutch electricity system. The research question was:

> *What is the maximum wind power capacity that can be integrated into the Dutch system in 2012, without exceeding the technical limiting conditions of the electricity system, and while utilising the Dutch power generating system?*

Data on loads, power generating units and wind patterns were collected and processed to answer this question. The data provided input for an existing simulation package (PowrSym), which is used for determining the deployment of power generating units for various wind penetration levels. The problems anticipated from high wind penetration levels are control problems (lack of flexibility of the thermal generating units) and minimum-load problems at times of low loads and high winds.

It can be concluded from the simulations that the amount of wind power that can be integrated in the power generating system in the Netherlands in 2012, without additional measures being taken, is around 4000 MW (half of which will be offshore). When the figure exceeds 2000 MW of wind generated power, additional measures will increasingly be required at times of low loads and high winds, to ensure wind power can be integrated safely.

This study can be considered as a basis for further analyses, in which market and grid aspects will also be taken into account. Further research should show the extent to which further measures are being taken by the market, under the influence of the existing system of programme responsibility. TenneT and Delft University of Technology (TU Delft) will conduct this research over the next few years. There are also plans to conduct similar analyses with other transmission system operators (TSOs) on a European scale.

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1. Introduction

In its 2005 energy report, Now for Later (*Energierapport 2005 "Nu voor later"*), the Dutch government set itself the goal of making energy management sustainable in the medium-long and long-term. A sharp increase in the share of wind power is mentioned as one of the means of achieving the goal. The aim in the original government plans was initially to have an installed capacity of 7500 MW by the year 2020, of which 6000 MW would be in the form of wind turbines offshore. The government has since abandoned its fixed goal for wind power. However, in view of long-term government objectives, the installed capacity of wind power generators seems likely to increase considerably. The present study examines the issues concerned with integrating this extra wind power into the Dutch system.

Operating electricity systems in which wind power accounts for a high percentage of the power calls for additional requirements in the rest of the connected system. The requirements are concerned with the grid (transmission capacity) as well as the rest of the generating equipment (installed capacity and controllability) in the system. This study examines the technical possibilities of thermal generating units for maintaining system balance at various wind power penetrations. The study is intended as an initial technical analysis and is not concerned with the economic consequences of the technical possibilities that have been examined. The study forms a good basis for further analyses, which will be conducted over the next few years and will also take into account market and grid aspects.

The report is arranged as follows. Chapters 2 and 3 further specify the subject of the study and define the question. Chapter 4 presents an initial estimate, based on load-duration curves, of the anticipated problems of integrating wind power. Chapters 5 and 6 discuss the development of wind power data and the predictability of the wind. Chapter 7 provides a quantitative overview of the investigated system, which is used as input for the PowrSym simulation program. Chapter 8 examines the starting points and results of the simulations that have been made. Chapter 9 discusses the conclusions of the study.

Arnhem / Delft, 22 November 2005

2. Delineation

2.1 Electricity supply system

A complete electricity supply system involves many aspects, not only the generating units, grids and consumers but also the market and trading. A complete electricity supply system therefore involves technical, economic and organisational aspects. The figure below shows a complete electricity supply according to Kling's description.

Primary energy (heat from gas/coal/nuclear reactions and kinetic energy from wind) is converted into electrical energy in an electricity supply system. The energy is traded and distributed to consumers, including consumers in other countries. It is important to ensure that capacity balance is constantly maintained. The grid authority is responsible for providing a reliable electricity supply, which includes both system services and transmission services. Various aspects of the electricity supply system are important for this project: Integrating Wind Power into the System. The aspects are shown in the figure below. The project is concerned with the large-scale integration of wind power into the Dutch electricity system. Wind speed data are used to determine the amount of wind power that is available at any time. A wind turbine model provides figures on the amount of wind power that is currently available. In addition to wind and wind turbines, the project also focuses on the possibilities offered by other power generating units, namely thermal power stations. These power stations should be able to compensate for fluctuations in wind power and variations in loads, to ensure the capacity balance is constantly maintained. An indication per aspect is provided below of which components are dealt with and how.

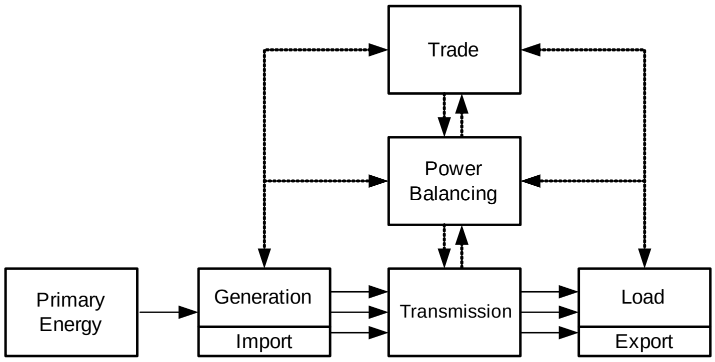


Figure 2.1: Electricity supply system

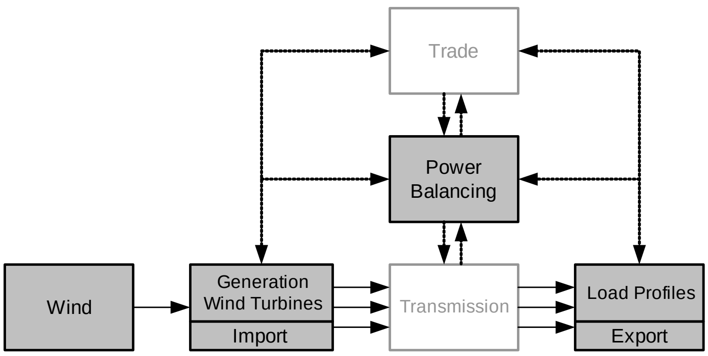


Figure 2.2: Delineation of this project

2.2 Maintaining balance

This project is specifically concerned with one aspect of the electricity supply system, namely maintaining balance. Whereas it is possible to directly control the primary energy in conventional generating units, and to thereby control electricity production, the primary source of wind energy is variable and unpredictable. This complicates balance maintenance. The project focuses specifically on balance maintenance with large-scale wind energy production in the Dutch system by using the other power generating units in the Dutch system.

The capacity balance is not only maintained at the level of the system in the Netherlands but also at the level of the UCTE (Union for the Co-ordination of Transmission of Electricity). The primary control reserve is kept at the UCTE scale, in which each control area has a particular share, and each control area regulates its secondary control reserve separately. The primary control reserve responds immediately (within 30 seconds) to stabilise the frequency in the case of a large-scale wind imbalance. As this happens at the UCTE scale, the deployment of primary control capacity influences the exchange of power between the various control areas; this means that interconnector capacity must be available for the primary reserve. After this, the secondary control reserve in the affected control area takes over, to ensure that the frequency and exchange values between the control areas are restored within 15 minutes.

The standard adopted for this project was the UCTE requirement for secondary reserve, namely the restoration of the exchange schedules and frequency within 15 minutes of a wind power imbalance. The project examined the extent to which thermal generating units are capable of compensating for the system imbalance within the UCTE requirement (wind power and demand profiles). It has been assumed in this project that fluctuations in wind power of less than 15 minutes are not critical in the investigation of imbalances caused by large-scale wind power. To verify that the critical period truly is 15 minutes, the fluctuations in wind power that can be expected within seconds, minutes, quarter hours, hours and days have been surveyed.

2.3 Production: thermal generating units and wind turbines

Production is defined for the purpose of the project as all the thermal generating units that will be in operation in the Netherlands in 2012, plus all the installed wind power capacity. The power generating system includes all the thermal generating units (gas, coal, nuclear etc.). This also takes into account the number of power stations that are not operating (owing to maintenance for example) and the likelihood of power station outages. Taking this definition of production as its basis, the project then examines the control range of the entire power generating system that is operating. This is followed by an assessment of how much of the installed wind power capacity can be deployed, whereby the requirements for maintaining balance serve as a check. Fluctuations in supply but also, for example, shut-downs owing to storm fronts are taken into account in determining deployable wind power capacity. It has been assumed that the supply of wind power will not be restricted at any time: wind power production varies with the amount of wind.

2.4 Consumption and exchange

The effect of the load and exchanges of electrical power with other countries have to be taken into account in determining the maximum deployable wind power capacity. For example, a low load, high import level and a plentiful supply of wind power means that the minimum number of conventional generating units will be in operation in the Dutch system. In such a situation, the allocation of secondary control reserves is more likely to be a problem than when the load is high and imports are low. This project also takes into account consumption curves and exchange programmes.

2.5 Transmission (grid aspects)

The physical transmission of electricity through the grids is beyond the scope of this project. The system of production, import, consumption and export is assumed to be connected by a 'copper plate'. It has been assumed that sufficient transmission capacity is available for delivery/receipt of the primary reserve at the UCTE level. Fluctuations in large-scale wind power would obviously affect the available transmission capacity and the capacity required for the primary reserve. The latter point will be discussed later, after an analysis of wind data.

Congestion and transmission losses are not discussed in the project. A possible follow-up project could examine grid aspects; this would enable a determination to be made of the extent to which the Dutch grid presents obstacles to deploying conventional power stations for balance maintenance (required interconnection capacity for the primary reserve and grid reinforcement for the integration of large-scale offshore wind power).

2.6 Trade (market aspects)

In a liberalised market like that of the Netherlands, the market players determine which generating units will produce electricity at a given time and how much, to continue to provide their contracted load. The system of programme responsibility is important in this process; the parties with programme responsibility individually ensure that their net exchange with the system is in accordance with their E-programme: what is produced is also consumed. Because wind energy also comes under programme responsibility, the parties with programme responsibility take measures individually to eliminate the imbalance of wind power in their portfolio. The extent to which the Dutch system will have to be able to compensate for imbalances on account of wind power depends on the composition of the portfolio, possibilities for exchanges, imbalance prices in the market, etc.

Although market aspects play a major role in the degree to which it is possible to compensate for imbalances caused by wind power, these aspects are beyond the scope of this project. The control regime that has been assumed for wind turbines is that all wind turbines produce power according to the amount of wind; i.e. maximum possible production at any given time. Central dispatching of generating units has also been assumed, in the way that it was applied for liberalisation. This approach enables the technical possibilities[1] to be determined. A follow-up project could examine the extent to which the technical limitations could be influenced, by market player's investments for example.

1 *This means that the deployment possibilities (flexibility) of power stations are assumed to be fixed in the dispatch model that has been used, whereas they may actually be adjustable subject to costs.*

3. Research question

This project has examined the extent to which it is possible to use the Dutch power generating units to accommodate electricity produced by wind power and fluctuations in wind power production. This is necessary to maintain the capacity balance between power generation and consumption in the Dutch system. The starting point adopted for determining the available technical flexibility for achieving this is central dispatching from generating units. Follow-up research will determine the extent to which the market (programme responsibility, trading) and/or the grid (transmission capacities) are able to influence the technical possibilities calculated here, and how. The research question is:

What is the maximum wind power capacity that can be integrated into the Dutch system, without exceeding the technical limiting conditions[2] of the electricity system, and while utilising the 2012 Dutch power generating system?

Although this project only considers the situation in 2012, it will also provide an impression of the situation after 2012. If demand continues to increase after 2012, the probable worst case (maximum wind with minimum load) that has been anticipated will be less of a determining factor than in 2012.

The key research question gives rise to the following secondary questions:

- What does the demand curve look like and what unpredictability and variations does it involve?
- What is the variation in wind power on a time scale of 15 minutes?
- What is the unpredictability of the wind power on different time scales?
  (quarter hours, hours and days)
- What will the Dutch power generating system of conventional generating units look like in 2012?
- What are the technical possibilities of the entire power generating system?
  (minimum downtime, minimum uptime, ramp rates)

Installed capacity currently amounts to around 1.2 GW onshore 0 GW and offshore. This project has investigated various amounts of installed capacity, namely:

- 0 GW onshore, 0 GW offshore
- 2 GW onshore, 0 GW offshore
- 2 GW onshore, 1.25 GW offshore
- 2 GW onshore, 2 GW offshore
- 2 GW onshore, 3 GW offshore
- 2 GW onshore, 4 GW offshore
- 2 GW onshore, 6 GW offshore

[2] *See footnote 1*

4. Load and wind power duration curves

An examination of the influence of large-scale wind power on the load curve was the first step in considering the influence of large-scale wind power on maintaining balance in the Dutch system. The load curve indicates what loads occur and for how long during the year (expressed in hours in this case). The load curve for 2012 was extrapolated from load data for 2003, assuming a predicted growth of 2.0% from 2006 to 2012 on the basis of scenarios from TenneT's capacity plan for 2006-2012. Part of this load was covered by wind power production; the rest will have to come from distributed generating units, imports and thermal generating units.

Ten-minute based time series for wind speeds were used for the development of wind power data. The data were measured at various locations onshore and offshore from June 2004 to May 2005 (Royal Dutch Meteorological Institute: KNMI) and a power curve was used to translate the data into wind power. Using this power curve, the operating time for the maximum number of wind turbines onshore worked out for the wind year used at 25%, whereas the figure for offshore came to 46%; these orders of magnitude can be expected on the basis of experiences in the Netherlands (onshore) and Denmark (offshore). The magnitudes will obviously differ each year. Using different power curves would result in different operating times for the maximum. Starting at the top, figure 4.1 shows the load duration curve for 2012 and four load less wind power curves (2000 MW onshore and 0 / 2000 / 4000 / 6000 MW offshore).

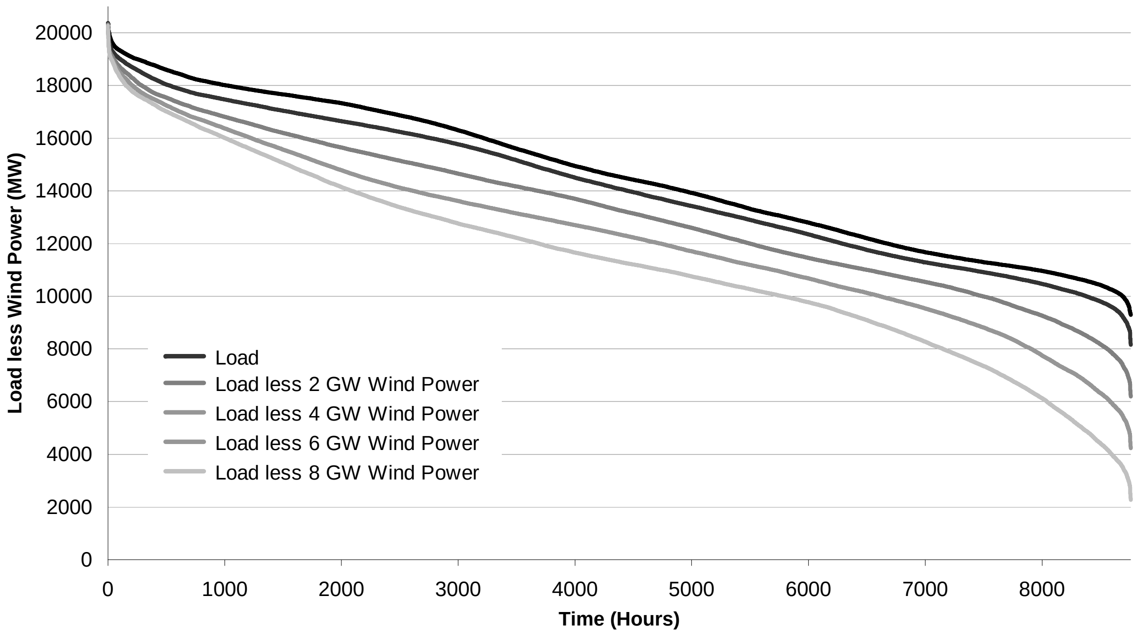


Figure 4.1: Load duration curve (black) and load less wind power duration curves (shades of grey) for various amounts of installed capacity.

The maximum load in 2012 is around 20,400 MW. Because the maximum load occurs relatively infrequently, the likelihood of maximum wind power occurring at the same time is small, which means that the maximum load less wind power is only slightly below the maximum load. Conversely, lower loads occur relatively often, which means that the likelihood of maximum wind power at such moments is relatively high. Load less wind power is covered by the distributed generated power, imports and conventional generating units. This means that these generating units are required to deliver less power and/or less has to be imported. As is clear from figure 2.1, the load sum and wind power capacity entail that the production capacity range of Dutch generating units, plus imports and the demand response, must increase in line with increases in the amount of installed capacity. It should be pointed out with regard to figure 2.1 that the load and wind power would work out differently for a different choice of load and/or wind years; however, the curves provide a good overall picture of the impacts of wind power on the capacity durations of the remaining generating units and imports.

5. Load and wind power variations

Variations in wind power depend on various factors, such as variations in wind speed, the geographical distribution of the wind turbines, the power curves of the wind turbines and the effects of wind turbines on each other (wind shadow). This chapter explains the calculated method used and presents the results for different offshore and onshore wind power capacities.

5.1 Method of calculating wind power

Variations in wind power depend primarily on wind variations. The data provided by the Royal Dutch Meteorological Institute (KNMI) for ten-minute intervals were used for wind speeds. Wind speeds were used for setting up a wind model, which was in turn used for calculating the wind speeds at axis height for the onshore and offshore locations. Because measurements are not possible at these locations, interpolations from existing measurements were made to obtain the wind speeds at the locations of wind farms. These calculations made allowances for the spatial correlation between wind speeds at various measurement locations, in connection with the small geographical size of the Netherlands. The ten-minute data were finally converted into quarter-hour values.

Wind data were first used to determine the extent to which a daily wind pattern exists. Figure 5.1 shows how different heating patterns of the land and sea affect wind speed onshore and along the coast. In addition to a daily effect, a seasonal effect that depended on the day of the year also emerged. The wind model therefore distinguishes between the sea, coast and locations on land, while taking the day of the year into account, whereby it should be noted that the energy content of a year is equal to the model of that year. The wind model was then used to interpolate wind speeds based on quarter hour intervals at the locations of wind farms.

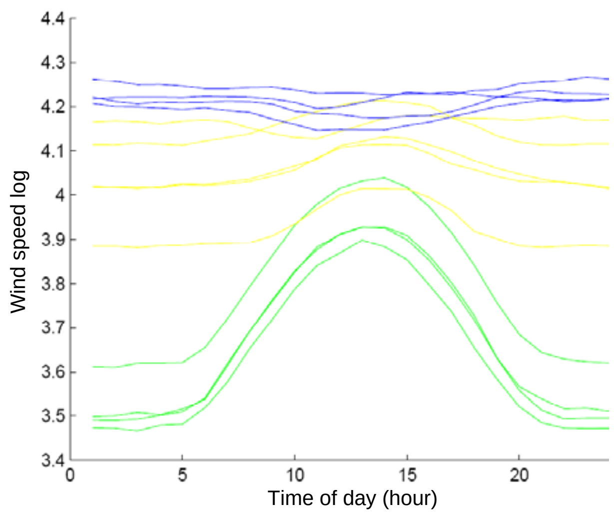


Figure 5.1: Average daily effect for wind speeds offshore (top, blue), along the coast (middle, yellow) and onshore (bottom, green).

Wind speeds were converted into wind power using a power curve, which shows the amount of power generated for different wind speeds. The cut-in speed, cut-out speed and rated wind speed are especially important for this power curve in connection with wind power fluctuations; the shape of the curve means that wind speed changes are translated into relatively large changes in electrical power at certain wind speeds. The level of production at wind farms varies with the variations in wind power of the different turbines; wind turbines on wind farms are set up differently to prevent large power fluctuations occurring simultaneously (e.g. almost simultaneous cut-out) in the wind turbines (Denmark).

There are currently many different types of wind turbines on the market, with different power curves. It is reasonable to assume that different wind turbines with different power curves are used for large-scale wind power. Besides the various set-ups for a given type of wind turbine on wind farms, each individual wind farm will include various types of wind turbines. Including these differences in this project would be difficult and time-consuming; moreover, developments are progressing rapidly in different types of onshore and offshore wind turbines. This research is therefore based on the same power curve for all wind turbines. However, it has been modified to approximate the effects of a collection of different types of power curves. Figure 5.2 shows the power curve used for this research.

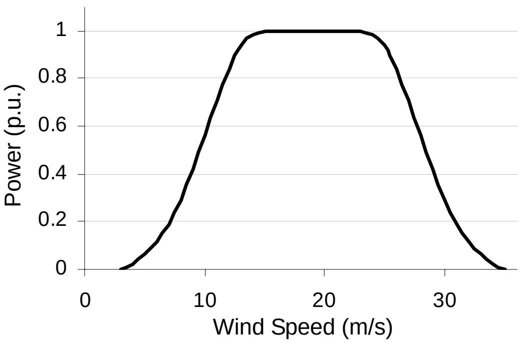
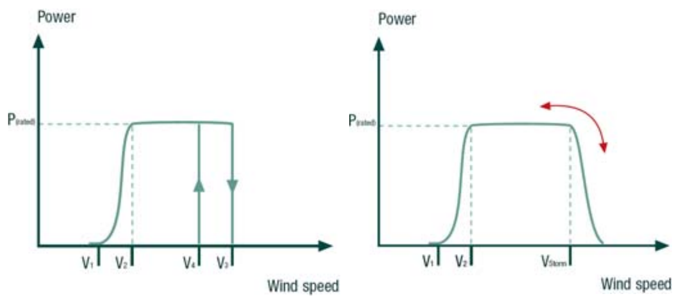


Figure 5.2: Power curve used

The power curve used differs from a typical power curve of today's wind turbines. However, the moment of cut-out on wind farms is also determined by the shadow effects of the wind turbines on each other and the way the turbine has been set-up, so there is no 'sharp' cut-out speed. The power curve used has been used in this research while making allowances for the development that wind turbines now only cut out at increasingly higher wind speeds and more evenly (compare the curves in figure 5.3).

Figure 5.3: Switching wind turbines on and off with cut-out and (left, cut-out speed V3, cut-in after cut-out speed V4) switching off evenly through a decrease in the rotational speed of rotor blades at high wind speeds (right). The figures are for Storm Control *on turbine type E70, ENERCON, http://www.enercon.de)*



The locations of onshore wind turbines in this research were determined by extrapolating the present distribution of onshore wind turbines per province to 2 GW. Offshore, the wind turbines were installed on wind farms at the locations proposed in Connect 6000. By far most wind farm locations would then be in an area of approximately 70 x 80 km^2, to the west of The Hague – Egmond, and a small section of the Wadden Sea, north of Groningen.

5.2 Summation of variations in load and wind power

Variations in loads and wind power create a need for control capacity, expressed as the number of MW divided by a given unit of time. The control requirement was determined on a 15-minute basis for this project (MW/15 min.). The total control requirement depends on the sum of the load and the wind power; variations in wind power and load will sometimes cancel each other or compound each other. The simultaneity of the variations was investigated to determine the control requirement for the total of the power variations in load and wind power together. Although the load and wind power data from different years have been linked in this study, this has little, if any, effect on the usefulness of the results, as it is very likely that *variations* in wind power and load are not correlated. The study involved a very large number of combinations of variations in loads and wind power (8,760 hours multiplied by 4 15-minute intervals = 35,040 combinations). The figure below shows a comparison of the control requirement for only the load and the control requirement at the same load moment less wind power onshore (2 GW) and offshore (6 GW); this provides an initial impression of the highest amount of wind power that was investigated.

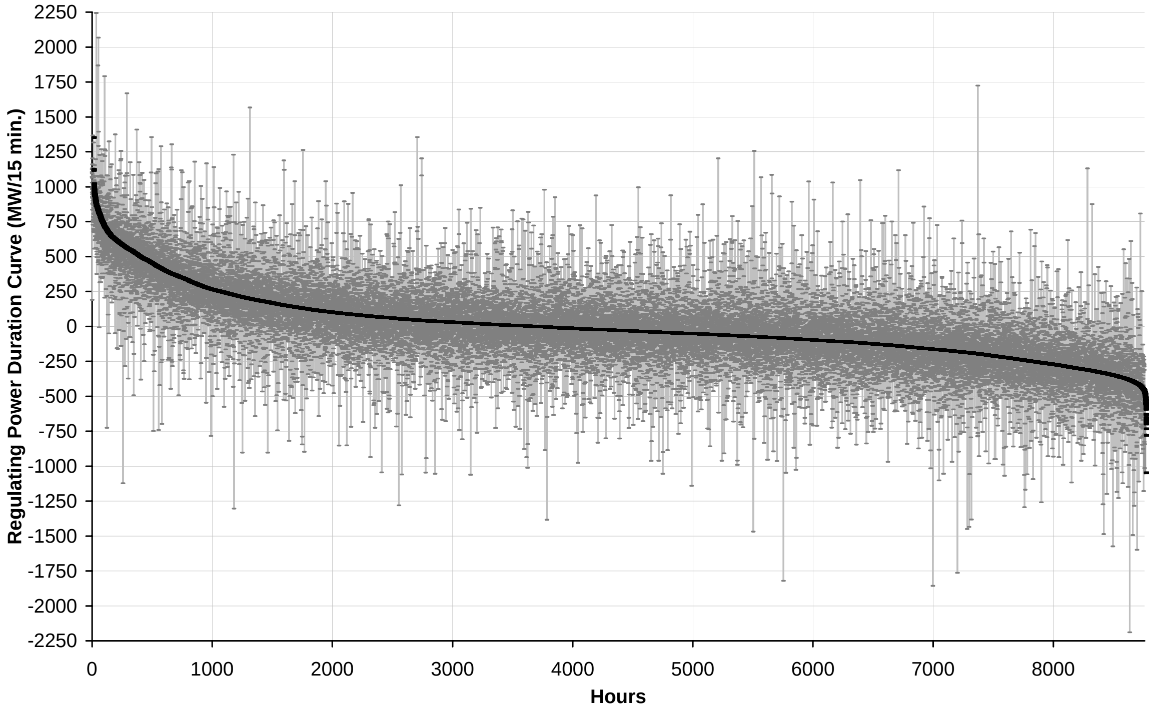


Figure 5.4: Comparison of control requirements of load alone (black line) and load, 2 GW wind power onshore and 6 GW offshore (grey). The control requirement for load alone is shown in descending order, the grey dots indicate the difference caused by 8 GW of wind power vis-à-vis load alone. An increase in load at the same time as a reduction in wind results in a maximum ramp-up requirement of +2243 MW/15 minutes, whereas the maximum ramp-down requirement is -2190 MW/15 minutes when a load reduction occurs simultaneously with an increase in wind.

Figure 5.4 shows the control requirements of load alone in order of size; the control requirement of load plus 8 GW wind power has been coupled to each of the values. The figure illustrates the extremes particularly well; a combination of variations in loads and wind power can increase or decrease the control requirement at any time throughout the year. However, it is impossible to see the extent to which wind power influences the total requirement for control capacity. To enable this comparison to be made, the figure below therefore shows the control requirement duration curves (ramp-up and ramp-down requirement shown separately) in order of size.

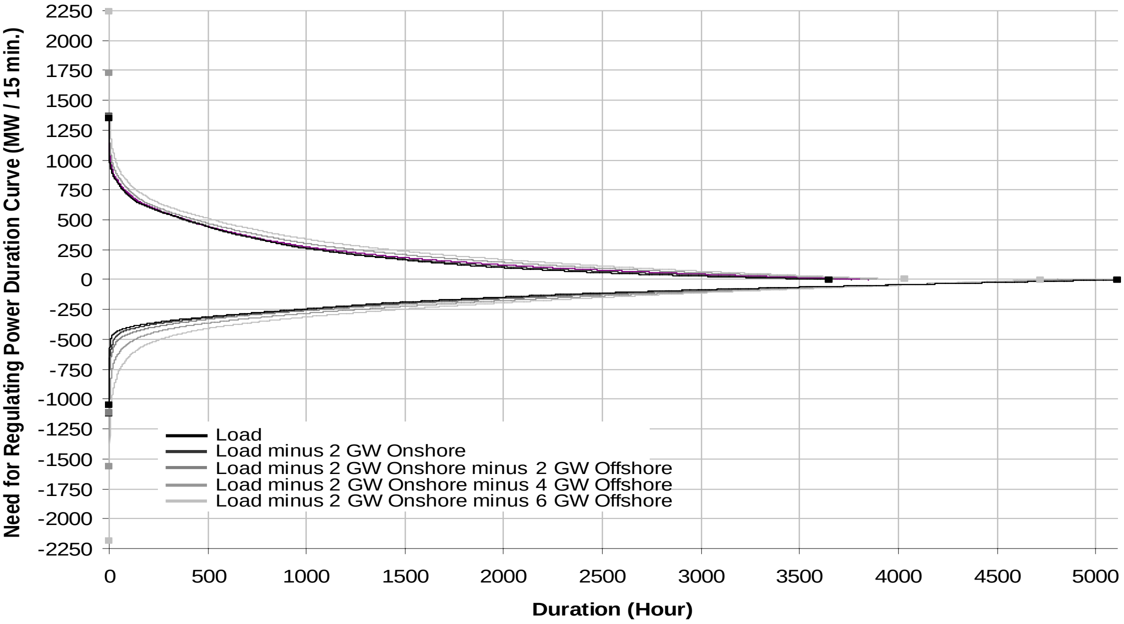


Figure 5.5: Control requirement duration curves for power variations of load alone (black line) and load and wind power simultaneously (shades of grey)

The first fact that the above figure reveals is that with load alone there is an annual requirement for 42% ramp-up capacity and 58% ramp-down capacity. This also means that the ramp-up requirement is on average greater than the ramp-down requirement: on average in the Netherlands, ramping up takes place less but more quickly and ramping down takes place on average more frequently but more slowly. With load variations alone, the maximum ramp-down requirement for the basic year that was extrapolated for this study is 1351 MW/15 minutes, whereas the maximum ramp-down requirement is -1048 MW/15 minutes.

The ratio of the ramp-up to ramp-down requirement changes as the amount of installed capacity increases: ramping up takes place fairly often (45% of the year) with 8 GW of installed capacity (2 GW onshore 6 GW offshore) and ramping down takes place less often (55% of the year). In addition, the maximum control requirements increase to +2,243 MW/15 minutes and -2,190 MW/15 minutes for 8 GW of installed capacity. Once again, these maximums may be different for other load years and wind years. However, generally speaking, both the upward and downward control requirement increase with increases in wind power.

6. Partial predictability of wind power

Wind power can only be predicted to a certain extent. Predictability depends on the period the prediction covers, for example. Wind power predictability is important in this project for determining the deployment of generating units. As some generating units are deployed for 24 hours, a 24-hour wind prediction seems the most obvious to choose. Using data from Energinet.dk (formerly Eltra), the Danish grid authority, we can assume that the *mean* absolute deviation from the prediction for 24 hours later will be around 27%.

It is extremely difficult to produce a program with a mean absolute error of 27% that can make a prediction for every quarter hour. It involves at least taking into account the dependency on the prediction deviation between the quarter hours themselves as well as the dependency on the prediction deviation from the weather conditions. There was unfortunately no opportunity in this study to make the required extremely extensive analysis of wind power data and to consult experts on wind predictions. Instead, it was decided to simulate two extremes: a perfect prediction of wind power (100% predictable) and a prediction of wind power of 0 MW. The two predictions represent the two extremes: the deployment of generating units will be optimal for a perfect prediction, whereas with a prediction of 0 MW the deployment of generating units at any time is sufficient to meet demand *without* wind power.

The optimum operational management will be known for the simulation of a perfect prediction of wind power; the deployment of generating units can be optimally geared to a perfect prediction of wind power because it is possible to count on 100% wind power. Taking the opposite case, it is not so that simulating the 0 prediction results in the most disadvantageous operational management. It is when a wind power prediction is only partially reliable that the likelihood of generating units being deployed suboptimally arises.

7. The power generating system in the Netherlands in 2012

The composition of the power generating system in the Netherlands in 2012 will be in line with the 'Green Revolution' scenario.

7.1 Composition of the power generating system

The power generating system in 2012 will largely consist of generating units that are operating at the moment (year 2005). A few generating units will have been added and some will have been decommissioned. The added generating units are XXX, XXX, XXX, XXX and XXX and a number of smaller combined heat and power plants. Generating units XXX and XXX have been decommissioned. The generating units were modelled using existing, comparable generating units that already existed in PowrSym. The figure below shows the main variables of all the generating units in PowrSym. It has been assumed that XXX will not be repaired, XEMS is the sum of all the generating units that are not in EMS. The total installed capacity of thermal generating units and decentral generating plants in 2012 is expected to be 22,932 MW, excluding wind power.

Station	Max.Power (MW)	Ramp Rate (%/minute)	Min.Up Time (hour)	Min.Do. Time (hour)	Station	Max.Power (MW)	Ramp Rate (%/minute)	Min.Up Time (hour)	Min.Do. Time (hour)

Figure 7.1: Control possibilities and minimum up and down times for generating units in 2012

7.2 Control possibilities

The control possibilities for various generating units are first estimated on the basis of the requirements (functional tests) of the Sep (former Dutch Electricity Generating Board), which were in force at the time that most of the generating units were built. The Sep requirements distinguish between three types of generating units, namely those for basic load and medium load operation, those for daily start-stop operation, and those for a limited number of operating hours. Each type of generating unit must at least be capable of achieving a control speed of 3.0% of net capacity per minute, whereby the ramp-up and ramp-down control in the power process must not be lower than 2.4% for any point. In addition, each type of generating unit must be capable of achieving an abrupt power increase of 5% of net power within 30 seconds, of which half (2.5%) must be within 5 seconds.

An exception applies to this requirement: generating units that were shown to have met the requirements before 1987 must be capable of achieving a control speed of 2.0% per minute. The same exception applies to generating units that were converted after 1987 into coal-burning power stations or that were fitted with primary gas turbines. This concerns the following generating units that will be in operation in 2012 XXXX, XXXX, XXXX, XXXX, XXXX, XXXX, XXXX and XXXX.

Generating units that were commissioned after the publication of the aforementioned document (1992 and/or 1994) but before 1998 need not meet any of the aforementioned requirements. These generating units only need to achieve a minimum ramp-up and ramp-down control speed of 1.5% per minute, and an abrupt power increase of 2.5% within 30 seconds.

Generating units that were commissioned after 1998 must meet the requirements laid down in the System Code. Because the System Code only contains requirements on the primary reaction (reaction within 15 and 30 sec), the minimum ramp-up and ramp-down control possibilities for these generating units have not been officially stipulated.

It can be concluded from the above that there will be considerable differences between the control possibilities of the generating units that are in operation in 2012 and it will not be feasible to determine the possibilities from stipulated requirements in some cases. The control speeds for generating units were not recorded in PowrSym because it has thus far only been used for hour simulations; it was assumed that generating units were capable of going through their entire control process within an hour. However, generating units will not generally ramp up or down at their maximum control speed (≈ minimum required control speed). A principle that can be adopted for this is that only 50% of the maximum control speed is actually used by producers (Dany).

Finally, KEMA Quality Authority and the daily experience of Ton Kokkelink are still used for the definite estimate of the control speeds. Barring a few exceptions, the final estimate of the control possibilities of generating units largely works out at 1.5% per minute, which is a conservative estimate of the actual technical possibilities of the power generating system in the Netherlands. Another point to note is that it has been assumed for this study that the distributed generating units (XEMS, 5261.4 MW) *are not* part of the controlled system. The total power generating system that is available for control therefore comes to 17,670.6 MW.

7.3 Minimum uptimes and downtimes

Unlike with control possibilities, PowrSym included data for minimum uptimes and downtimes for all generating units. The generating units concerned were compared at various times with similar generating units and an estimate was made on the basis of experience. The minimum times were also redetermined using EMS data for generating units with an uptime and downtime of more than six hours (PowrSym). An important factor here is whether or not generating units are able to undergo daily start-stop operation, for which the minimum downtime in each case cannot be more than 8 hours. The minimum uptimes and downtimes are also obviously closely connected with the economic costs and benefits of operational management and the increase in flexibility, but these issues have not been investigated here.

7.4 Heating supply

Many generating units supply heating as well as electricity. The heating obligation for these generating units is generally the determining factor for their deployment and the use of heating boilers has to be taken into account. Heating boilers enable more flexible deployment of combined heat and power plants; the generating unit could be taken out of operation during times of low loads, after which the heating boiler could take care of the demand for heating.

The size of the heating boilers of the existing heat-supplying units in PowrSym has been maintained, as little supplementary information is available on the possibility of making the units more flexible. It appears from the model that some of the existing generating units for district heating are equipped with boilers, which means the generating units could operate on a nightly start-stop basis for part of the year. During certain winter peak periods (extremely cold periods) combined heat and power plants and boilers will be in operation to supply the high demand for heating.

It has been assumed for the new power generating units that each one supplies electricity as well as heating. It is also known that XXX (x MW), XXX (x MW) and XXX (x MW) will supply heating, but it is not known whether XXX and XXX (both x MW) will. It has also been assumed that these generating units have no boiler, which means the five generating units will remain in operation during the hours of low loads so that they can supply their heating demand.

8. Starting points and results of simulations

The PowrSym simulation was used to simulate the entire electricity system, including onshore and offshore wind power. PowrSym determines the choice (unit commitment) as well as the deployment (dispatch) of the power generating units on the basis of a large number of limiting conditions, including the anticipated load and predicted electricity from wind power. Unit commitment determines a significant proportion of the possibilities of thermal generating units for deploying electricity from wind power.

8.1 Starting points for the simulations

8.1.1 Electricity demand

The total load in 2012 was calculated using the EMS data from 2003. The data include all the larger generating units plus Dutch imports and cover around 80% of the total load, depending on the size of the generating units in operation. Besides the 5-minute power values of the larger generating units, the general composition and a mean pattern of consumption are known for the smaller industrial generating units (largely constant consumption), and a number of gas engines and combined heat and power plants of market gardeners. These generating units were modelled assuming that 50% of the power changes in relation to the EMS total and that the other 50% is constant. The values have been added to the EMS data, which were then translated into 15-minute values and used to extrapolate the approximate total load on a 15-minute basis. The 15-minute data on load, distributed generated power, imports and wind power are entered into PowrSym using a Fortran routine.

8.1.2 Calculation variants

Simulations were run with seven different wind penetration levels. Variants were considered for each penetration level in relation to electricity imports, the degree of predictability of wind power production and the amount of heating boiler capacity in the system. Two import variants were analysed: one without imports and one with imports that were in line with the pattern that applied in 2003. The variants considered in connection with predictability were a 100% accurate prediction of wind power on a 15-minute basis (*perfect prediction*) and a constant prediction of 0 MW (*0 prediction; wind power production was not taken into account*). Finally, two variants were considered for the amount of heating boiler capacity in the system: one variant with an average estimate and one with a high estimate of the capacity of heating boilers in the system. The results for the total of 56 simulations are summarised in section 8.3.

The starting point in the basic scenario is a wind power prediction of 0 MW, with the presence of electricity imports (based on EMS data from 2003 and therefore without the possible influence of wind power on international power exchanges) and with the average estimate for heating boiler capacity.

8.2 Limiting conditions

Some limiting conditions were set in PowrSym for the simulations. PowrSym is primarily intended for minimising production costs. Various limiting conditions must also be met: the load has to be covered, the heating has to be covered and the maximum possibilities of the generating units must not be exceeded. Using heating boilers is an important possibility but it involves costs. As the variable costs of wind energy are the lowest of all the generating units, namely zero, the possibility of ramping down wind power will only be used in exceptional cases to prevent minimum load problems.

The following situations can be expected in the simulations and indicate possible limits on the deployment of large-scale wind power:

- *Insufficient ramp-down capacity*: increase in heating with boilers, unused wind energy
- *Insufficient ramp-up capacity*: electricity not supplied[3]
- *Minimum load problems*: increase in heating with boilers, unused wind energy

Unused wind energy or an increase in heating production indicate an increase in the costs that have to be incurred for the deployment of wind power. In these simulations, electricity that is not supplied signifies a hard technical limit; such a case means there is insufficient technical scope in the Dutch system to deal with decreasing wind power. Finally, the following assumptions were made in the simulations:

- Central dispatch was assumed in the simulations: The Netherlands is an 'area' in which the cost of deployment is optimally distributed over all available generating units.
- A few generating units have a 'must run' status; these generating units do not operate on a daily stop-start basis. In the simulations, these are the generating units XXX, XXX, XXX, XXX, XXX, XXX and XXX , XXX and XXX and XXX . The minimum production achieved with the deployment of these generating units is more than 2 GW.
- District heating units and industrial generating units are assumed to have boilers with a heating capacity, as shown in figure 8.1 (next page). Heating districts 1-15 and boiler sizes had already been established in PowrSym; heating districts 16 to 20 have been added. Boiler capacities of 0 have been assumed for the corresponding new generating units in the basic scenario.
- The required reserve capacity has been fixed at the size of the largest generating unit in operation. It has been assumed that the BritNed cable (1320 MW) will be the largest generating unit in 2012.[4] At least this reserve will be maintained at the system level.

[3] *This refers to the part of the electricity demand that cannot be supplied by the assumed programmed imports and domestic production. However, as reserves are kept at the international level (UCTE), insufficient ramp-up capacity will probably not lead to electricity not being supplied but to 'arbitrary imports', which is a problem for the TSO.*

[4] *The operational reserve (primary, secondary and tertiary) that has to be kept at the UCTE level is currently around 1000 MW for the Netherlands. The assumption that the BritNed cable can be counted as the largest unit is conservative, as imports entering through the Britned cable may also be intended for other countries.*

Heat Area	Station	Boiler Capacity (MW)	Heat Area	Station	Boiler Capacity (MW)

Figure 8.1: Generating units and boiler capacity per heating district

8.3 Results

The simulations showed that, if the amount of installed capacity continues to increase, the minimum load problem will be the first problem to occur; the combined power generation from wind and the other generating units will exceed demand. Measures will have to be taken in these cases, such as cutting back wind power production.

In all the variants, the Dutch generating units proved capable of accommodating the combined *fluctuations* in wind power production and load within 15 minutes, even for large amounts of installed capacity. However, to achieve this, increasingly more reserve has to be maintained to accommodate the fluctuations, which means that the thermal generating units with a lower load factor or lower efficiency will have to be operated. The reserve will also have to be shared between more generating units (also cheaper ones) to increase the ramp-up and ramp-down response. This obviously has consequences for the emission reductions and fuel savings that can be achieved by using wind energy.

The failure to respond to ramp-up and ramp-down problems in the simulations can also be explained by the starting points that were used. Figure 5.5 shows that the maximum ramp-up and ramp-down requirement for an installed capacity of 8 GW is around 2.2 GW per quarter hour. The presence of around 16 GW[5] controllable thermal production capacity, with a ramp-up and ramp-down control speed of around 1.5% per minute, provides a maximum possible response of around 2.4 GW per quarter hour, which is therefore sufficient. Given a perfect prediction, sufficient capacity will always be committed to accommodate fluctuations. There will always be more than enough generating units in operation for a zero prediction, which means the total control possibilities will be sufficient to compensate for wind power fluctuations.

[5] *Total present 17.7 GW with a mean availability of 90%*

Because minimum-load problems proved to be the first limiting factor, this aspect in particular is discussed in greater depth below.

8.3.1 Electricity production and unused wind power

Figure 8.2 shows annual electricity production from onshore and offshore wind energy for increasing installed capacity (0 GW to 2 GW onshore + 6 GW offshore). The figure clearly shows that offshore wind power operates for more full-load hours and therefore produces more electricity. For a total installed capacity of 8 GW comprising 2 GW onshore and 6 GW offshore, the wind turbines can produce a maximum of approximately 28.7 TWh. As the amount of installed wind power capacity increases, electricity production from wind energy is less readily deployed in combination with load, imports and conventional electricity generation. If imports are assumed at their present level, electricity production from wind energy of up to 2 GW installed capacity can be deployed at any time. The percentage of unused wind energy (wind power cut-out to avoid minimum-load problems) increases after this to 0.6% (58 GWh at 3.25 GW) and 1.7% (216 GWh at 4 GW) and finally to around 17% at 8 GW of installed capacity.

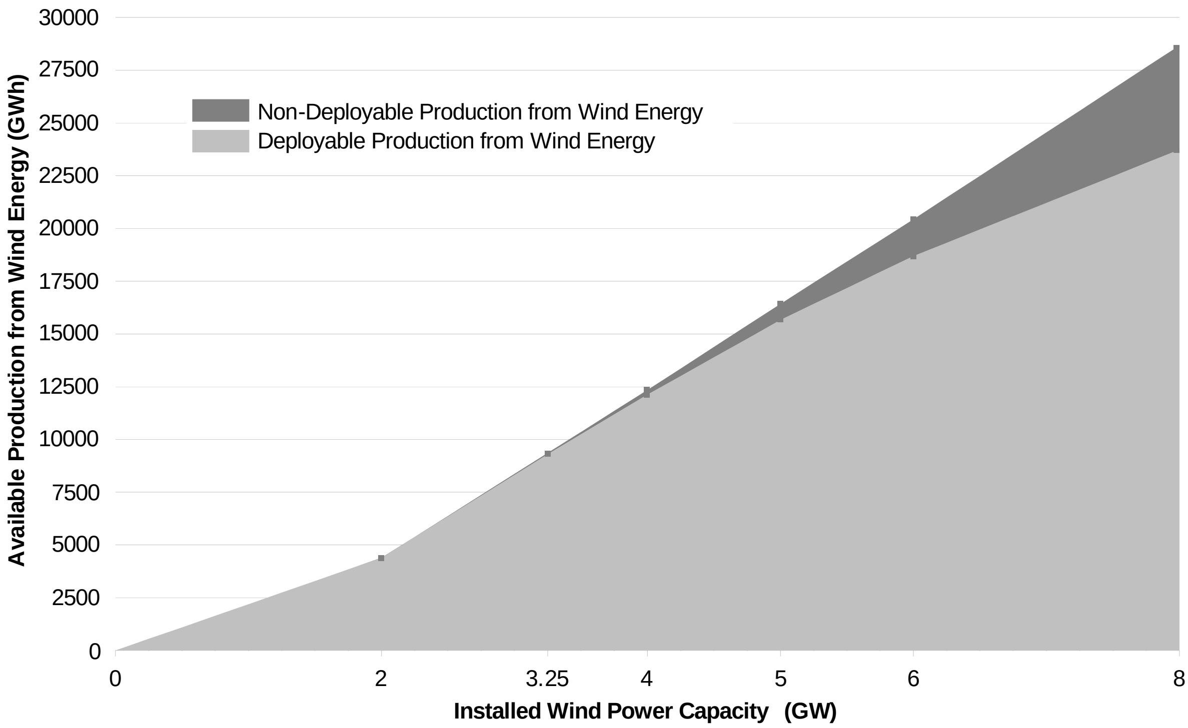


Figure 8.2: Deployable and non-deployable electricity production from wind energy for the simulated basic variant; 0 MW wind prediction and imports at the present level have been assumed

Figure 8.3 shows the percentage of additional available electricity production from wind energy that cannot be deployed per tranche of additional installed capacity of wind power. The figure shows a little more clearly than figure 8.2 at what penetrations the problems begin to occur. The figure shows that the first 2000 MW can be deployed without any problem. Around 2% of the production of the next 1250 MW of installed capacity cannot be deployed. The percentage for the next 750 MW is around 5%, and the figure rises rapidly after this. Almost 40% of electricity production from the final tranche of 2000 MW (between 600 MW and 8000 MW) cannot be deployed.

Figure 8.4 (next page) shows the weekly relationship between the amount of available wind energy and the percentage of unused wind energy for the basic simulation. The figure shows a considerable fluctuation in the available supply of wind energy from week to week. The amount of unused wind energy is close to zero for all the weeks up to an installed capacity of 2 GW onshore and 1.25 GW offshore. The percentage of unused wind energy increases as the amount of installed capacity increases and the relationship to the supply of wind energy is obvious. An exception to this is week 52, when a relatively large amount of wind energy was not used during high wind power penetrations; this is connected with a low load in that week (Christmas and New Year).

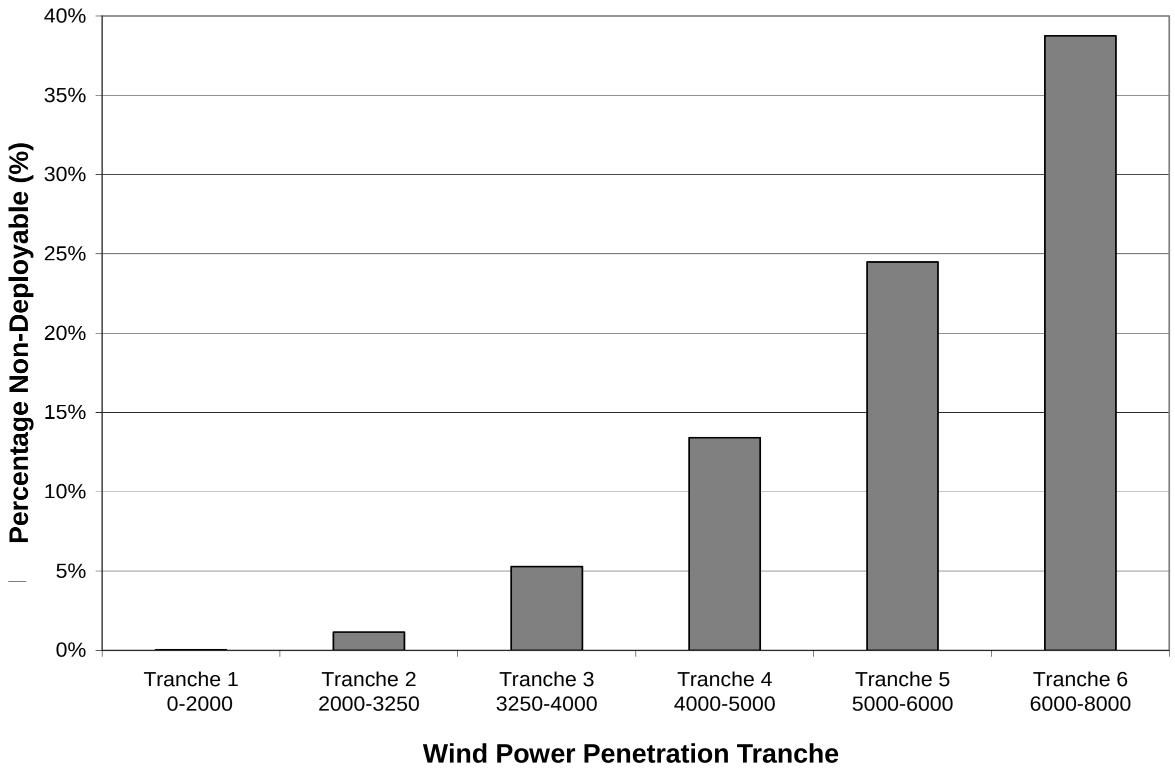


Figure 8.3: Percentage of additional available production per tranche of additional installed capacity that cannot be deployed (which equals the increase in non-deployable production per increment/increase in available production per increment)

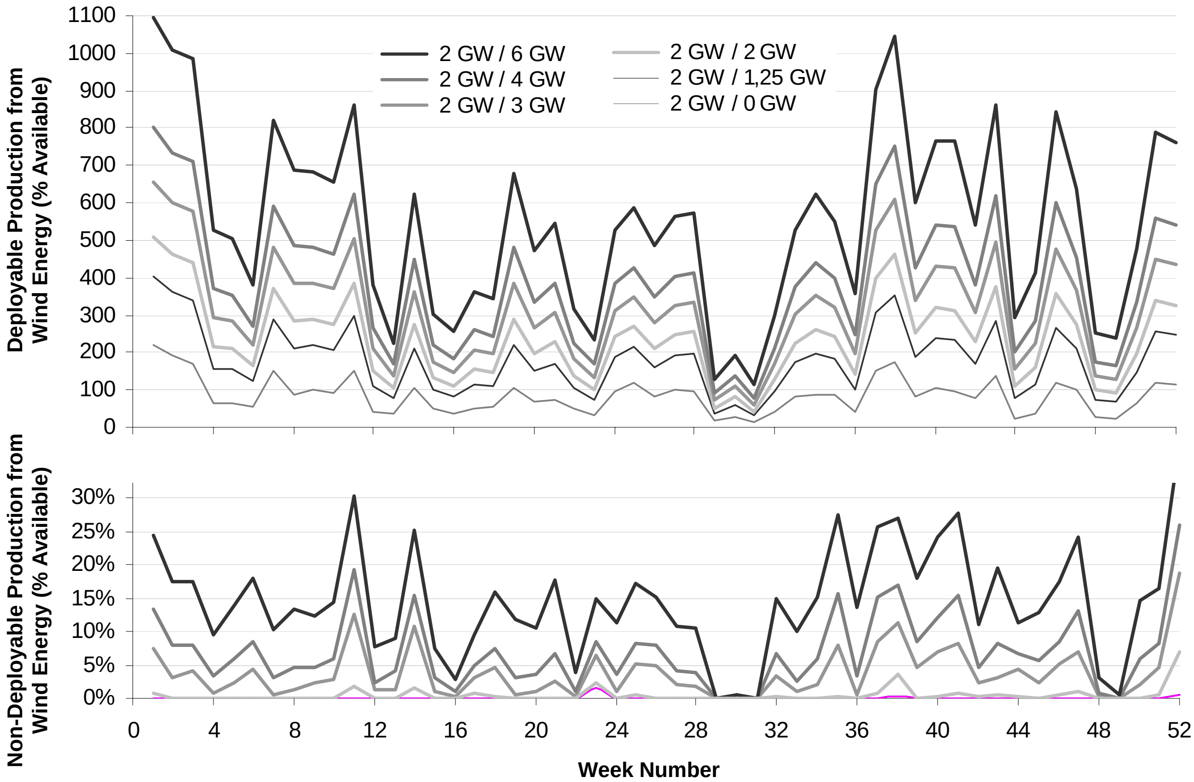


Figure: 8.4: Available production from wind energy (GWh) and percentage of unused wind energy per week at various wind penetration levels for the basic variant

8.3.2 Heating with boilers

Figure 8.5 (next page) clearly shows that the use of heating boilers increases as the installed capacity of wind power rises. The increase comes about because there is a growing need to ramp down the thermal power generating system further during the hours with a low load and increased wind power production. Combined heat and power plants can be ramped down and, as an extreme measure to avoid cutting back wind power production, they can even be stopped, if back-up provisions exist for the heating supply in the form of heating boilers. Deploying heating boilers therefore creates extra scope for ramping down during the hours with a low load. An increase in the use of heating boilers does not indicate a fixed technical limit but an increase in the costs that will have to be incurred for the deployment of wind power. Moreover, the extra deployment of boilers obviously has an adverse impact on the emission reductions and fuel savings that could be achieved using wind energy. The graph shows in the variant without wind that the approximate figure of 3000 TJ per year of heat production from heating boilers increases by a factor of 6 to around 18,000 TJ per year for a wind penetration of 8 GW.

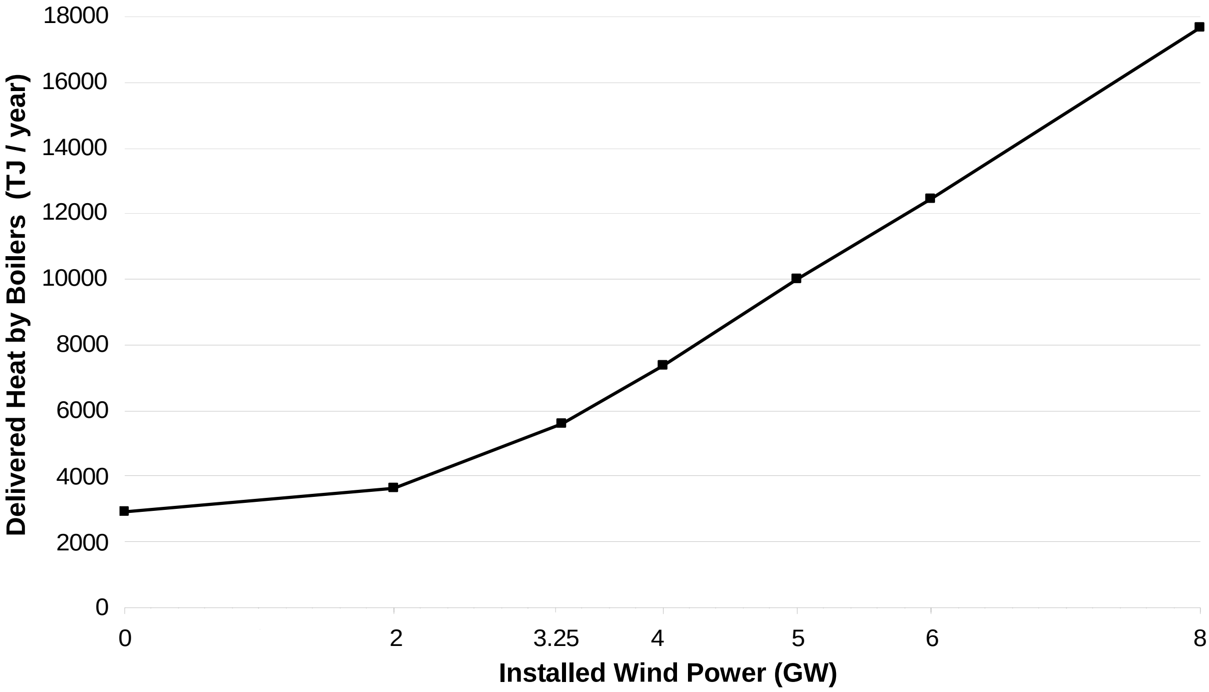


Figure 8.5 Heating with boilers with imports at 0-prediction level

8.3.3 Energy saving and CO_2 reduction

Using wind energy for electricity production saves fuel at conventional power stations, while also reducing emissions. The next two figures provide an indication of the energy saving and reduction in CO_2 and NOx emissions that can be obtained with wind energy.

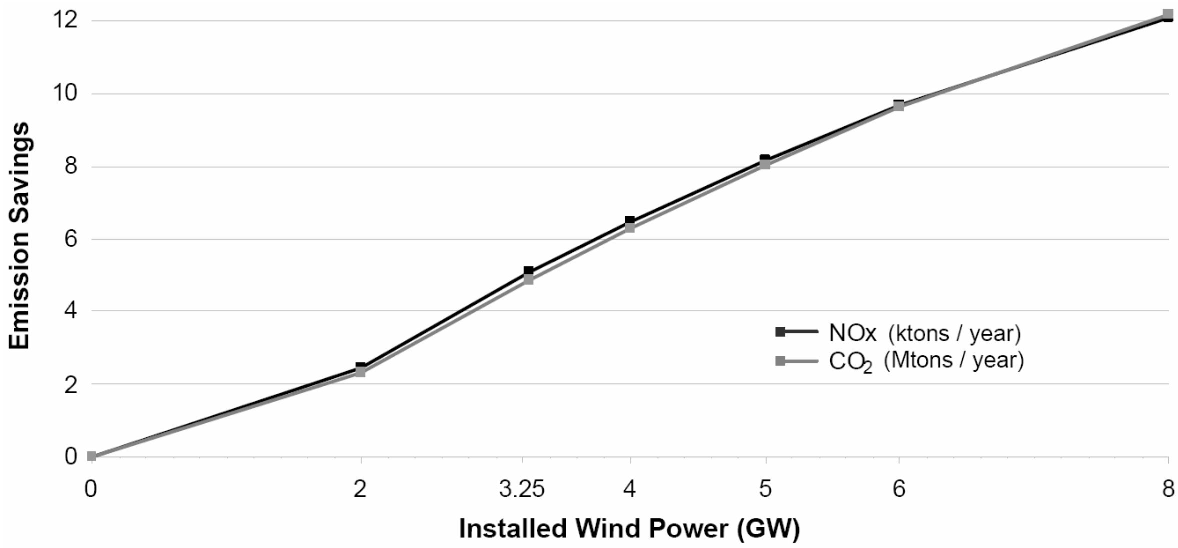


Figure 8.6 NOx and CO_2 emission reduction achieved by using wind energy for basis variant

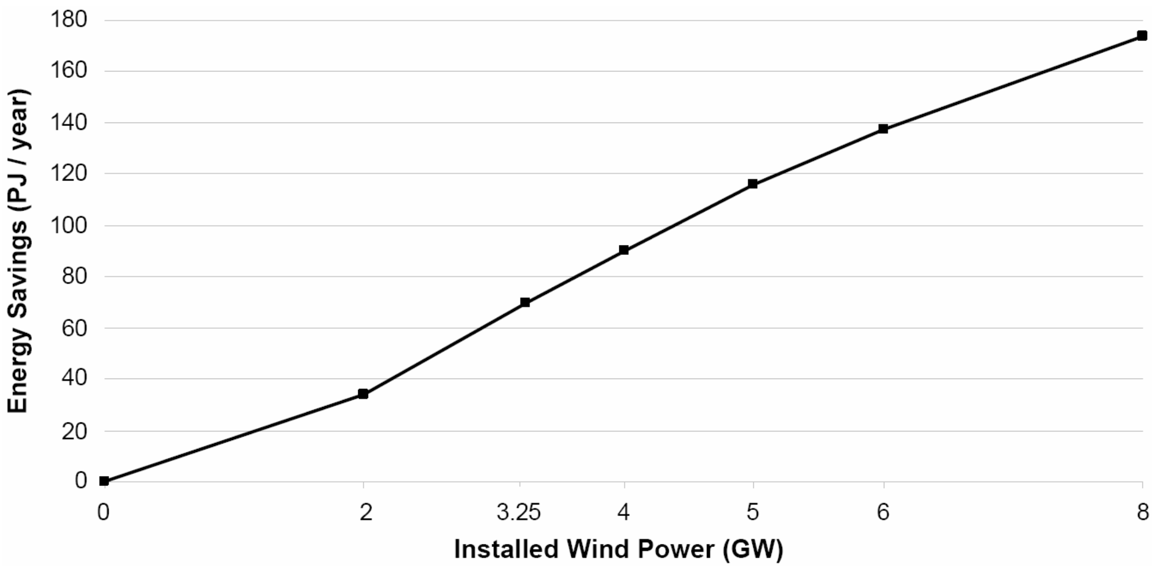


Figure 8.7: Energy saving achieved by using wind energy to reduce fuel consumption

Figures 8.6 and 8.7 clearly show how the relative saving/reduction decreases as installed capacity increases.

8.4 Sensitivity analysis

As indicated earlier (8.1.2), calculations were made using other variants, in addition to the basic variant, to determine the sensitivity of the results for different calculation starting points. The following starting points were varied:

- Predictability of electricity from wind power. The basic variant was calculated using a constant prediction of 0 MW (*0 prediction; electricity from wind power was not taken into account*). At the opposite extreme, calculations were made with a 100% accurate wind power prediction.
- The amount of heating boiler capacity in the system. The basic variant assumes an average estimate of available capacity. Sensitivity calculations were also made using high estimates of available capacity. It was assumed that complete back-up will exist to cover the heat demand for all newly constructed combined heat and power projects.
- Electricity imports. Electricity imports in the basic calculation were assumed to be at the level for 2003. Sensitivity calculations were made for a situation without any electricity imports.

The calculations showed that the degree of predictability for electricity from wind power only has a slight effect on the results and is not a determining factor for the maximum amount of wind power that is deployable in the system. Both the 100% accurate prediction of wind energy and a constant prediction of 0 MW are more likely to lead to minimum load problems than to control capacity shortages: in the case of a perfect prediction, enough generating units will be in operation to accommodate power variations, whereas with a prediction of 0 MW wind power there will most probably be sufficient capacity in operation to accommodate the variations.

The sensitivities of the results for making assumptions about the *heating boiler capacity in the volume of imports* are relevant. The following is therefore concerned solely with these sensitivities. The sensitivities are explained below with the aid of a graph of three model results, namely:

- The unused electricity from wind power as a function of the amount of installed capacity, in both absolute and incremental terms (figures 8.8 and 8.9).
- Heating with boilers as a function of the amount of installed capacity (figure 8.10).
- The energy saving achieved as a function of the amount of installed capacity (figure 8.11).

8.4.1 Sensitivity to heating boilers in the system

As mentioned earlier, an increase in installed wind power leads to heating boilers being used more often to create extra ramp-down capacity for combined heat and power plants during hours with a low load. Therefore, increasing heating boiler capacity will lead to an increase in the deployable amount of wind power in the system. This is clear from figures 8.8 and 8.9.

Figure 8.9 shows that the first deployment problems in the variant with extra heating boilers only occur in the installed capacity range between 3250 MW and 4000 MW. Figure 8.10 shows that the deployment of boilers at the maximum wind penetration level of 8000 MW increases by around 7.5 PJ (40%) to a total of 25 PJ. In spite of the extra heating boilers deployed, the energy saving (see figure 8.11) in this variant still increases vis-à-vis the basic variant by 8 PJ because more electricity from wind power can be deployed.

8.4.2 Sensitivity to volume of imports

Figures 8.8 and 8.9 show that the effect of reducing imports to 0 during hours with a low load is similar to that of having extra heating boilers. The absence of imports creates more scope for ramping down during hours with a low load, which means that wind power needs to be ramped down less often. The energy saving achieved is highest in the variant without imports, because more wind power can be deployed without having to cut back the combined heat and power capacity or bring it to a standstill; this represents an extra saving of around 27 PJ, or more than 15% vis-à-vis the basic variant at the maximum wind penetration level. The combined effect of extra heating boiler capacity and an import reduction leads to the highest deployable wind penetration level.

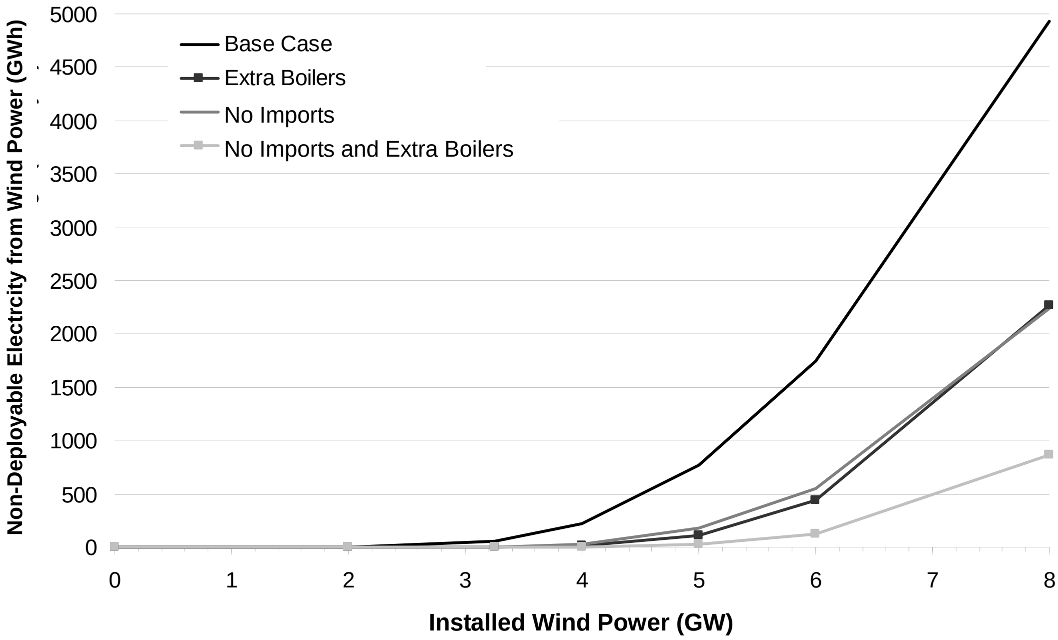


Figure 8.8: Deployable and non-deployable electricity from wind energy for the basic and sensitivity variants

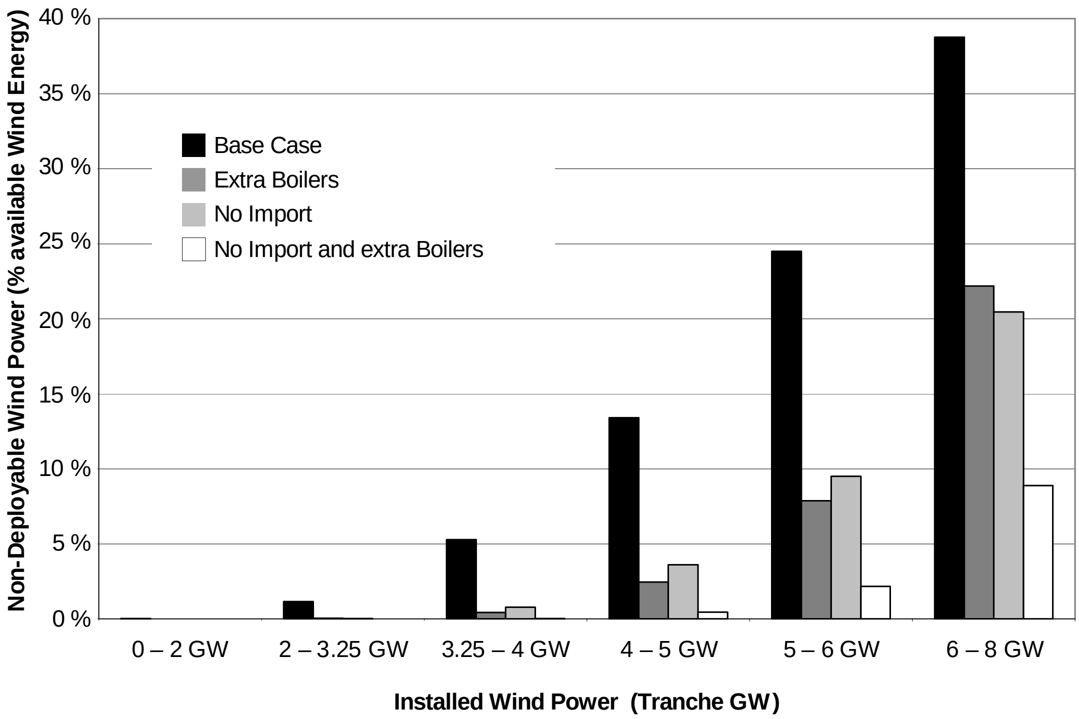


Figure 8.9: Percentage of additional available production per tranche of additional installed capacity that cannot be deployed (which equals the increase in non-deployable production per increment/increase in available production per increment) for the basic and the sensitivity variants.

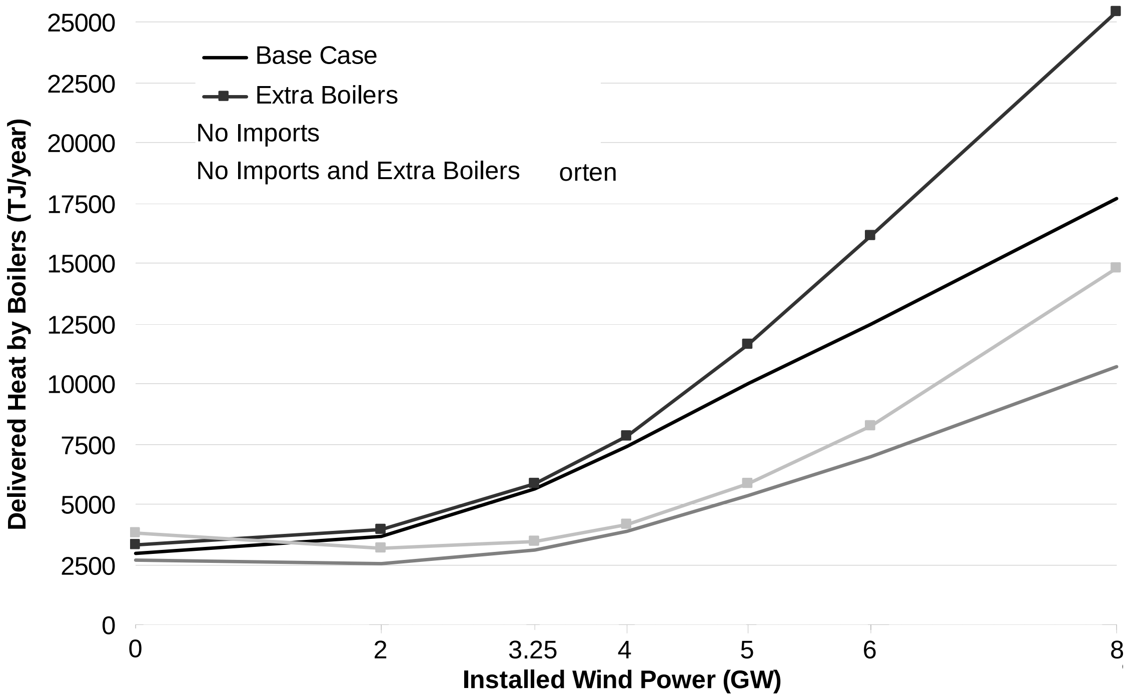


Figure 8.10: Heating with boilers for the basic and the sensitivity variants.

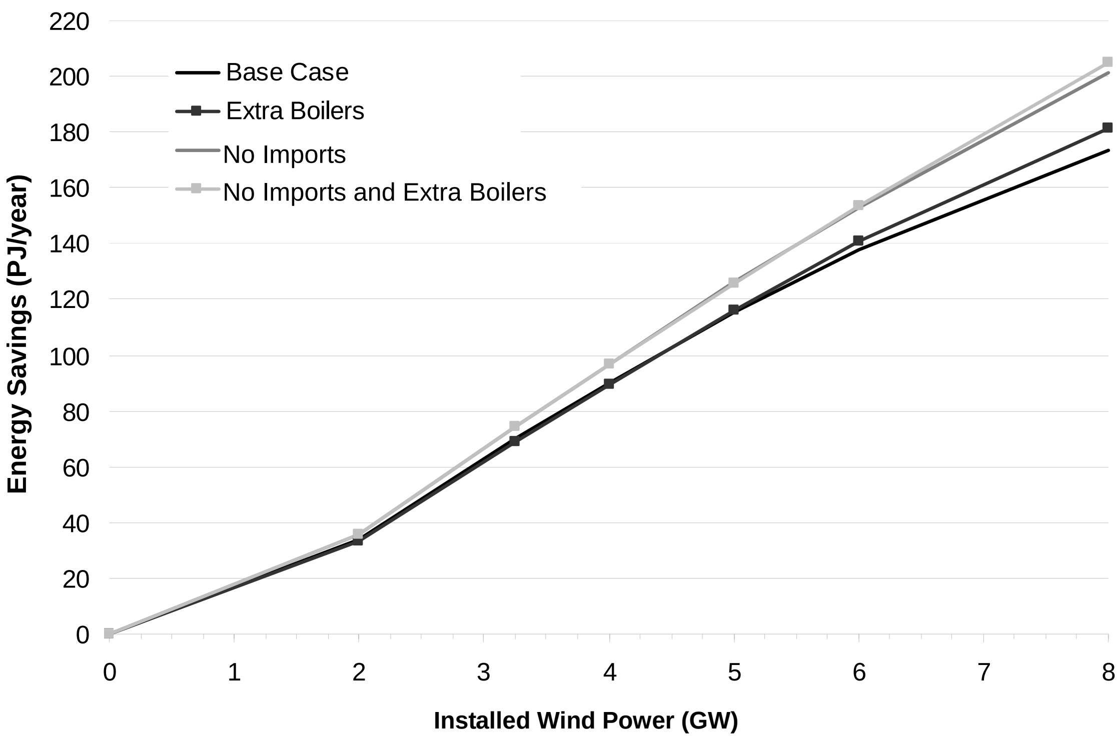


Figure 8.11: Energy saving through wind energy for the basic and the sensitivity variants.

9. Conclusions

9.1 Outline

This study provides an initial estimate of the technical possibilities available in the Dutch generating units for the integration of wind power in the Dutch electricity system. The research question was:

> *What is the maximum wind power capacity that can be integrated into the Dutch system in 2012, without exceeding the technical limiting conditions of the electricity system, and while utilising the Dutch power generating system?*

The study provides an insight into the technical possibilities of the system and is not concerned with their economic consequences. The study forms a good basis for further analyses, in which market and grid aspects will also be taken into account.
An outline of the study's conclusions is provided below:

- It can be concluded from the simulations that the amount of wind power that can be integrated in the power generating system in the Netherlands in 2012, without additional measures being taken, is around 4000 MW (half of which will be offshore). Upward of 2000 MW of wind generated power, increasingly more additional measures will be required at times of low loads and high winds to ensure wind power can be integrated safely. Further research should show the extent to which these measures are being taken by the market, under the influence of the existing system of programme responsibility.
- The variants studied showed that the Dutch generating units are capable of accommodating the combined fluctuations in wind power production and load, even in the case of large-scale wind power. However, as the amount of installed wind power capacity increases, so do the consequences for electricity production from wind energy, emission reductions and fuel savings.
- The results of the simulations indicate significant sensitivity to assumptions about exchanges of power with other countries and the presence of heating boilers in the case of combined heat and power plants.

9.2 The starting points used

- Conservative estimates were taken as the starting point for determining the ramp-up and ramp-down control possibilities of both existing and newly constructed conventional power stations.
- The analysis did not take into account limitations that may be caused by large power surges in the grids: when power changes in offshore wind occur, conventional generating units at other locations in the grid will adjust their production, which will result in other power surges and possible congestion.

- The analysis did not take into account the system of programme responsibility, which covers all Dutch wind energy. This means that parties with programme responsibility who have wind energy in their portfolio will compensate for imbalance by taking individual measures to change electricity production from wind power, as opposed to the central dispatch of Dutch generating units that has been assumed here.
- The analysis did not take into account technical solutions for accommodating power changes in offshore wind other than the use of conventional generating units in the Dutch grid. Other possible solutions include the use of international connections (trade), demand control and large-scale wind energy storage in grids or otherwise; none of these possibilities has been investigated here. Further research is required to integrate these aspects in simulations.

9.3 Follow-up research

This initial study was limited to the technical possibilities of the underlying system and provides a good basis for follow-up research. Future analyses will include the following aspects as well as technical aspects:

- Market aspects: The design of the market, especially the system of programme responsibility, will affect the integration of wind power into the system in various ways. These include the effect on prices, international trade and the maintenance of the reserve and control capacity by market players. An examination will be conducted of the extent of the influences and what changes could be made to the market model to enable the efficient and safe large-scale integration of wind power into the system.
- Grid aspects: Follow-up research is required to determine the extent to which the grid is a limiting factor in adapting the system for wind power.
- Predictability of wind power: this study has shown that the predictability of wind power has little effect on the maximum amount of wind power that it is technically possible to deploy. Follow-up research can examine what the added value is of predicting wind power for both its technical deployment and for cost efficiency.
- Optimisation of deployment at the system level: measures in the electricity system could not only make the deployment of wind power more possible but could also optimise its deployment. Although the development of the possibilities for this (heating boilers in the case of combined heat and power plants, the use of the NorNed cable, control on the demand side, large-scale wind energy storage) are largely in the hands of the market players, it would be relevant for the TSO to know what the optimum measures are from the system point of view. A survey of the possibilities would enable the TSO to advise the government about the developments that ought to be encouraged.

10. Background material

Presentation: General Introduction into the Danish Case - Eltra, TSO of Western Denmark
Presentation: Wind Power and Regulating Power - Eltra, TSO of Western Denmark

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