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Research Article

Impact of Hourly Wind Power Variations on the System Operation in the Nordic Countries

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Key words: ■■

The variations of wind power production will increase the flexibility needed in the system when significant amounts of load are covered by wind power. When studying the incremental effects that varying wind power production imposes on the power system, it is important to study the system as a whole: only the net imbalances have to be balanced by the system. Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output. The goal of this work was to estimate the increase in hourly load-following reserve requirements based on real wind power production and synchronous hourly load data in the four Nordic countries. The result is an increasing effect on reserve requirements with increasing wind power penetration. At a 10% penetration level (wind power production of gross demand) this is estimated as 1·5%–4% of installed wind capacity, taking into account that load variations are more predictable than wind power variations. Copyright © 2005 John Wiley & Sons, Ltd.

Introduction

Integration of wind power in large power systems is mainly subject to theoretical studies, as wind power penetration levels are still modest. Even though the penetration in areas such as West Denmark is already high (about 20% of yearly electricity consumption), wind power represents only 1%–2% of the Nordel and Central Europe (UCTE) systems.

Wind power production is characterized by variations on all time scales: seconds, minutes, hours, days, months and years. Even the short-term variations are to some extent unpredictable. The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily due to the fluctuations in power output generated from wind. To what extent extra costs will occur depends on how large a share is produced by wind power, as well as on the power system in question: the inherent load variations and flexibility of the production capacity mix.

For the power system the relevant wind power production to study is that of larger areas. This means large geographical spreading of installed wind power, which will reduce the variability and increase the predictability of wind power production. Not taking this into account can result in an exaggeration of the impacts of wind power.

Integrating wind power in power systems means taking into account the varying pattern of wind power production in scheduling the generation and reserve units in the power system. Integration costs or system costs are the costs incurred in incorporating the electricity from wind power into a real-time electricity supply, ensuring system security.

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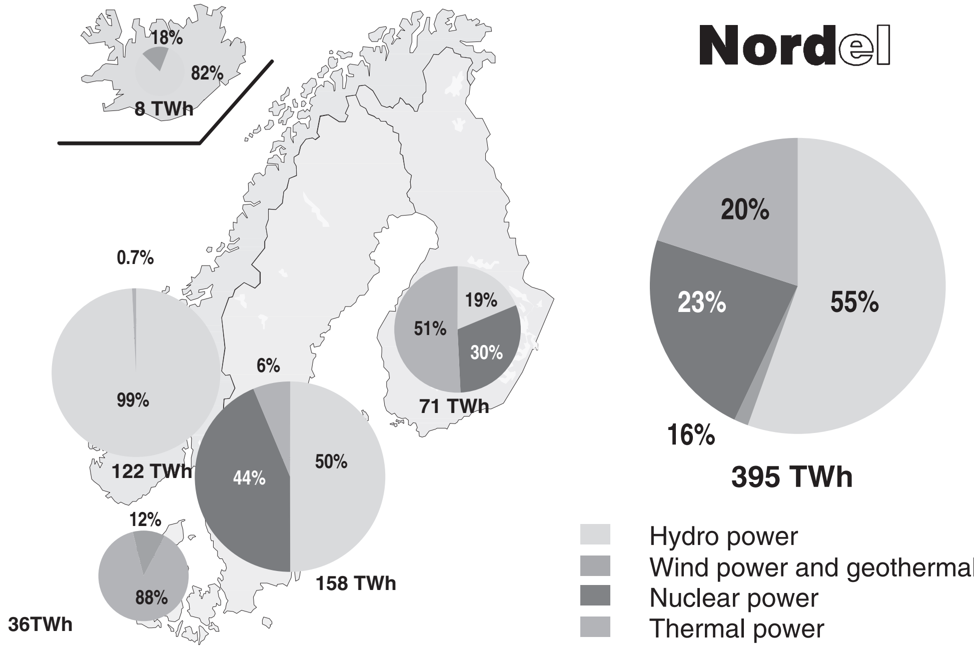


Figure 1. Electricity production in the Nordic countries in 2001[1]

The Area of the Study

The joint, liberalized Nordic electricity market covers Norway, Sweden, Finland and Denmark. East Denmark is part of the Nordel system, while West Denmark is part of the Central Europe UCTE system. They are not connected by a transmission line, but both are connected to Sweden and Germany, and West Denmark is also connected to Norway by a DC link. The production mix is shown in Figure 1.[1] A large share of hydro power is characteristic for the Nordic area: Norway covers almost 100%, Sweden almost 50% and Finland almost 20% of electricity consumption by hydro power.

The installed wind power capacity at the beginning of 2003 was 2200 MW in West Denmark,[2] 573 MW in East Denmark,[3] 345 MW in Sweden,[4] 97 MW in Norway[5] and 41 MW in Finland.[6] In Denmark, system integration of wind power is already a reality, whereas in other countries it is still a subject for discussion. In Denmark the scheduling of production units takes into account wind power production, and prediction methods together with the hourly trade in the spot and regulation markets are used in order to accommodate the substantial share of wind power in the system.[7]

Previous work

Studies of large-scale wind power production, its variability and its effects on energy systems have been carried out to some extent in the 1990s and increasingly in the first years of the new millennium. The first comprehensive article about the system impacts of wind power was by Grubb,[8] considering the UK power system.

First experiences from West Denmark and the Northern coast of Germany have shown that, when significant amounts of electrical demand are covered by wind power, increased flexibility is needed in the system. This is first seen as increased transmission with neighbouring countries.[7,9,10] There is experience from as well as studies on thermal systems that take in wind power production but leave, even in high winds, the thermal plants running at partial load in order to provide regulation power. The results show that about 10% (energy) penetration is the starting point where a curtailing of wind power may become necessary. When wind power production is about 20% of yearly consumption, the amount of discarded energy will become substantial and about 10% of the total wind power produced will be lost.[11,12]

As a conclusion of several studies in the USA[13] it has become clear that, to estimate the impacts of wind power on the power system, the wind-induced imbalances have to be treated together with aggregated system imbalances. Estimating the increased reserve requirements has resulted in a very small impact on the regulation time scale.[14,15] However, on the load-following time scale, increasing penetration of wind power will result in an increasing impact.[16–20] In many cases the studies give conservative estimates because they lack detailed, representative data for both the large scale wind power production and the load from the same area.

The present study is one step towards quantifying the impacts of large-scale wind power on the operation of the power system, based on existing production data on an hourly level. The wind power data used in this article and the smoothing effect of large-scale wind power production are analysed in detail in a previous article from this study.[21]

Power System Operation and Wind Power

Electric power systems include power plants, consumers of electric energy, and transmission and distribution networks connecting the production and consumption sites. The power system, which is operated synchronously, has the same frequency. At nominal frequency (in Europe 50 Hz) the production and consumption (including losses in transmission and distribution) are in balance. When the frequency is below 50 Hz, the consumption of electric energy is higher than the production. If the frequency is above 50 Hz, the consumption of electric energy is lower than the production. This constantly fluctuating interconnected system should maintain the balance so that faults and disturbances are cleared with minimal disadvantage in the delivery of electricity.

Merit order of electricity production

Power systems comprise a wide variety of generating plant types, which have a range of capital and operating costs. The operation of a power system involves providing a total amount of electricity, at each instant, corresponding to a varying load from the electricity consumption. To achieve this cost-effectively, the power plants running at low operational costs will be kept running almost all the time (base load demand), while the power plants with higher costs will be run only when the load is high.

When ignoring second-order costs (e.g. start-up, shutdown, reserves), plants can be stacked in merit order, where production with low marginal costs runs first. Wind power plants (as well as other variable sources such as solar and tidal) have very low marginal costs, usually assumed as zero, so they come to the top of the merit order, i.e. their power is used whenever available.[8]

The electricity markets operate in a similar way, at least theoretically. The price the producers bid to the market is slightly higher than their marginal costs, because it is cost effective for the producers to operate as long as they get a price higher than their marginal costs. When the market is cleared, the power plants operating at lowest bids come first.

Reserves

Failure to keep the electricity system running has serious and costly consequences, so the reliability of the system has to be kept at a very high level. Security of supply needs to be maintained in both the short and the long term. This means maintaining both flexibility and reserves necessary to keep the system operating under a range of conditions, also in peak load situations. These conditions include credible plant outages as well as predictable and uncertain variations in load and in primary generation resources, including wind.

Load following is performed partly beforehand and partly by operational reserves. Beforehand the scheduling and dispatch of power plants is done according to the load forecast. This involves also the start-ups and shutdowns of slower power plants, called unit commitment, on the time scale of 3–12 h. The operational reserves are used to balance the load forecast errors. Figure 2 gives an example of the actual load in the system over 3 h compared with the hourly forecasted load, showing forecast errors and short-term load deviations in the system.

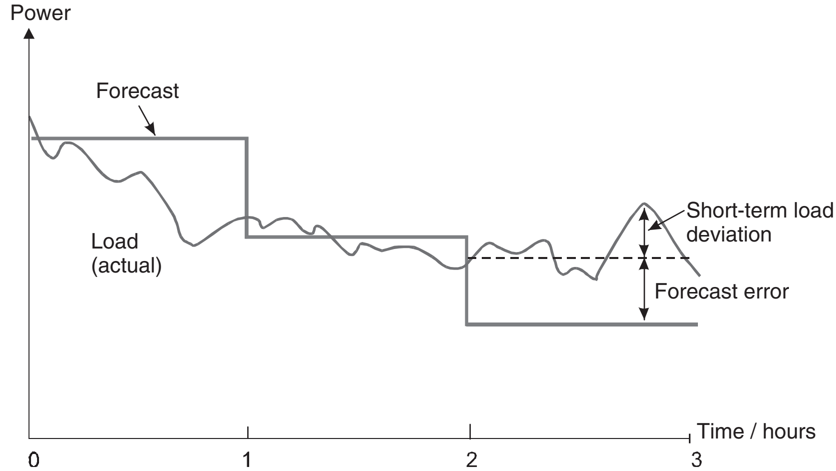


Figure 2. Example of actual load in the system during 3 h compared with forecasted load

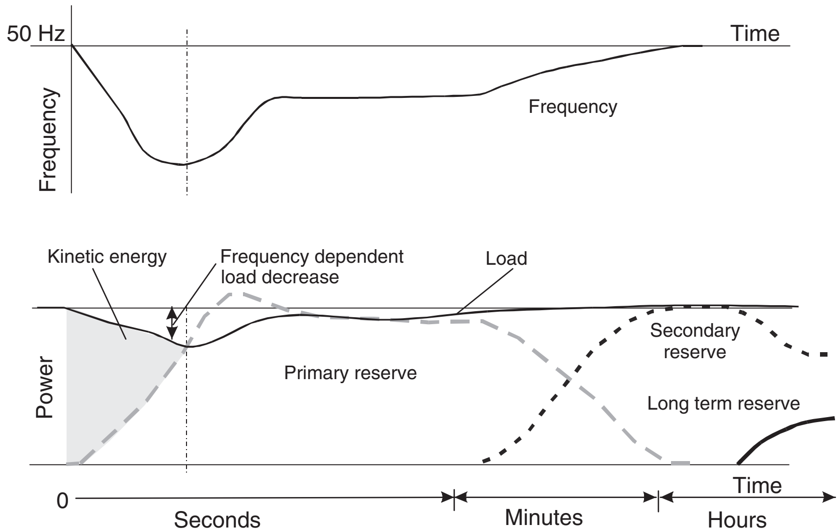


Figure 3. Activation of power reserves and frequency of power system as a function of time when a large power plant is disconnected from the power system[22]

The reserves are divided into different categories according to the time scale within which they operate. An example of how the reserves operate is illustrated in Figure 3.[22] It shows the frequency of the system and activation of reserves as a function of time when a large power plant is disconnected from the power system. Activation of reserves divides the reserves into primary reserve, secondary reserve (also called fast reserve) and long-term reserve (also called slow reserve or tertiary reserve). The primary reserve in power plants is activated automatically by frequency fluctuations. The secondary reserve is activated within 10–15 min of the occurrence of a frequency deviation from nominal frequency. It replaces the primary reserve and will be in operation until itself being replaced by the long-term reserve, as seen from Figure 3. The secondary reserve consists mostly of rapidly starting gas turbine power plants, hydro (pump) storage plants and load shedding.

The operation of the power system has to be guaranteed also in the liberalized electricity markets. In the Nordic electricity market there is an independent Transmission System Operator (TSO) in every country as a system-responsible grid company securing system operation. The scheduling and dispatch of the power plants (unit commitment and load following according to load forecasts) can be dealt with in the Nordpool Elspot market as well as by bilateral contracts between the players. The TSOs take over the regulation of the balance during the hour of operation. First the balance is secured by means of primary reserve (automatic frequency reserve and instantaneous disturbance reserve). In the event of a major frequency deviation the TSOs adjust the production or the consumption manually, using a secondary reserve called regulating power. They do this through a common regulating power market where the players submit their bids for upward and downward regulation of production or consumption. Contracts between some producers (and consumers) and system operators can also be made to allocate the primary and secondary reserves. The primary control of the synchronous part of Nordel is according to the total net balance. The TSOs in Sweden and Norway have agreed to share the responsibility of maintaining the frequency of the whole area during operation (primary reserve for operation). All the TSOs are responsible for activating the secondary reserve of their own areas and for ensuring that the physical constraints of the transmission grid are observed.[23] The balancing management for the liberalized market remains the same in that the TSOs only regulate the net imbalance of the system.

The impacts of wind power on the power system

The system impacts of wind energy are presented schematically in Figure 4. These impacts are divided into two: short term, balancing the system on the operational time scale (minutes to hours), and long term, providing enough power and energy in peak load situations. The additional requirements and costs of balancing the system on the operational time scale (from several minutes to several hours) are primarily driven by fluctuations in wind generation output. Some of the fluctuations are predictable 2–40 h ahead. The varying production pattern of wind power changes the scheduling and unit commitment of the other production plants and the use of transmission between regions—either losses or benefits are introduced to the system—compared with the situation without wind. Some of the fluctuations remain unpredicted or mispredicted and have to be

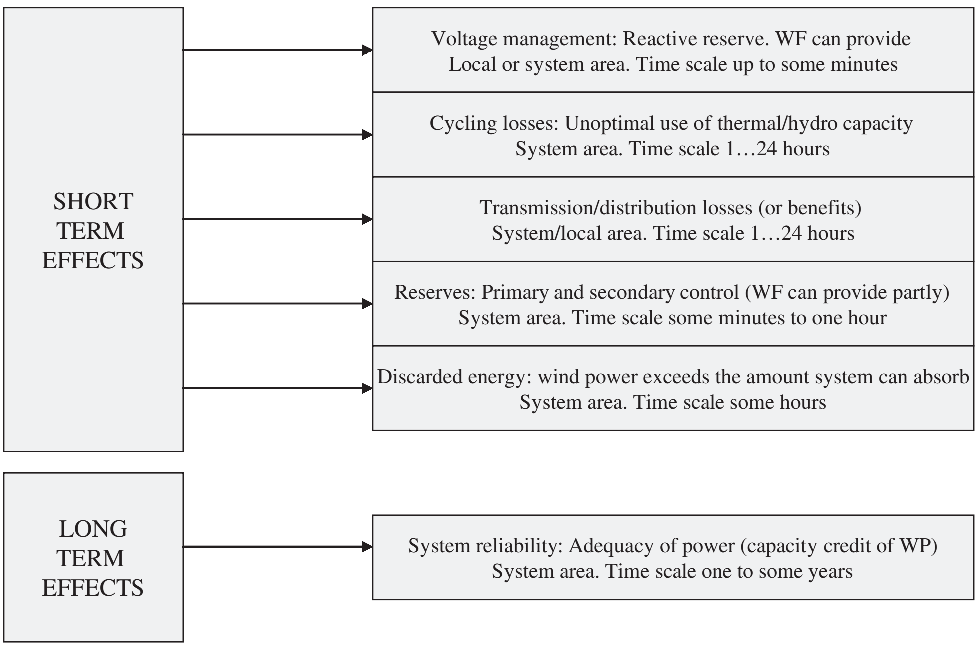


Figure 4. System impacts of wind power (WP) and wind farms (WF) causing integration costs. Part of the impacts can be beneficial for the system, and wind power can have a value, not only costs

Figure 5. Data for hourly wind power production were available from 21 sites in Finland, six sites in Sweden, 6–12 sites in Norway (the lighter-coloured sites only for part of the time) and the aggregated total production of hundreds of sites in West and East Denmark

handled by the regulation market and balancing services (mainly secondary reserves). There are means to reduce the variations of wind power production. Staggered starts and stops from full power as well as reduced (positive) ramp rates can reduce the most extreme fluctuations, in magnitude and frequency, over short time scales.[24] This is at the expense of production losses, so any frequent use of these options should be weighed against other measures (in other production units) in terms of cost-effectiveness.

This study is involved with the short-term effects and, more specifically, the operating reserve requirements of wind power. The relevant system area to look at varies according to the impact studied (Figure 4).[25] For intra-hour variations, frequency control and load following, the synchronously operated system forms a relevant area. DC links connecting synchronously operated areas can also be automated to be used for primary power control; their power reserve capacity is usually, however, only allocated as emergency power supply. When looking at a large interconnected area, it has to be taken into account that benefits exist when there are no bottlenecks of transmission between the areas.[26] The relevant time scale for the operating reserve requirements is from several minutes to several hours. For wind power, also prediction errors 2–36 h ahead can affect the operating reserve. However, this will depend on how the producers or the balance-responsible players act, as they have the possibility to compensate for the prediction errors as the time of delivery approaches. In this study the hourly time series are used owing to a lack of 1 or 10 min data. As the hourly variations are greater than the 15 or 1 min variations, the results drawn will be conservative.

Data Used in This Study

The data-used in this study are the measured output of wind power plants and wind parks (Figure 5). Realized hourly wind power production time series from the four Nordic countries were collected. The total electricity consumption of the countries, also as hourly time series, was obtained to see the effect of wind variations compared with load variations. Data were collected for years 2000–2002.

For the hourly load time series for Finland there were some conspicuous load variations from one hour to the next. To be sure not to overestimate the initial load variations, one peak in 2001 and four peaks in 2002 data were corrected. For the Norway data, 12 conspicuous peaks in spring/summer 2000 load data were corrected as well so as not to be reflected in the total Nordic load data.

The data-handling procedure for wind power time series is described in more detail in Reference 27 and the data series used in Reference 21. A Nordic data set was formed from the data sets of the four countries. The production at each hour was a simple average of the % of capacity production of the four countries. In terms of capacity this would mean setting for example 3000 MW in each country, a total of 12,000 MW. This is somewhat theoretical, as Denmark is now dominating the installed wind power and probably will be for quite some time, even though the wind energy potential is probably as large in all four countries taking into account offshore potential. To see the effect of a more concentrated wind power capacity in the Nordic countries, also a data set called “Nordic 2010” was formed where half of the wind power capacity is in Denmark.

Wind power production varies according to wind resource, the yearly production is typically within ±20% of the long-term average production. The representativeness of the wind data has been looked at in Reference 21. As a total period, 2000–2002 will give a production that is less than average compared with wind power production indices available for the Nordic countries: 90% of average production in Denmark, 87% in Finland and 96% in Sweden. Year 2000 was close to average and year 2001 was clearly less windy than average. Year 2002 was close to average in Denmark and Sweden and a very-low-wind year in Finland. In addition to the representativeness of the study period, it is important to look at the representativeness of the data to describe the hourly variations of large-scale wind power production. The data need to be upscaled to look for the future impacts of large-scale wind power. If too few time series are used, upscaling the time series will also upscale the hourly variations, not taking into account the smoothing effect of thousands of turbines at hundreds of sites. At some stage the smoothing effect will saturate and adding more turbines/sites will not result in less variability. These data were deemed sufficient for Denmark, Finland and the total Nordic time series, but unsatisfactory for upscaling the time series of Sweden and Norway.[21]

Wind Power Production and Load

In this section the basic patterns of electrical load together with wind power production are presented. The main focus is on the hourly variations and on peak load situations.

Wind power is a production form that partly resembles electric consumption, the load. It varies each moment, with part of it being unpredictable, causing unexpected variations in the system. As an example, the wind power production in January 2000 is presented together with the load in Figure 6. The wind power production is here upscaled for Finland to represent approximately the same wind power penetration level* as in Denmark (roughly 10% of gross demand).

Basic statistics of the hourly load and wind power time series

Time series of load in the Nordic countries, featuring also duration curves, are presented in Figure 7 for year 2001. Electric load is characterized by a daily pattern, higher on weekdays than at weekends.[28] In addition to

* Wind power penetration is the share of produced wind power in the power system, presented here as % of energy, yearly gross demand. Penetration as % of installed capacity is also used in some studies, which is a considerably larger figure than expressing it as % of energy owing to the low capacity value of wind power.

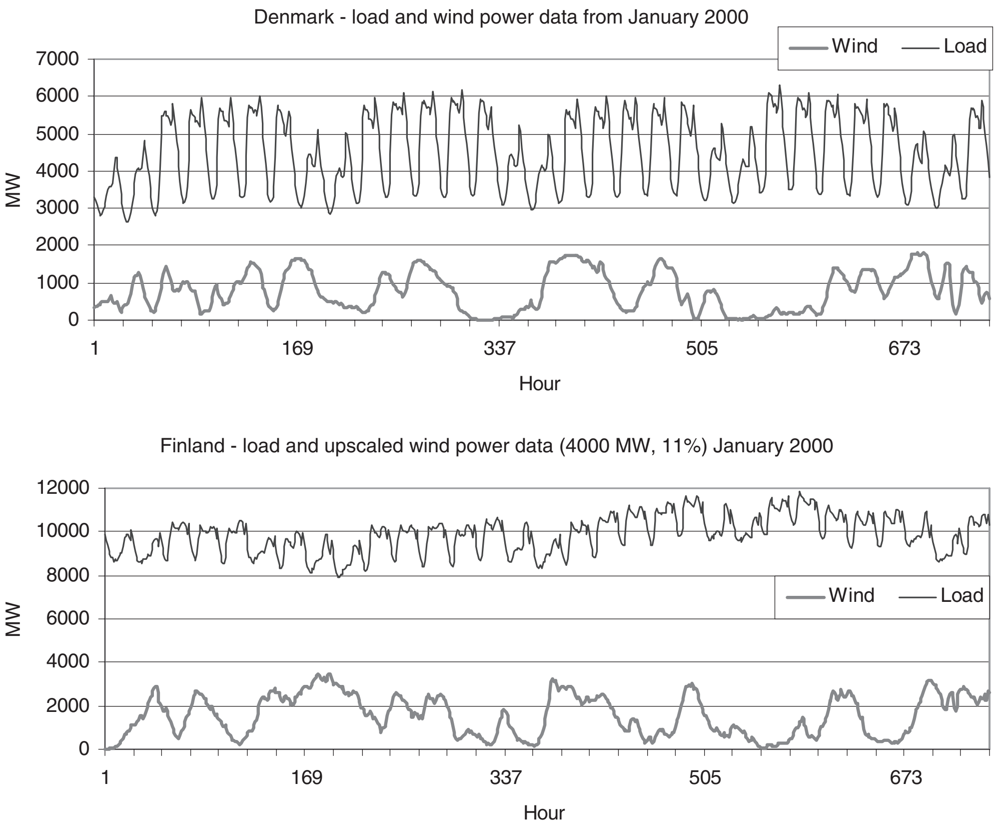


Figure 6. Electricity consumption (load) and wind power production in January 2000. Denmark is real data (12% wind power). For Finland, data from wind parks are scaled up to wind power penetration of about 11% of gross demand

daily cycles, temperature effects can be seen in the graphs: the load is generally lower during summer, and different weeks in winter show a dependence on temperature. As the *y*-axis scale is relative to the peak load, it can be seen that the load varies relatively more in Denmark compared with the other three countries with energy-intensive industry. Also electric heating used in Sweden and Norway and to a lesser extent in Finland can explain part of the difference.

Basic statistics of the load time series are presented in Table I for years 2000–2002. In both Sweden and Norway the consumption is larger than in Finland and Denmark together. Denmark has by far the lowest consumption, only about 10% of the total Nordic demand. The total yearly electric consumption in the Nordic countries has been rising by 2% between 2000 and 2001 and stayed about the same in 2002. In Finland the increase has been highest and continued from 2001 to 2002. In Denmark the consumption is quite stable.

The maximum peak load was in 2001, except for Finland in 2002. The peak load is about three times larger than the minimum load. Some smoothing can be seen in the total Nordic load time series: the peak is lower and the minimum load higher than the sum of the countries, as the peaks do not coincide. The Finnish load series is considerably less variable than for the other countries, as can be seen from the standard deviation relative to the mean value.

An example of year 2001 data for wind power production is presented in Figure 8. The basic statistics of wind data for years 2000–2002 are given in Table II. When wind power production comes from geographically distributed wind farms, the total production never reaches the total installed capacity and it is hardly ever totally calm. From the combined production in the Nordic countries, production above 50% of rated capacity

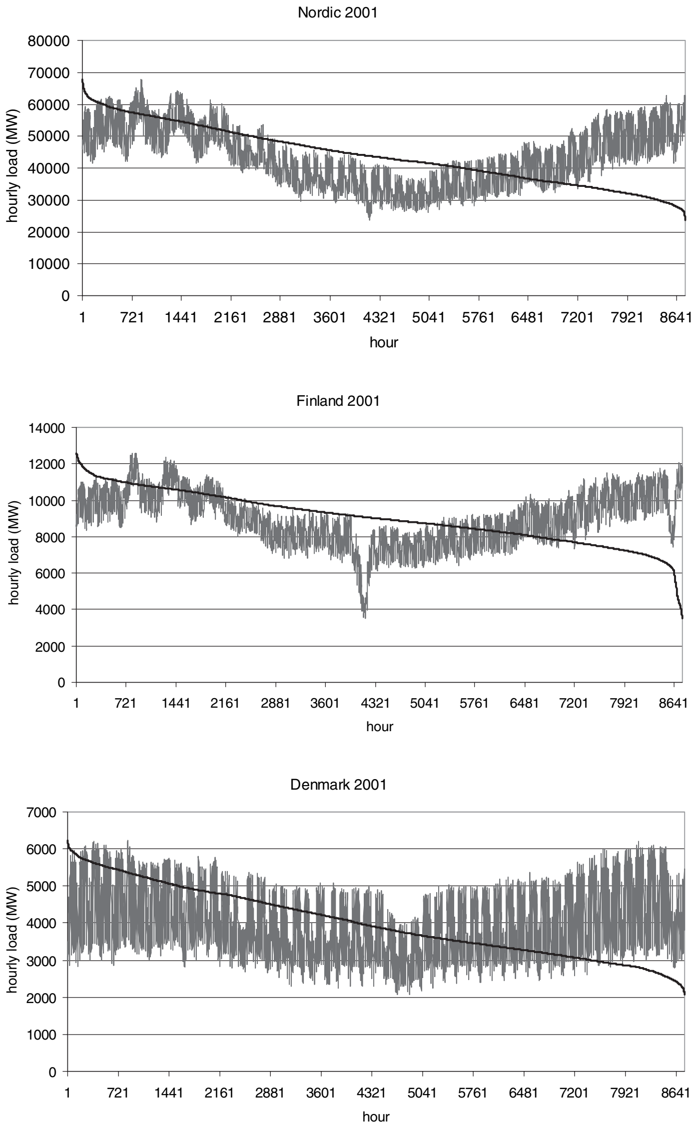


Figure 7. Hourly load of Finland, Denmark and the total of Nordic countries, chronologically and as duration curve. The y-scale is different for each graph

is rare in summer and production above 75% is rare in winter. The lowest hourly production was 1·2% of capacity for the Nordic wind power production time series.[21]

Correlation of load, wind power and other variable energy sources

The correlation between production and electrical load is of importance when considering the power system effects of a variable production form such as wind power. If wind power production has a tendency of following the load, e.g. wind power production increasing in the morning and decreasing in the evening, this has a beneficial effect.

For the Nordic data there is a slight positive correlation between wind power production and load, which means that somewhat more often the wind power production increases when the load increases, and *vice versa*,

Table I. Key figures for electric load in the study period 2000–2002.[a] The values are in MW and in % of peak load and the statistical parameters are presented here as averages of the values calculated separately for the three years (except for the maximum peak)

Statistic	Denmark	Finland	Norway	Sweden	Nordic
Sum (TWh a^{-1})	35/35/35	76/79/83	120/123/118	141/147/149	372/385/385
Max peak (MW)	6,284	13,654	23,054	26,323	67,854
Min (MW/%)	2,020/32	3,600/28	7,410/35	9,100/35	24,130/37
Peak/min[b]	3·09	3·52	2·89	2·84	2·69
Average (MW/%)	3,990/64	9,050/71	13,750/64	16,620/64	43,410/67
Stdev (MW/%)	930/15	1,380/11	3,030/14	3,580/14	8,530/13
Stdev/average (%)	23	15	22	22	20

[a] The total electrical consumption in the hourly time series is not exactly measured. This is why the electricity statistics show slightly different values:[1] the total consumption in the countries was 1%–4% higher in 2000, 1%–3% in 2001 and 1%–2% in 2002 (for example, the consumption for year 2001 was 35·4 for Denmark, 81·2 for Finland, 125·5 for Norway and 150·5 for Sweden, a total of 392·5 TWh).
[b] Peak/min is the reciprocal of min as % of peak load in the row above.

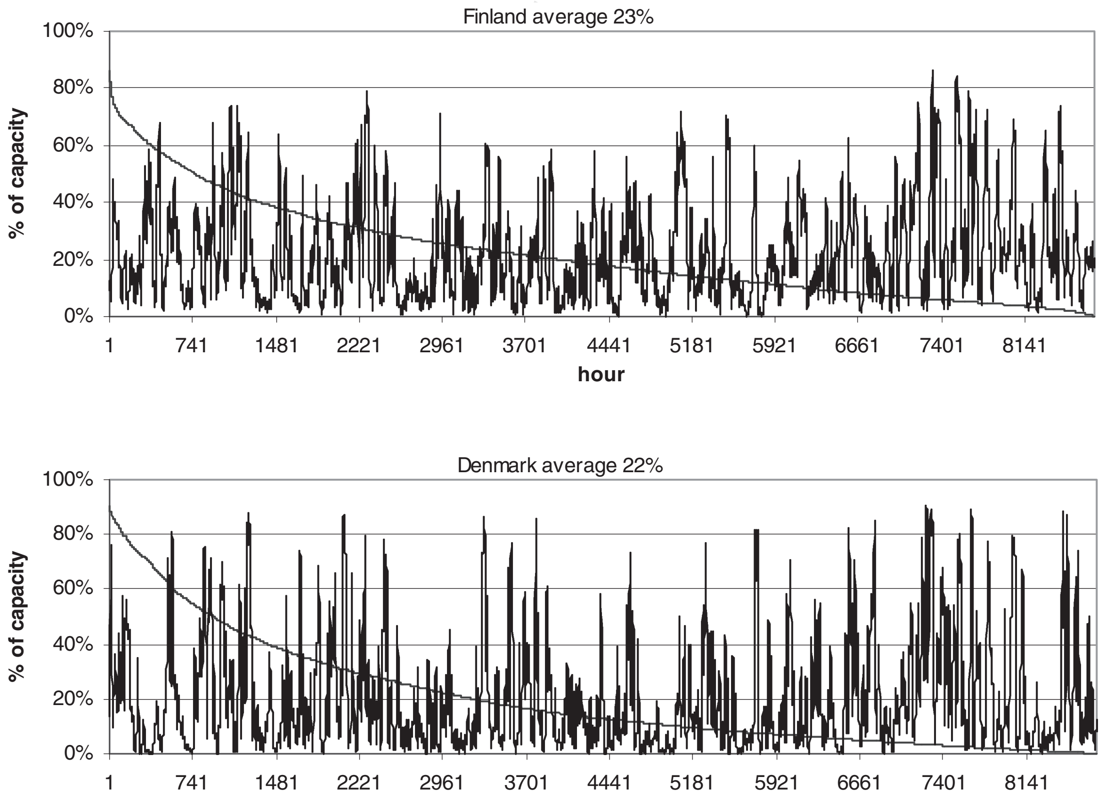


Figure 8. Hourly wind power production as % of capacity in Denmark and Finland in 2001, chronologically and as duration curve

Table II. Key figures for wind power production data in years 2000–2002. The values are relative to installed capacity. The width of the areas is presented as largest distance North–South (NS) and West–East (WE)

Statistic	Denmark	Finland	Norway	Sweden	Nordic
Largest distance NS/WE (km)	300/300	1000/400	1400/700	1300/400	1700/1100
Average (%)	24/20/22	24/22/20	34/31/32	24/23/24	27/24/25
Standard Deviation (%)	21·2	17·6	19·6	18·3	14·5
Minimum (%)	0·0	0·0	0·0	0·0	1·2
Maximum (%)	92·7	91·1	93·1	95·0	86·5
Correlation with load	0·21	0·16	0·37	0·24	0·31

than the opposite (Table II). However, when looking at the winter months only, the correlation is near zero. Thus the positive correlation probably comes from the diurnal pattern of wind power, mostly present in the summer.

Even simple statistical independence makes different variable sources more valuable than just more of the same. When variable sources are directly complementary (wind and solar in the same location), there are potentially large benefits. Also, combining variable sources with energy-limited plants can be beneficial. An example of an energy-limited production form is hydro power, where the maximum power cannot be produced during all hours of the year as there is not enough water to run through. Hydro inflow has a peak in May/June in the Nordic countries, whereas wind power production is dominant in the winter (October–February). Studies in Sweden and Norway show that wind power production combined with hydro power brings benefits for the system.[29,30]

Wind affects the heat demand. In the case of electric heating, this might have a positive impact through electric demand. In these data this effect was not seen, as the correlation between load and wind power production was close to zero in the winter also for Norway and Sweden, where electric heating is used. In the case of producing heat by district heating with combined heat and power (CHP) plants, this can be a negative impact, both wind power and CHP producing peaks at the same time.[7] The correlation of wind power production and district heating CHP production is only slightly positive for Denmark (0·14–0·24) and Finland (0·17–0·27). In the winter, again, the correlation is nearly zero.

Hourly variations of load and wind power production

The hourly load variation is here defined as the difference in load between two consecutive hours:

$$\Delta L_i = L_i - L_{i-1} \tag{1}$$

For wind power the nominal power (installed capacity) is here chosen as a relative measure:

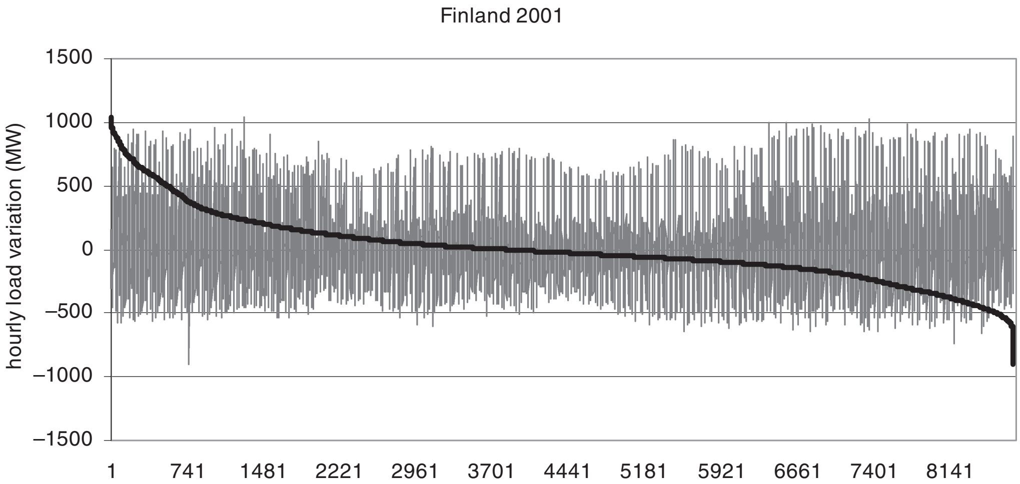
$$p_i = \frac{P_i}{P_{\mathrm{TOT}}} \tag{2}$$

where p_i is the relative wind production for hour i as % of capacity, P_i is the wind power production MWh h^{-1} for hour i and P_{TOT} is the installed capacity. Thus the hourly variation of wind power production can be written as:

$$\Delta p_i = p_i - p_{i-1}, \qquad \Delta P_i = P_i - P_{i-1} \tag{3}$$

An example of the hourly variations of load and wind power is presented in Figures 9 and 10 for Finland and Denmark in year 2001. Large upward variations of load are more frequent than large downward variations. The up-variations are also more costly to the system.

Basic statistics of hourly variations are shown in Table III for load and wind power production.



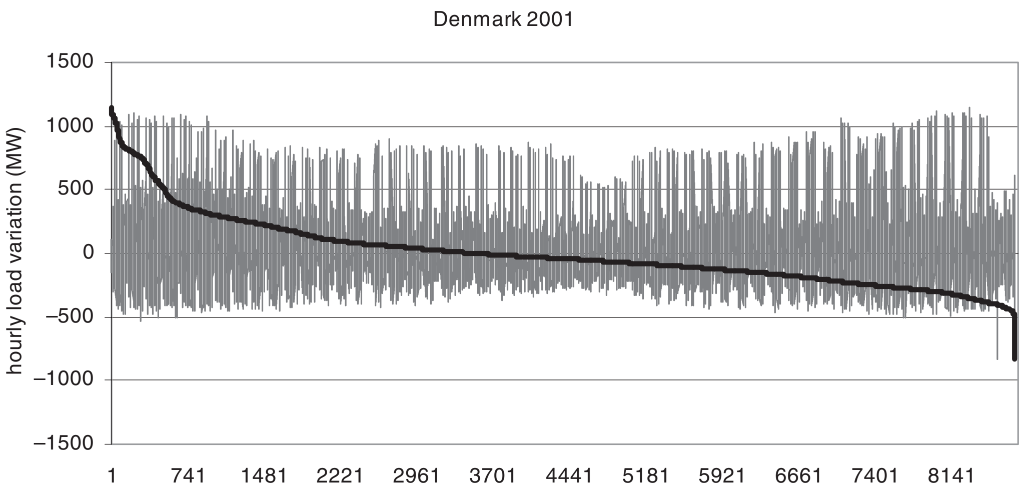


Figure 9. Hourly load variations, example Finland and Denmark, 2001, chronological time series and duration curve

The range of hourly variations of load is ±10% of peak load for the total Nordic load and for Finland; for Denmark it is higher, −14% to 18% of peak load. The hourly load variations are 99% of the time between −450 and 1000 MW in Denmark, −600 and 900 MW in Finland and −3000 and 5000 MW in the total Nordic time series. The typical range of daily cycle can be estimated from Figure 7. It is 16,000 MW for the total Nordic load, nearly 2500 MW for Denmark and 2000 MW for Finland. For Norway it is 2000 MW in summer and 4000 MW in winter, and for Sweden 4000 MW in summer and 6000 MW in winter.

The hourly variations of large-scale wind power production are within −23% to 20% of capacity for Denmark and well within ±20% of capacity for the larger countries. For the total Nordic time series the variations are within −12% to 11% of capacity. For a single country the wind power variations are 90% of the time within ±5% of capacity and 99% of the time within ±10% of capacity. For the total Nordic time series the hourly variations are about 98% of the time within ±5% of capacity.[21] The range of 4 h variations is about ±30% of capacity in the total Nordic time series and −62% to 53% of capacity in Denmark. The range of 12 h variations is about ±50% of capacity in the total Nordic time series and ±80% of capacity in Denmark.

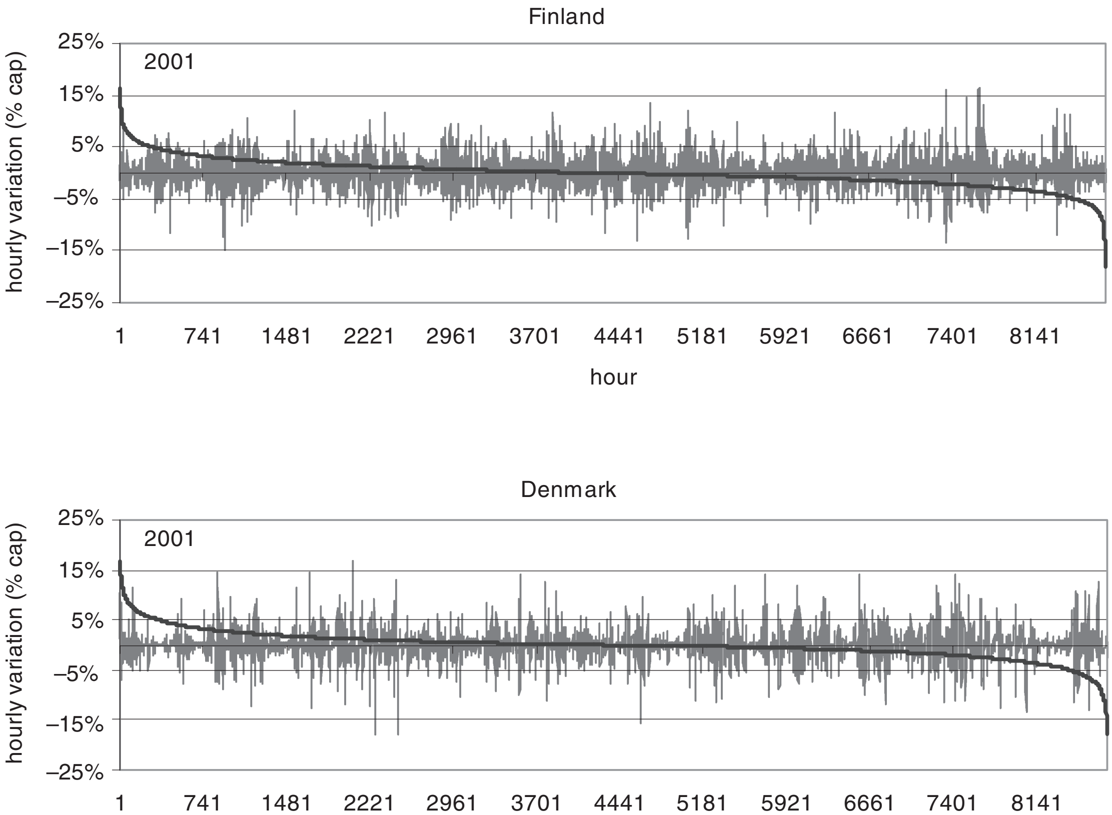


Figure 10. Hourly wind power variations, example Finland and Denmark, 2001, chronological time series and duration curve. Wind power production is relative to installed capacity

Table III. Hourly variations of load and wind power production in the Nordic countries in 2000–2002. The standard deviation of wind power production in MW is at 10% penetration level (of gross demand)

Statistic	Finland	Denmark	Nordic
Load: max up-variation (% of peak)	8·4	18·1	9·9
Load: max down-variation (% of peak)	–7·2	–13·7	–7·6
Load: standard deviation of variations (MW)	268	273	1438
Load: standard deviation of variations (% of peak)	2·0	4·3	2·1
Wind: max up-variation (% of P_{nom})	16·2	20·1	11·7
Wind: max down-variation (% of P_{nom})	–15·7	–23·1	–10·7
Wind: standard deviation of variations (MW)	104	58	336
Wind: standard deviation of variations (% of P_{nom})	2·6	2·9	1·8

Increase in Net Load Variations by Wind Power

To estimate the impact of wind power on power system operational reserves, it has to be studied on a control area basis. Every change in wind output does not need to be matched one-for-one by a change in another generating unit moving in the opposite direction. It is the total system aggregation that has to be balanced. The need for more flexibility in order to meet larger fluctuations in the system depends on how much wind power there is in the system, i.e. what proportion of consumption is covered by wind power production. Also systems are different: the amount of load variations and the flexibility in the system differ from country to country.

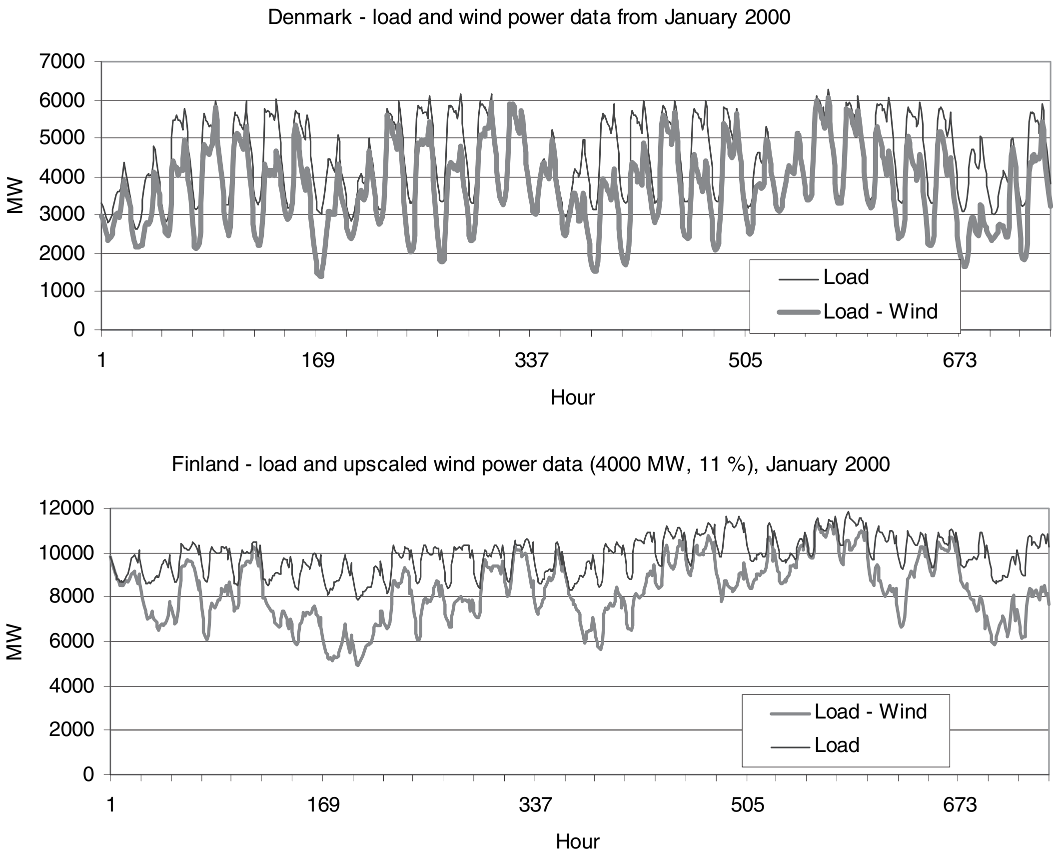


Figure 11. Electricity consumption (load) and net load (wind production subtracted from load) for 2000 MW wind power in Denmark and 4000 MW wind power in Finland

In Figure 11 the same time series as in Figure 6 are shown for January 2000, but the wind power production is subtracted from the load to show the effect of wind on the variations that the system will see. As the load in Finland varies considerably less than that in Denmark, a 10% penetration of wind would result in larger changes in the system in Finland than in Denmark. As the scale in Figure 11 is 1 month, 740 h, mainly the longer term variations (12–48 h) and the changes in those can be seen. On longer time scales there is time for the system to react to these changes—it is the time scale of electricity markets. It is clear from Figure 11 that, to accommodate larger shares of wind power, good prediction models for wind power production are needed.

The short-term variations were studied by hourly time series. Large-scale wind power production varies less the smaller the time step considered.[14] Therefore hourly variations can be used as an estimate for 10–15 min variations. The effect of large-scale wind power on primary reserve on a second to minute time scale has been estimated to be very small.[14]

The net load hourly variations are calculated like the hourly variations in equation (1), but now for the net load time series, where the wind power production is subtracted from the load:

$$\Delta NL_i = NL_i - NL_{i-1} = (L_i - P_i) - (L_{i-1} - P_{i-1}) = \Delta L_i - \Delta P_i \tag{4}$$

where *NL* denotes the net load (MW), *L* the load (MW) and *P* the wind power production and *i* is the hour (from 2 to 8760 in 2001 and from 2 to 8784 in 2000).

In Figure 12 the amount of hourly variations that the system sees is depicted, without wind (the hourly variations of the net load) and with wind (the hourly variations of net load). The difference in the maximum values

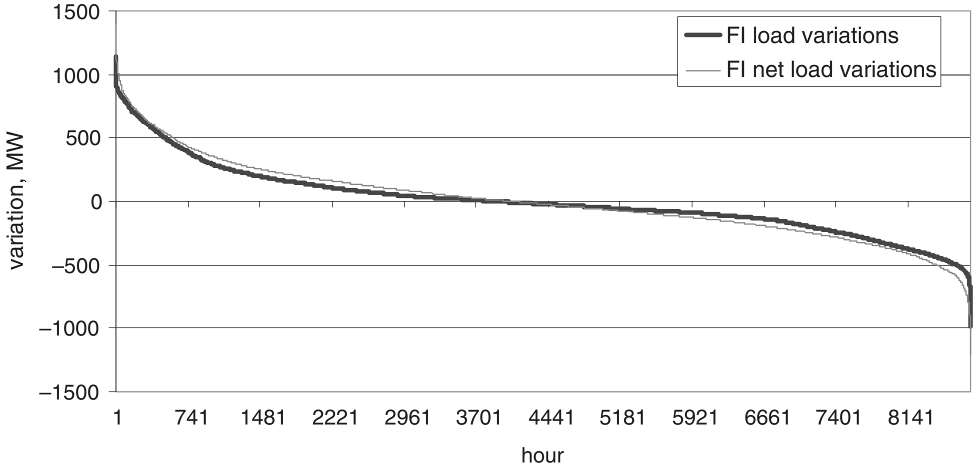


Figure 12. Duration curve of load variations (without wind power) and net load variations (load minus wind power), example Finland, year 2000, 6000 MW wind power (17% of gross demand)

indicates the amount that the operating reserve capacity has to be increased. The difference in the duration curves indicates the amount that the existing reserve capacity is operating more when wind power is added. The same capacity can in principle be used for both up- and down-regulation, and the variations as well as the increase should basically be symmetrical. Either up- or down-variations can determine the need for increase in the reserves. In many systems, e.g. Nordel, it is the up-regulation that is more critical to handle by the system.

The increase in hourly variations due to wind power is estimated below in three ways. This increase in hourly variations can be taken as an estimate for increase in the requirement for load-following or secondary reserve in the system. The results are summarized later in Table IV.

Wind power increasing the largest hourly variation in the system

Wind power has an effect on the total amount of load-following reserve capacity if the maximum of net load variations is larger than the maximum of load variations. The largest difference in hourly variations was looked for. This is the maximum increase in variations that the system will see.

The results for years 2000 and 2001 for Finland and Denmark are presented in Figure 13 for both the maximum upward variation (increase in down-regulation) and maximum downward variation (increase in up-regulation). Upscaling the wind power production and looking for the increase in maximum hourly variation in the net load time series, the curves are sometimes increasing linearly and sometimes piecewise linearly depending on what the wind power variation was in relation to the critical few hours of largest load variations. It can be seen from Figure 13 that this kind of analysis is very sensitive to the hourly data in question and can give very different results for different years. The increase in variations can be 0%–4% of installed capacity at 5% penetration, 0%–5·5% at 10% penetration and 2%–7% at 15% penetration.

Looking at a single maximum hourly variation per year when determining the increase in the variations due to wind can overestimate the effect, especially if there is any doubt on the reliability of the data. The largest hourly variations of load can be due to erroneous data. Some conspicuous peaks were removed from the Finnish load time series, however, some downward excursions that were not as clearly faulty data are still present in the data, as can be seen in Figure 9. More reliable data would be needed to avoid over- or underestimating the load variations. Variational analysis could be applied, e.g. as in Reference 12, but this might not be enough if there are erroneous peaks in the data. Another approach is presented in the next subsection.

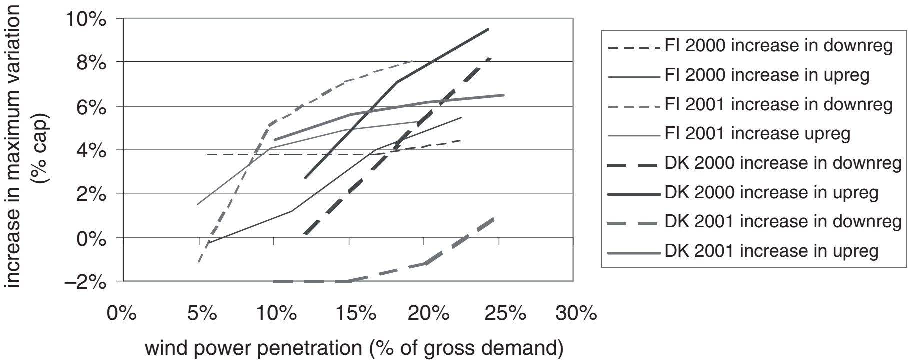


Figure 13. Maximum hourly variation of net load time series compared with load time series gives the increase in variations seen by the power system (as % of installed wind power capacity). Example from upscaling wind power production data for Denmark and Finland

Wind power increasing the hourly variations in the system

Planning and operating a power system is based on probabilities and risk. Reserves in the power system are determined so that variations within a certain probability are covered, e.g. 99·99% of the variations.

The standard deviation σ tells us about the variability of the hourly time series; it is the average deviation from the mean value μ:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu)^2}{n}} \tag{5}$$

For a normally distributed probability distribution the standard deviation σ is a measure indicating that about 68% of the data are within $\pm\sigma$ of the mean value. Taking a range of $\pm 3\sigma$ will cover 99%, and $\pm 4\sigma$ will cover 99·99% of all variations. For hourly variations the mean value is zero.

From Table III, the standard deviation of the hourly variations can be seen for load and wind power production. As the variations of load and wind power production can be assumed uncorrelated,* the standard deviation of net load time series (σ_{NL}) can be determined by a simple square root sum of the standard deviations of load (σ_L) and wind power (σ_W) time series:

$$\sigma_{NL} = \sqrt{\sigma_L^2 + \sigma_W^2} \tag{6}$$

Finally, the increase in the variations can be formulated as the increase in 4σ variations (Figure 14):

$$I = 4(\sigma_{NL} - \sigma_L) \tag{7}$$

Calculating in this way, we are assuming that wind power only contributes to the reserve requirement by the increase due to its addition to the system. This means that wind power gets the benefit of the existing power system. In the USA, different allocation methods have been elaborated,[31] where the benefit of joining two varying elements is divided by two; in this case the system would benefit a part of the addition of wind power. This would demand more from wind power than the simple increase in variations calculated here by equation (7). Both methods are numerically correct, it is a question of fairness or design of regulation payments. In the Nordic countries, different loads and production units do not pay different tariffs for the regulation burden they

*The hourly variations of wind power production and load are not correlated in these data. However, the distribution of the variation is not normal in the strict sense. This is why the use of equation (6) was checked for these data, and it produced accurate results for the standard deviation of the net load.

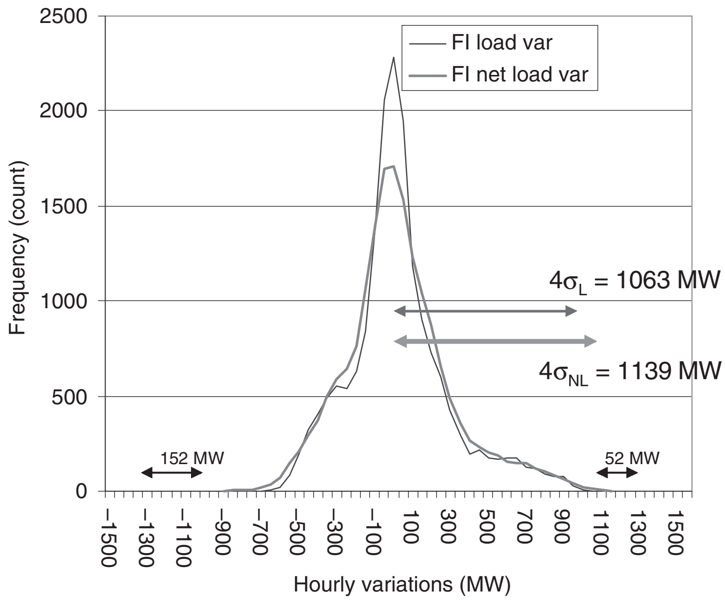


Figure 14. An example of estimating the increase in hourly variations seen by the system for Finnish 2000–2001 data. If only maximum variation is looked at, the increase is determined at the tails of the distribution (52 MW increase in up-variation and 152 MW increase in down-variation). Looking at the standard deviation of the distributions, there is a difference of 76 MW in the 4σ coverage of the variations

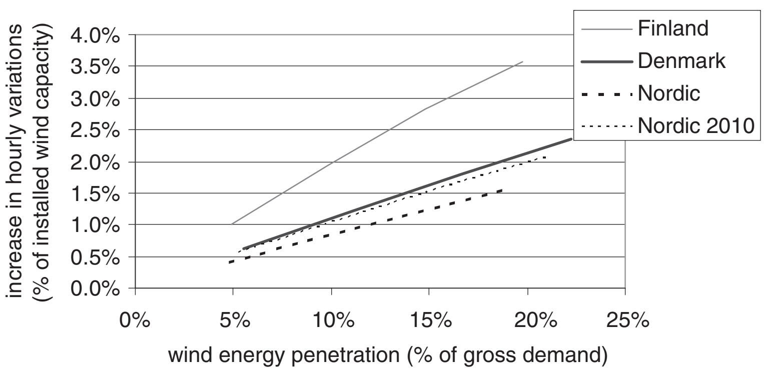


Figure 15. Increase in hourly load-following requirement for wind power, calculated from the standard deviation values of load and wind power production from years 2000–2002. Increase is relative to installed wind power capacity

pose to the system. Until the reserve requirements are allocated to loads and production units, it is well justified to calculate only the simple addition to reserve requirements for wind power.

The probabilistic approach gives lower requirements than only looking at the maximum changes. The increase in variations is 0·5%–1% of installed wind power capacity at 5% penetration (of gross demand), 1%–2% at 10% penetration and 1·8%–2·8% at 15% penetration (Figure 15). More specifically, 2000 MW in Denmark increases the variations by 1% (20 MW), and the same penetration level for Finland, 4000 MW, increases the variations by 2% (80 MW). The reason why the effect of wind power on variations is smaller in Denmark than in Finland is mainly based on the relatively larger load variations in Denmark, absorbing wind variations. Part of the difference may come from overestimated hourly variations of wind power data used here for Finland, due to the non-representative low number of wind power time series.

The same analysis was also made on the combined time series representing the Nordic wind power production. If the Nordic market area was working without bottlenecks of transmission, also the short-term variations of wind power could be absorbed by the system. If the total wind power production was distributed evenly to the four countries, this would result in increased hourly variations in the system, compared with the load variations today, of less than 1% of installed wind power capacity at 10% wind penetration (of gross demand). In other words, 19,000 MW of wind power in the Nordic countries would increase the hourly load-following requirements by about 160 MW. A more concentrated wind power capacity in the Nordic countries, with half of the capacity in Denmark and only 5% in Finland, would result in increased hourly variations in the system of slightly more than 1% of installed capacity at 10% wind penetration (of gross demand).

The total time period analysed here, years 2000–2002, had less than average wind resource. As the wind variability is stronger when the winds are stronger,[27] this might imply that the results presented above are underestimating the impact of wind power production. To check on this, the same analysis was made for the individual years 2000, 2001 and 2002. The variability of wind was slightly larger in 2000 than in the other years for Denmark. For Finland and the total Nordic time series the variability was largest in 2002, probably owing to some wind power time series missing that year. However, the differences in the analyses for the increased variability were not significant. The 4000 MW in Finland would produce 9%–11% of yearly gross demand in 2000–2002 and increase the variations by 76–80 MW (1·9%–2·0%). The 2000 MW in Denmark would produce 10%–12% of gross demand and increase the variations by 22–26 MW (1·1%–1·3%). The 19,000 MW in the Nordic countries would produce 10%–12% of gross demand and increase the variations by 139–166 MW (0·7%–0·9%) or, with a more concentrated wind power capacity, 187–220 MW (1·0%–1·2%).*

The impact of different wind resource years can be looked for from the Danish data. The result for the close to average wind years (2000 and 2002, 95% of average production) is 25 and 26 MW, compared with 24 MW using the three years 2000–2002 (90% of average production). This is a 4%–6% increase in the results, correcting the data of less than average wind resource to represent an average wind year. If only the low-wind year was used (80% of average), this would need to be corrected by 15% (from 22 to 26 MW).

These results suggest that one year of data may be enough to give an estimate in studies of variability of the system if some correction is applied in the case of low-wind years.

Wind power increasing the unexpected hourly variations of load

The analysis in the previous subsection assumes that the hourly variations of both load and wind power production are unexpected. However, as the load with its clear diurnal pattern is easier to forecast than wind power production, this should be taken into account when analysing the increase in operating reserve requirement due to wind power.[19]

For wind power the production an hour ahead can be reasonably well forecasted by persistence, i.e. taking the production level at hour $i - 1$ for the predicted value at hour i. Actually this results in using the hourly variation as used in previous subsections as a measure of forecast error of wind power production. The short-term prediction tools can improve on this to some extent, taking into account the forecasted trend of wind speeds in the area, as well as time series techniques that have proven to work quite well for some hours ahead.[32] The persistence is therefore a conservative estimate for the wind power production an hour ahead.

The load prediction has been studied for decades, it is well known and the predictions are quite accurate (within 1%–2% of peak demand). There is a diurnal pattern and dependence of temperature in the demand for electricity. A case study for Finnish year 2001 load data was carried out to estimate load forecasts. A model at VTT Technical Research Centre of Finland was used, based on calendar days of loads (from year 2000 data) and temperature.[33,34] The mean absolute error, hour ahead, was 0·7% of peak load. This is probably lower than what is experienced in different system areas on average.[19] The forecast error for the load was then compared with wind power variations. The standard deviation of forecast error was 123 MW (1% of peak load), in com-

*Penetration level of wind power is here varying with varying wind resource of the years. It is on average slightly above 10%, to compensate for the total consumption of the hourly time series being 1%–4% lower than the realized load.

Table IV. Summary of results for the increase in hourly variations by wind power in Finland. For maximum hourly variation: if positive, the value is increasing from last hour to current hour. Year 2001 data

Wind power (MW)	2000	4000	6000
Wind power penetration (% of gross demand)	4·9	9·8	14·6
Maximum hourly variation of wind (MW)	280/–310	560/–620	840/–930
Maximum hourly variation of load (MW)	1144/–985	1144/–985	1144/–985
Maximum hourly variation of net load (MW)	1138/–1061	1191/–1137	1385/–1214
Increase in maximum hourly variation (MW)	–6/76	47/152	241/229
Stdev wind power hourly variations (MW)	52	103	155
Stdev load hourly variations (MW)	269	269	269
Stdev net load hourly variations (MW)	274	288	310
Increase in variations, 4σ (MW)	20	76	165
Stdev load forecast error (MW)	123	123	123
Increase in forecast error variations, load forecast only, 4σ (MW)	41	150	298
Stdev wind forecast error (MW)	41	82	124
Increase in forecast error variations, 4σ (MW)	27	100	206

parison with 267 MW for the load hourly variations, so this method assumes that about half of the variability in load can be predicted.

Now, making the same analysis as in the previous subsection but using load forecast error instead of the hourly variation of load, we get the results in Table IV for different wind power prediction error levels.

The results in Table IV show that the results in the previous subsection, based on the simple hourly variations from load and wind power time series, should be increased by 50%–100% depending on the level of wind power forecast (no forecast to hour ahead . . . forecast improving by 20% over persistence). This means that, when producing 10% of yearly electricity consumption with wind power, the increase in hourly load-following requirement would be 1·5%–4% of the installed wind power, instead of 1%–2% as in the previous subsection. More specifically, for Denmark the 2000 MW of wind power would increase the load-following requirement by 30–40 MW, for Finland the 4000 MW by 120–160 MW and for the Nordic countries the 19,000 MW by 240–320 MW.

Summary and Conclusions

In this study the focus is on the hourly time scale impacts on the power system, based on real and synchronous load and wind power production data. The incremental changes to the system due to wind power were studied. The area of study was one country (Finland, Denmark) or the whole Nordic area.

Example years 2000–2002 were studied. As a total period, 2000–2002 will give a wind power production that is less than average: 90% of the average production in Denmark, 87% in Finland and 96% in Sweden.

Electrical load is characterized by a daily pattern, higher on weekdays than at weekends. In addition to daily cycles, strong temperature dependence can be seen in the Nordic countries. Wind power has a slightly positive correlation with the load, especially in Denmark. However, during the winter months the correlation is practically non-existent.

The range of hourly variations of load is ±10% of peak load for the total Nordic load and for Finland; for Denmark it is higher, –14% to 18% of peak load. The hourly load variations are 99% of the time between –450 and 1000 MW in Denmark, –600 and 900 MW in Finland and –3000 and 5000 MW in the total Nordic time series. The hourly variations of large-scale wind power production are within –23% to 20% of capacity for Denmark and well within ±20% of capacity for the larger countries. For the total Nordic time series the variations are within –12% to 11% of capacity. The hourly variations of large-scale wind power production are 99% of the time within ±10% of capacity. For the total Nordic time series the hourly variations are about 98% of the time within ±5% of capacity.

The need for more flexibility in the electricity system, due to short-term variations of wind power, was estimated for Denmark, Finland and the combined Nordic countries. Net load variations (load minus wind production) compared with load variations give an estimate for the needs of the system to react to large-scale wind power. An analysis based on only the maximum hourly variation was found to be very sensitive to the hourly data in question, giving different results for different years of data, depending on what the wind power change was during the critical hours of maximum load changes. A probabilistic approach gave estimates for the range of variations, from the standard deviation (σ) values, taking $\pm 4\sigma$ as the range that covers most variations (99·99% of all variations are within this range). The results are that at 5% wind power penetration (of gross demand) the increase in variations is 0·5%–1%, at 10% penetration 1%–2% and at 15% penetration 1·8%–2·8% of installed wind power capacity. The effect of wind power on variations was smaller in Denmark than in Finland. This is mainly due to the relatively larger load variations in Denmark, absorbing wind variations. If the Nordic electricity market area was working without bottlenecks of transmission, 10% of wind energy distributed in the area would require extra flexibility of less than 1% of installed capacity at 10% wind penetration (of gross demand).

The estimation is based on hourly wind power and load data from three years. The years were less than average wind years, meaning that the hourly variations could be underestimated. The underestimation in these results, due to less than average wind resource during the study period 2000–2002, is of the order of 4%–6% only.

The estimates of increase in hourly variations do not take into account the fact that the variations are easier to predict for the load than for wind power production. To estimate the effect of load and wind forecasts on these analyses, a case for Finnish year 2001 load estimates was run based on the information from year 2000 load data. This analysis showed that the results above, based on the simple hourly variations from load and wind power time series, should be increased by 50%–100% depending on the level of wind power forecast (no forecast versus forecast being 20% better than not using any). This means that, when producing 10% of yearly electricity consumption with wind power, the increase in hourly variations would be 1·5%–4% of the installed wind power, instead of 1%–2% neglecting the forecasts. More specifically, for Denmark the 2000 MW of wind power would increase the hourly variations by 30–40 MW, for Finland the 4000 MW by 120–160 MW and for the Nordic countries the 19,000 MW by 240–320 MW. This can be used as an estimate for the increase in requirements for load-following or secondary reserve for the power system due to wind power.

The smoothing effect of thousands of wind turbines at hundreds of wind farm sites is underestimated by the wind power data sets used for Finland and the total Nordic area. This means that the estimates for the variations of wind power production are probably still somewhat conservative.

Another basic assumption is that the hourly variations give an estimate of the short-term variations relevant for operating reserve of the power system. Secondary reserve is operated in 10–15 min. Hourly data are used here, as 15 min data are very limited and would not allow for a large-scale system study. However, as the wind varies less within an hour than on an hourly basis, using hourly data would not underestimate the effects. The results from a study from Ireland suggest that at 10% penetration the increase in hourly variations of the net load is less than 2% of wind power capacity, whereas the half-hourly data give an increase of less than 1% of wind power capacity.[19]

The conclusion of this study is that the hourly variations of large-scale wind power will be seen as an increase in the hourly variations and thus operating reserve requirements of the power system. The impact will increase the larger the share of gross demand produced by wind power. At a 10% wind power penetration level this is estimated as 1·5%–4% of installed wind capacity, taking into account that load variations are more predictable than wind power variations.

The costs of this increase in operating reserves, as well as electricity market studies, focusing on longer-term variations of wind power, are subjects for future work.

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