Research Article

Hourly Wind Power Variations in the Nordic Countries

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Studies of the effects that wind power production imposes on the power system involve assessing the variations of large-scale wind power production over the whole power system area. Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output. In this article the patterns and statistical properties of large-scale wind power production data are studied using the data sets available for the Nordic countries. The existing data from Denmark give the basis against which the data collected from the other Nordic countries are benchmarked. The main goal is to determine the statistical parameters describing the reduction of variability in the time series for the different areas in question. The hourly variations of large-scale wind power stay 91%–94% of the time within ±5% of installed capacity in one country, and for the whole of the Nordic area 98% of the time. For the Nordic time series studied, the best indicator of reduced variability in the time series was the standard deviation of the hourly variations. According to the Danish data, it is reduced to less than 3% from a single site value of 10% of capacity. 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. These are the main reasons why large-scale wind power production poses a challenge to the rest of the energy system.

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.

This study is based on existing production data on an hourly level. Detailed statistical analyses of hourly wind power production are presented. The aim is to see how large-scale, regional wind power production looks compared with the production of a single wind farm and, going further, how wind power production from the whole Nordic area looks compared with the production from one country only.

The installed wind power capacity at the beginning of year 2003 was 2200 MW in West Denmark,[1] 573 MW in East Denmark,[2] 345 MW in Sweden,[3] 97 MW in Norway[4] and 41 MW in Finland.[5] In Denmark, system integration of wind power is already a reality, whereas in other countries it is still a subject for discussion.

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Previous Work and Scope of This Study

The extent of wind power variability has been the subject of several studies. European meteorological station wind data for 1 year have been used in two studies, though not covering all the Nordic countries.[6,7] In The Netherlands a detailed analysis of wind speed data was done including variability and persistence.[8] In Ireland and France the variations of dispersed wind power production have been studied with wind speed data across each country.[9,10] For the Nordic countries a study based on Reanalysis (weather prediction) long-term 12-hourly wind speed data was made looking at the longer variations and correlation of production.[11] For Finland, yearly and monthly wind power variations were studied in Reference 12 and 3-hourly variations based on data for five geographically dispersed weather stations in Reference 13.

All the studies above have been based on wind speed data from several geographically dispersed measurement masts, converting wind speeds first to higher altitude (hub height of wind turbines) and then to the production of a single wind turbine using a power curve. There are possible caveats firstly in upscaling the wind to higher altitudes, as the wind profile is dependent on atmospheric conditions,[8] and secondly in using a single-point measurement to represent a wind farm stretching from one to several kilometres in dimensions.

Studies based on wind power production are scarcer owing to the fact that large-scale wind power production has only started to emerge in the past few years. In The Netherlands the variability and persistence of dispersed wind farm data of 250–500 kW turbines[14] confirm most of the wind speed data analyses of Reference 8, but an indication of somewhat less variability when using wind turbine data can be seen. In Germany, statistical analyses from production and measured wind speed data have been made in conjunction with a comprehensive 10 year follow-up project of the 250 MW programme.[15,16] Annual, seasonal, diurnal and hourly variations are one result of this activity. Faster measurements of these data were further analysed to look at the trends of power fluctuations as well as fast regulation needs of wind power.[17] Fast ramp rates (from 1 s to 1 h) for a large wind farm have been recorded in the USA.[18,19] For power system impact studies, wind farm data have been used;[20–22] however, often the problem has been to get enough wind power production data to represent the whole of the area in question, as well as getting synchronous data from both the electrical load and wind power production. The representativeness of the data, especially for the variations of wind power production, is crucial for the studies, as upscaling too few data series to large-scale wind power production will also upscale the variations, not taking into account the smoothing effect.[23] A study of the smoothing effect and its saturation has been made for the Northern part of Germany.[24] To take into account the smoothing effect, extrapolation of statistical parameters has been used,[25] as well as preprocessing of wind power data by sliding averages.[26]

This work is based on a data set of realized hourly wind power production values from three example years. The study is mainly concentrated on the extent of wind power hourly variations, and the results can be used to assess the impacts on the secondary reserve or hourly load-following reserve of the power system (dealt with in the second part of this study[27]). It is common sense as well as proven by earlier studies that geographical spreading of wind power will reduce variability. However, the quantification of this phenomenon is not straightforward. This is a relevant research topic in itself, needed in order to determine what kind of input data for wind power should be used when studies of wind power in power systems are made.

Data Used in This Study

The data used in this study are the measured output of wind power plants and wind parks (Figure 1). Realized hourly wind power production time series from the four Nordic countries were collected. Data were collected for years 2000–2002.

To compare the data sets of different installed capacity, they were represented as relative production, as % of installed capacity:

$$p_i = \frac{P_i}{P_{\text{TOT}}} \tag{1}$$

Figure 1. 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

where p_i is the relative production for hour i as % of capacity, P_i is the production MWh h^{-1} for hour i and P_{TOT} is the installed capacity.

For wind power production time series in Finland, Sweden and Norway the available data represented far less than 100 MW of capacity. This means that these time series had to be upscaled more than 10-fold to make large-scale wind power production time series for the countries. Upscaling the hourly values means upscaling also the hourly variations. Real large-scale wind power production would mean that the output would be smoothed out by hundreds or thousands of turbines located at tens or hundreds of sites. An example of the problem is illustrated in Figure 2, taken from real data in Denmark. This is why several geographically dispersed sites were looked for to make the aggregate time series for the countries. Also hourly wind speed measurement data were used to complement the production data for Finland, Sweden and Norway. There were two wind speed series for Finland and one for Sweden. Most of the data for Norway were wind speed time series. An effort was made to make single-point measurement data represent wind farm production when wind speed was converted to wind power production. First the wind speed was smoothed out by taking a 2 h sliding average for each hour. This smoothed wind speed was converted to power production using an aggregated, multi-turbine power curve (Figure 3).[28] The data handling principles are described in more detail in Reference 29.

The Nordic data set was formed from the data sets of all 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
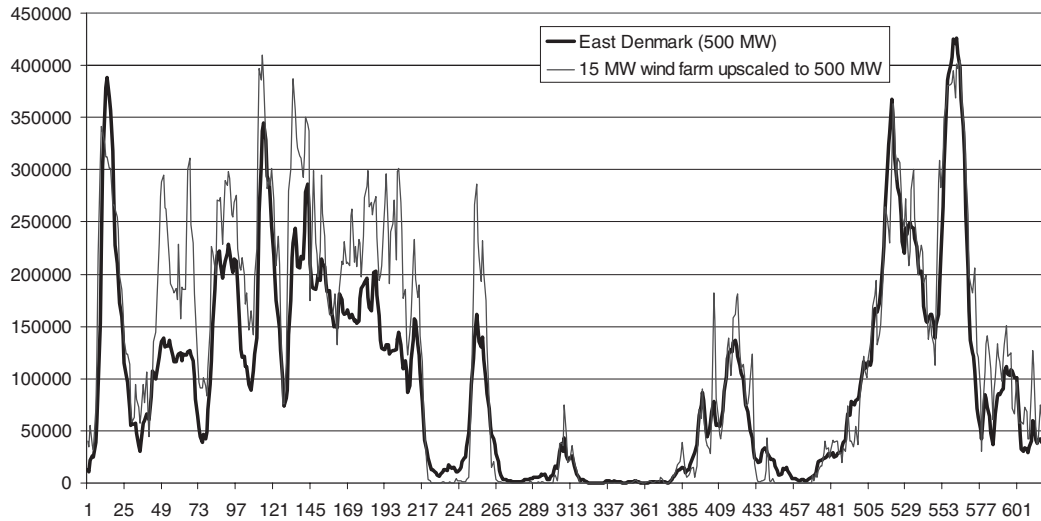
Figure 2. An example of wrong upscaling: a single site would see more variations, peaks and calms than dispersed, large-scale wind power production (here 500 MW, 200 × 100 km²)
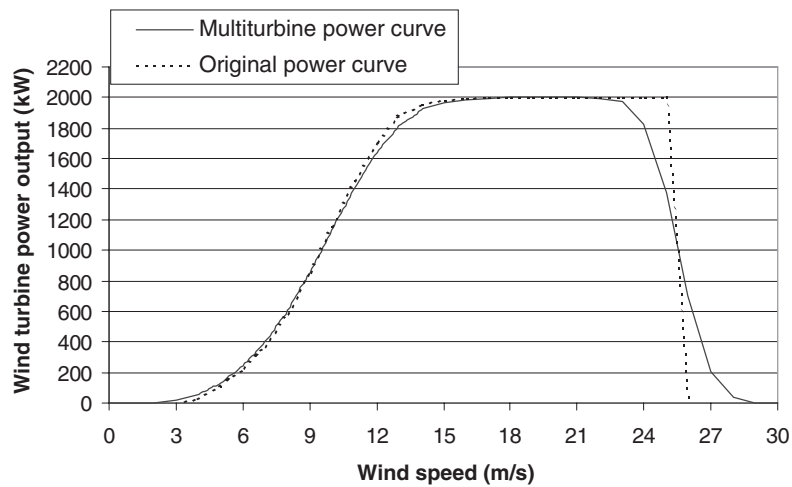

Figure 3. To convert the wind speed time series to wind farm power production, a multi-turbine power curve was used, smoothing out the production near the cut-in (3 m s⁻¹) and cut-out (25 m s⁻¹) wind speeds compared with a single-turbine power curve

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 the offshore potential. Also a time series called 'Nordic 2010' was formed where half of the capacity is in Denmark.

Data set for Finland

By courtesy of 10 wind power producers and two power companies with wind speed measurements for high masts, wind power production data were available from a total of 55 turbines at 21 sites and wind speed data were available from two sites (on the Internet[30]).

The maximum distance between the sites is 1000 km North–South and 400 km West–East. As the data were used to represent large-scale wind power production, they were upscaled. To represent the geographical distribution of potential wind power production in Finland, Lapland and the South coast were reduced to a tenth of total capacity each, and the West coast was given the bulk of wind power production: 400 MW in the Gulf of Bothnia South and 400 MW in the Gulf of Bothnia North.[29]

Data set for Sweden

For Sweden, wind power production data were acquired from two sites in South Sweden (West and South coast), one by the large inland lake Vättern and the other on the island of Gotland (East coast), and one site in North Sweden by the East coast. From the Northern part, also one wind speed measurement time series was acquired.[31] The maximum distance between the wind power data sites in Sweden is 1300 km North–South and 400 km West–East.

For upscaling, 80% of capacity was assumed in South Sweden and 20% of capacity in North Sweden.

Data set for Norway

For Norway, wind power production data were acquired from one site. However, the data had missing periods, especially for year 2001. Two wind speed measurement time series were acquired from potential wind power sites in Middle and South Norway covering part of year 2000.[32,33]

Norwegian meteorological institute (NMI) data were well representative for wind power production: it is measured hourly and with high average wind speeds. Five sites along the coastline were used for 2000–2002, and additionally six sites for year 2001.

Norway is the largest country when considering the largest dimensions between the potential wind farm sites: about 1400 km North–South and 700 km West–East.

For upscaling, Norway was divided into three regions, first aggregating the available data as simple averages per site for each of South, Middle and North Norway. The total wind power production was also a simple average: the same amount of wind power was assumed for South, Middle and North Norway.

Data set for Denmark

For Denmark the system operators Eltra (West Denmark) and Elkraft System (East Denmark) have hourly production data available at their Internet sites, starting from year 2000.[1,2] Also some subarea data (15–60 MW) were available for East Denmark in 2001, courtesy of Elkraft System. The maximum distance between the sites in West Denmark is roughly 300 km North–South and 200 km West–East. For the Eastern part the dimension is about 200 km North–South and 100 km West–East. Bornholm island, south of Sweden, is a part of East Denmark.

The Danish data represent the realized production of thousands of turbines and hundreds of sites. However, there has been a significant increase in wind power capacity from 1730 MW at the start of 2000 to 2612 MW at the end of 2002 (Table I).

To be correct in converting the hourly production in MWh h^{-1} to relative production, as % of capacity, exact data on each wind farm's network connection would be needed. This means making an hourly P_{TOT} time series

Table I. Installed wind power capacity (MW) at the start of the year in Denmark

Year	Denmark, West	Denmark, East	Denmark, total
2000	1340	390	1730
2001	1790	503	2293
2002	1970	554	2524
2003	2040	572	2612

in equation (1), P_{TOTi}. If the information on capacity addition (or reduction, as some old wind turbines have been taken from operation) was not correct, a step-up in the MW time series at a wrong hour could distort the real production time series. This would either add more variations or damp the real variations from one hour to the next.

Daily data on capacity development in East Denmark were obtained for years 2001 and 2002. For West Denmark, and for year 2000 in East Denmark, no exact data on capacity were available. For these data sets an approximate hourly MW series has been constructed to convert the data to % of capacity. For West Denmark the capacity has been rising at an average rate of 50 kW h^{-1} in 2000 and 13 kW h^{-1} in January 2001, after which a constant capacity has been used, until a rise in November/December 2002 of 48 kW h^{-1}. The large offshore wind farm at Horns Rev was started in December 2002. However, owing to low availability during the first testing period, this 160 MW was not taken as an increase in the installed capacity in this study. For East Denmark the capacity has been rising at an average rate of 16 kW h^{-1} in 2000. The maximum rise of capacity, in the daily capacity data of East Denmark, is 17·8 MW in 2001 and 11·5 MW in 2002.

Looking at the capacity increase in Denmark,[1,2] it has been quite linear. The difference between the approximation used here and real life would stay below 20 MW at any hour. The errors for the hourly variations are even smaller, as the capacity increase in practice comes as one to three turbines at a time when the test operation of a wind farm starts. Assuming a maximum 10 MW instantaneous capacity increase in an hour, this would be seen as an error of 0·5% of capacity in the hourly variation, either overestimating an upward variation or underestimating a downward variation in the data set used in this study. The error is very small in the situation where there is in real life no increase in the capacity from one hour to the next—an assumed 60 kW increase in capacity is 0·003% of the total capacity at the beginning of year 2000 and 0·002% at the end of year 2002.

Large-Scale Wind Power Production

Large-scale wind power means the production of hundreds (or thousands) of turbines at tens (or hundreds) of sites. Geographical spreading of production evens out the total production from an area. The smoothing effect can be seen from the statistical analyses presented in this section. Examples of the data sets in this study are shown in Figure 16 (see Appendix) for February 2000.

Basic statistics of the wind power production data used

The basic statistics of the yearly time series are presented in Table II. Wind power production statistics from the four countries and their combination are shown. As a comparison, data from a single site in Finland are also shown. For stall-regulated turbines the maximum power can exceed the nominal capacity, especially in cold weather.[34]

Table II. Descriptive statistics of hourly wind power production in the Nordic countries for years 2000–2002. Wind power production is presented as relative production as % of installed capacity. The width of the areas is presented as largest distance North–South (NS) and West–East (WE)

Statistic	Single site	Denmark	Finland	Norway	Sweden	Nordic
Largest distance NS/WE (km)	—	300/300	1000/400	1400/700	1300/400	1700/1100
Mean (%)	25·9	22·2	22·3	32·3	23·5	25·1
Median (%)	14·9	14·6	17·5	29·2	18·6	22·4
Standard deviation (%)	28·2	21·2	17·6	19·6	18·3	14·5
Standard deviation/mean	1·09	0·95	0·79	0·61	0·78	0·58
Range (%)	105·0	92·7	91·1	93·0	95·0	85·4
Minimum (%)	0·0	0·0	0·0	0·0	0·0	1·2
Maximum (%)	105·0	92·7	91·1	93·1	95·0	86·5

First of all, the difference in wind resource is notable: Norway has an excellent wind resource, with an average production of 32% of capacity compared with 22%–24% for the other Nordic countries. Over the years, average production varies between 31% and 34% of installed capacity in Norway and between 22% and 25% of capacity in the other countries.[35] Denmark has here the lowest production rates as % of capacity. This is probably due to the data including also inland sites and sites with older turbines with 20–40 m towers: the rotors are not reaching as good a wind resource as the new, 60–100 m high MW-scale turbines. The production here does not yet have large offshore wind power included, with better wind resource (two 160 MW wind farms erected in late 2002 and 2003).

The median is the value in the middle when sorting all the values in increasing or decreasing order. For wind power production it is typical that the median is lower than the mean value. Most of the time the production is less than average. When aggregating production from a larger area, the median gets closer to the mean value.

The smoothing effect can be seen in the range of production, the maximum and minimum encountered during the years. Duration of calms will be substantially decreased, as the wind blows almost always in some part of the system area. Maximum production level will not reach installed nominal capacity, as the wind will not blow as strongly at all sites simultaneously, and of hundreds or thousands of wind turbines not all are technically available at each instant. For the total Nordic time series the production never goes to zero; however, the lowest production is only 1% of installed capacity. The maximum production from geographically dispersed wind power production stays under 90% for the Nordic countries. Even if we are talking about large-scale wind power production, the production range will still be large compared with other production forms: maximum production will be three to four times the average production, depending on the area (Table II).[11]

Another trend of smoothing can be seen in the standard deviation values. The standard deviation σ reveals the variability of the hourly time series, it is the average deviation from the mean value μ:

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

For a single turbine the standard deviation is somewhat larger than the mean, about 30% of capacity (nearly 40% for some sites in Norway). For a country the standard deviation gets closer to 20% of capacity. For larger countries such as Norway, Sweden and Finland, where the sites are spread 1000 km apart, the standard deviation is less than 20%. For the total Nordic time series the standard deviation is close to 15% of capacity (Table II). The standard deviations for European data derived from wind speed measurements suggest that the standard deviation relative to the mean value is 0·5–0·8 for a circle of radius 200 km and 0·4–0·6 for radius 1000 km, and the smoothing effect saturates at about 0·3 when the radius gets larger than 2000 km.[7]

Frequency distributions of wind power production

To take a closer look at wind power production, the hourly production is plotted as a frequency distribution in Figure 4.

It can be seen in Figure 4 that large-scale production of wind power means shifting the most frequent ranges from low production to near average production. For a single site the production is almost half of the time below 10% of capacity. For the wind power scattered to all Nordic countries, the production is most of the time between 5% and 30% of capacity and is seldom below 5% or above 70% of capacity.

The probability of wind power production can also be presented as a duration curve. In Figure 5 the Nordic wind power production for year 2000 is shown chronologically (the varying curve) and as a duration curve, where the production values are sorted in descending order before drawing the curve. In Figure 6 the smoothing effect is presented as duration curves.
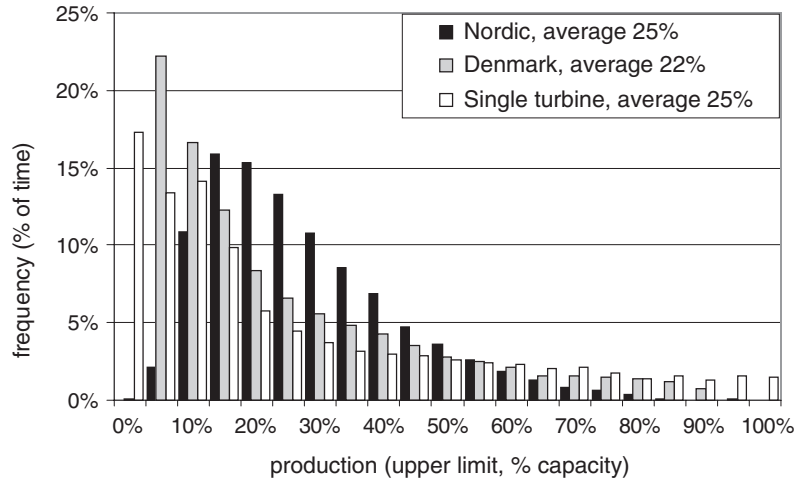
Figure 4. Frequency distribution of wind power production from one site, from a country and for a theoretical total Nordic production. Example years 2000 and 2001. The production values on the x-axis denote the upper value of the range
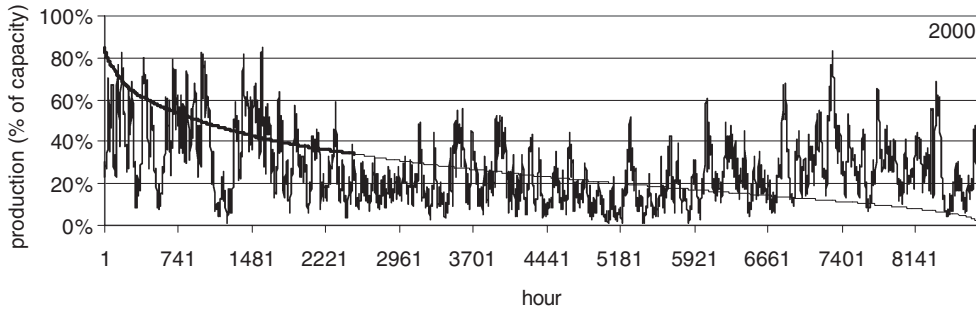

Figure 5. Example of data for this study: the total Nordic wind power production as a chronological time series and as a duration curve
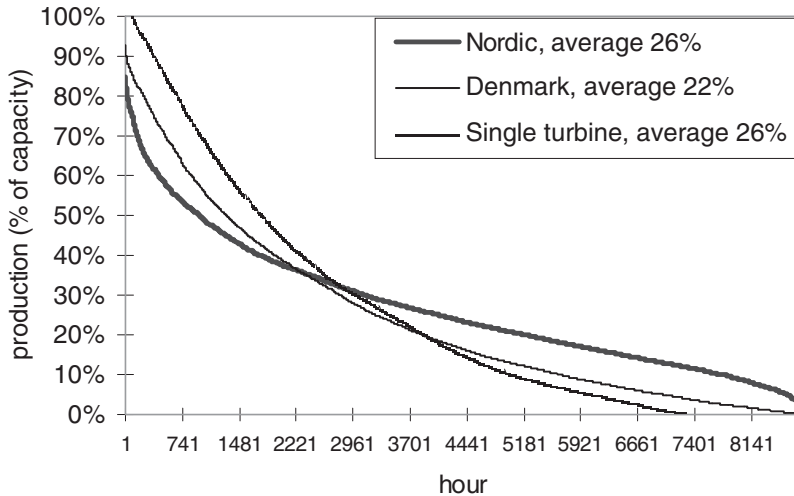

Figure 6. The effect of geographical spreading is to flatten the duration curve of wind power production. Example of year 2000 hourly data, where wind energy distributed to all four Nordic countries is compared with one of the wind farms and one of the countries (Denmark). Average production for the curves is denoted in the legend text
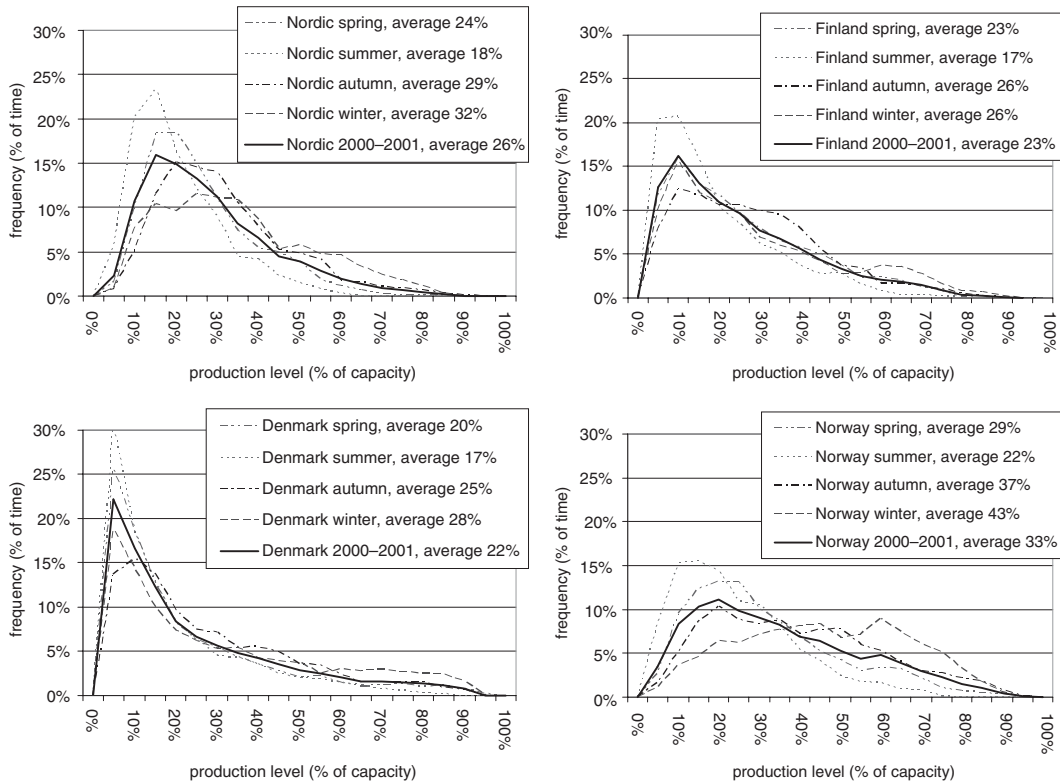
Figure 7. Difference in frequency distributions of wind power production for seasons: the lower production levels have a higher probability in summer, and higher production levels are more probable in winter. Average production during the seasons is denoted in the legend text

Seasonal variation of wind power production

In Central and Northern Europe there is a distinct seasonal variation in wind power production: more production in winter than in summer. The production during the summer months is 60%–80% of the yearly average, while the production during the winter months is 110%–150% of the yearly average, according to these data for years 2000–2002.

This is also reflected in the range of production values, for example, the hourly data for the Nordic countries for years 2000 and 2002 range between 1% and 61% in the summer and between 2% and 85% in the winter.

Frequency distributions for the four seasons are presented in Figure 7. Duration curves for summer and winter are presented in Figure 8 for Denmark and the combined Nordic wind power production.

Diurnal variation of wind power production

Wind is driven by weather fronts and a daily pattern caused by the sun, so, depending on whether one or other of these dominates, there is either a significant or hardly any diurnal pattern in the production. In Europe there is a tendency for winds to start blowing in the morning and calm down in the evening (Ireland,[9] Germany[16]). In Northern Europe this is more pronounced during the summer (Figure 9).

In winter there is no clear diurnal variation to be seen, except for a slight one in Denmark (the uppermost curve in the Figure 9 graph for Denmark). In summer the average production between 11 : 00 and 18 : 00 is above 20% of capacity, compared with less than 15% of capacity during the night. The diurnal variation here
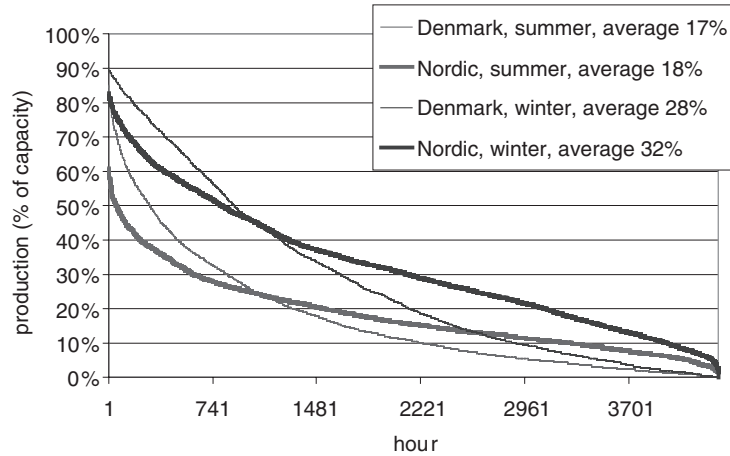
Figure 8. The wind power production is higher during the three winter months (upper curves: January, February and December) than during the three summer months (lower curves: June, July and August). Duration curves for production in 2000 and 2001
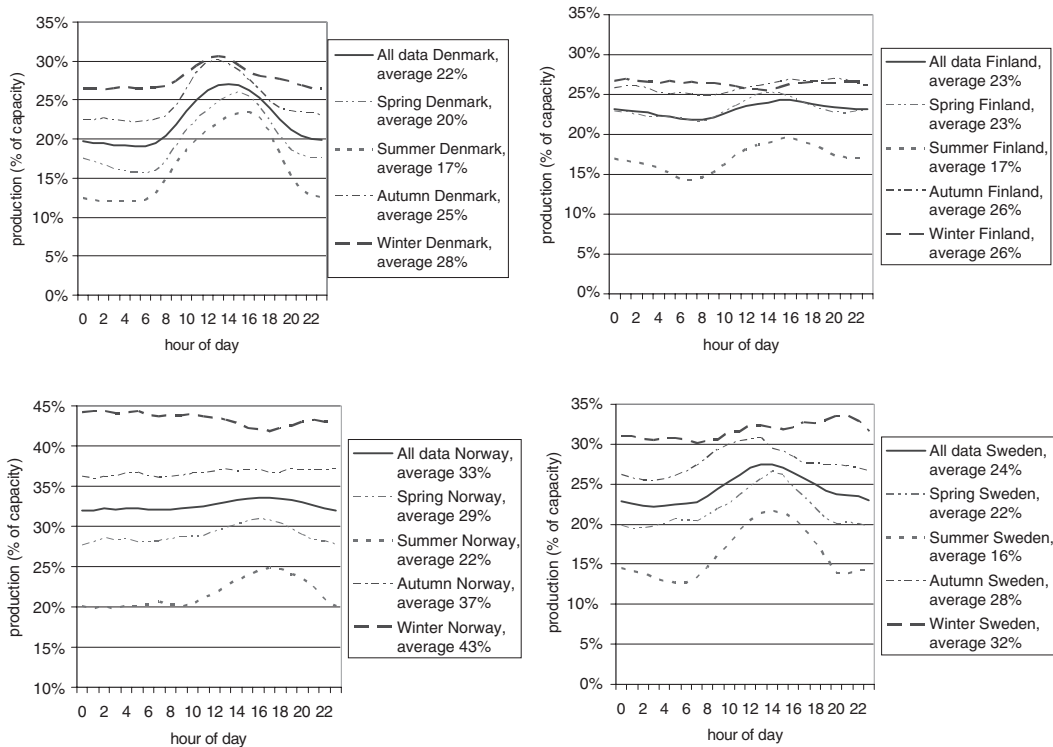

Figure 9. For the Nordic countries, diurnal variation is more pronounced in summer

is presented in Central Europe time, as used in Denmark, Norway and Sweden. The hours have a shift for summer time in the spring and back to normal time in the autumn.

Wind power production in Denmark and Sweden experiences a more pronounced diurnal variation, whereas the sites in the Northern parts of Finland, Sweden and Norway do not experience any detectable diurnal variation, which has also been observed before for Norway.[36]

Persistence of wind power production

Frequency distributions and duration curves give some idea of how often certain production levels occur. However, for a varying power production such as wind power, persistence of different production levels is also of interest—how long does a certain production level last? There are two special cases presenting the greatest challenges in integration of wind power into the system: duration of calms or low wind power production, and occurrence of peaks, which are especially pronounced in wind power production.

Duration of calms has here been defined as the time when wind power production is less than 1% of capacity. As the average production is of the order of 20%–25% of capacity, this can also be put as about 4%–5% of average production. Additionally, low-production persistence has been studied, i.e. when wind power production is less than 5% of capacity (roughly 20% of average production). A production level of 10% of capacity is already almost half the average production, and wind power production is almost a third of the time below the 10% level (for the total Nordic production, almost 15% of the time; Figure 6).

In Denmark the production was below 1% of capacity nearly 5% of the time (4·6%, 4·9% and 6·0% of the time in 2000, 2001 and 2002 respectively), whereas for the larger areas of Finland and Sweden, this occurred 1%–2% of the time. For Norway, calms were very rare (0·1%, 0·3% and 0·8% of the time in 2000, 2001 and 2002 respectively). The longest duration of calm (production below 1% of capacity) for Denmark was 58 h in 2002 and 35 h in 2000. For Finland and Sweden it was 19 h and for Norway 9 h. For the total Nordic data set there were no totally calm periods, the production always being above 1% of capacity.

The longest duration of low production, less than 5% of capacity, was 95 h for Finland and Denmark and less than 50 h for Norway, Sweden and the total Nordic time series. The longest periods occurred during spring/summer months (April–August). For the Nordic time series the production was below 5% of capacity 2%–3% of time.

Peak production was here studied for the level of above 75% of capacity. As the average production is of the order of 25% of capacity, this can also be defined as roughly three times the average production. The longest periods with high wind power production exceeding 75% of capacity were 27–38 h in the countries and 14 h for the total Nordic data.

Correlation of wind power production

Cross-correlation ($r_{x,y}$) is a measure of how well two time series follow each other:

$$r_{x,y} = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)(y_i - \mu_y)}{\sigma_x \sigma_y} \tag{3}$$

where μ denotes the average, σ the standard deviation and n the number of points of the time series. Cross-correlation is near the maximum value 1 if the ups and downs of the production occur simultaneously, near the minimum value −1 if there is a tendency of decreasing production at one site and increasing production at the other site, and close to zero if the two are uncorrelated and the ups and downs of production do not follow each other at the two sites. When distributing wind power production to a larger area, the total production will be smoother and less variable if the correlation between the sites is low.

Correlation can also be calculated for a single time series but with time lags. This is called autocorrelation. For wind power production the autocorrelation decreases soon with increasing time lag; already at 12 h lag the correlation becomes weak.[37]

The cross-correlations were calculated for all sites in the Nordic countries for one year, 2001, when the data available included most sites, altogether 33 time series. Some of the time series were aggregated production data from a larger area, for which the co-ordinates were estimated from the centre of the area. The results are presented in Figure 10. The cross-correlation decreases fast at first, $r_{x,y} = 0·7$ for a distance of about 100 km and 0·5 for a distance of about 300 km, after which the decrease is slower.

There is significant variation in the cross-correlation coefficients for a similar distance, as expected. The correlation becomes weak, below 0·5, with distances above 200–500 km. When local phenomena influence the
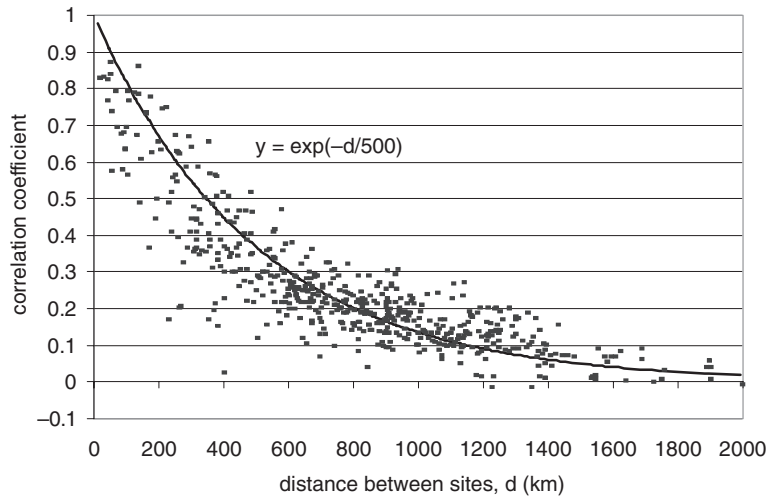
Figure 10. Cross-correlation coefficients for the sites of the Nordic data for year 2001

wind resource, the winds do not correlate with sites even some 200 km apart. The lowest points in Figure 10 for distances of 200–800 km come from the westernmost site in South Norway, for which the correlation with all other sites is weak. In Figure 10 the lowest cross-correlations are slightly negative, for Finnish Lapland with South Norway sites. Slightly negative correlations between two points in Europe have been reported for weather data from Ireland/Portugal (1500 km apart) and Spain/Greece (3000 km apart).[7] The results from correlation between weather station wind speed-based data calculated from 9 years in Finland are similar to the ones here for year 2001.[13] There is no significant change in correlation coefficients calculated from different years. A year of hourly data contains enough different weather situations to be able to determine the correlation between the wind power production at different sites.

The cross-correlation can be modelled by exponential fitting, decay parameters (D) of 500–700 have been reported.[7] For the present data, $D = 500$ fits them (Figure 10).

Looking at large-scale wind power production for the four countries, Swedish and Danish wind power production is correlated, $r_{x,y} = 0.71$ (assuming that most of the Swedish wind power is in the Southern part). Wind power production in the other countries is only weakly correlated, $r_{x,y} = 0.42$–0.45 for Sweden/Norway/Finland and 0.22–0.33 for Denmark/Finland, Norway.

Taking a closer look at the regions in the Nordic countries, there is practically no correlation between Lapland (North Norway, Sweden and Finland) and the Southern areas (Denmark, South Sweden, Norway and to some extent South Finland).[29]

Short-term variations of wind power production

For power system operation the variations from day to day, from hour to hour and from minute to minute are of interest. The larger the area, the longer time scales are affected by the smoothing effect. Within a wind farm, all the wind turbines will experience different gusts (seconds), but the hourly wind power production will see approximately the same ups and downs. In a larger area covering several hundred kilometres, the weather fronts causing high winds will not pass simultaneously, but the good and poor months will occur at the same time. This can be seen in Figure 11, where the decreasing correlation of the variations is depicted for different time scales.[17] The correlation is here calculated for the differences between consecutive production values (ΔP). For the time series of production values (P) the correlation does not decrease as rapidly as shown in Figure 11, as can be seen from Figure 10.
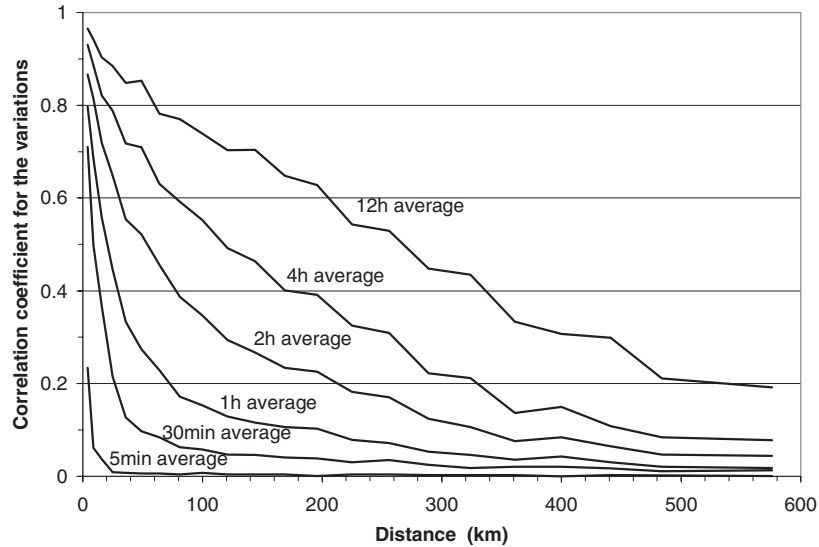
Figure 11. Variations will smooth out faster when the time scale is small. Correlation of variations for different time scales, example from Germany[17]

The Intra-hour Variations

Already the inertia of large rotating blades of a wind turbine will smooth out the very fast gusts of wind. For variable speed wind turbines the second-to-second variations will be absorbed in the varying speed of the rotor. For a wind farm the second-to-second variations will be smoothed out, as the same gusts will not occur simultaneously at all turbines, situated several hundred metres apart.

The extreme ramp rates recorded from one 103 MW wind farm are 4%–7% of capacity in a second, 10%–14% of capacity in a minute and 50%–60% of capacity in an hour.[18] These examples are from a limited area compared with system operation: a large wind farm or three smaller wind farms some 10 km apart. For a larger area of geographically dispersed wind farms the second-to-second and minute-to-minute variations will not be significant.

For the 15 min variations in Denmark, the production can vary by 8·4% of capacity six times per month, and the maximum is 11%.[38] This is not as much as for the hourly variations, as seen in the following subsection.

There are means to reduce the fast variations of wind power production. Staggered starts and stops from full power as well as reduced (positive) ramp rates could reduce the most extreme fluctuations, in magnitude and frequency, over short time scales.[39] 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.

The Hourly Variations

The hourly variation is here defined as the power difference between two consecutive hours. It is here measured relative to the nominal capacity, to compare it among several countries with different amounts of installed capacity:

$$\Delta P_i = P_i - P_{i-1}, \qquad \Delta P_i = P_i - P_{i-1} \tag{4}$$

For large-scale, dispersed wind power production there will be a significant smoothing effect in the hourly variations. The correlation of the variations between two wind turbines decreases faster than the correlation of the production. For hourly variations the correlation becomes weak already at distances less than 100 km

Table III. Largest hourly variations (%) of wind power production in the Nordic countries for years 2000–2002. Maximum variations are as % of installed capacity. The percentage of time that the variations are more than 5% or 10% of capacity is also presented

Country	Max up-variation	Max down-variation	Above 5%	Below −5%	Above 10%	Below −10%
Denmark	20	−23	4·5	4·4	0·6	0·5
Finland	16	−16	3·3	3·2	0·2	0·2
Norway	27	−29	8·7	8·6	1·5	1·3
Sweden	22	−27	6·7	6·5	1·0	0·8
Nordic, evenly	12	−11	0·7	0·6	0·0	0·0
Nordic 2010	13	−14	1·7	1·5	0·0	0·0

(Figure 11).[17] Correlations of hourly variations for the countries and areas within the countries were calculated and most of them were between −0·01 and 0·04, so there is no correlation between the hourly variations. Hourly variations in East and West Denmark are weakly correlated (0·46). For the other closest areas, South Sweden/Denmark, South Norway/West Denmark as well as the Western part of Finland, the correlation of variations is below 0·2.

The largest hourly variation is about ±30% of capacity when the area is of the order of 200×200 km^2 (e.g. West/East Denmark), and ±20% of capacity when the area is of the order of 400×400 km^2 (e.g. Germany, Finland and Iowa, USA).[15,40] For the Nordic data the largest hourly variations are 11% up and 10% down. For Norway and Sweden, despite the large area, the variations are higher than for Denmark and Finland (Table III). This is due to the limited number of sites included in the data sets. The Nordic variations are probably overestimated as a result of this.

These are the extreme values, most of the time the hourly variations will stay within ±5% of installed capacity (Figure 12 and Table III). It is notable that, as the average production is about 25% of capacity, this 5% of capacity represents 20% of average power. For the individual countries the hourly variations are more than 5% of capacity 6%–20% of the time. For Denmark this occurs 10% of the time, so probably the large variations of the Norwegian and Swedish data sets are due to too few time series in these countries to represent the variations correctly. Omitting Norway and Sweden, the conclusion is that the hourly variations of large-scale wind power production are 90%–94% 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 (Table III).

Theoretically, the largest variations of hourly wind power production occur owing to high wind speeds above the cut-off limit of the turbines (usually 25 m s^{-1}), when the production from individual turbines is reduced to zero from full power. However, for large-scale wind power production the turbines do not see the same high wind speed levels simultaneously. This is proved by the Danish data, where the largest down-variations are not more than 23% of capacity in Denmark and 26% of capacity in West Denmark. For the largest down-variations the initial production level in the countries was 70%–80% of capacity in most cases. There may well be some cut-off situations present in some of the areas where the initial production level was more than 90%.

Probability of significant variations is a function of production level. Significant changes occur most probably when wind farms are operating between 20% and 80% of capacity, as this is the steep part of the power curve when changes in wind speed produce the largest changes in power output of the turbines. For large-scale wind power the production is rarely above 80%, so an analysis of the Nordic data was done for the production level of above 20% of capacity (at the first hour). Hourly variations were analysed for these periods only, representing altogether about half of the data. The large variations occur nearly twice as often (relatively) for the countries when looking in this way, compared with the results for all data in Table III.[29]

Reduction in standard deviation for hourly time series is a measure of reduced variability in the time series with geographical dispersion of wind power. For North Germany the standard deviation of hourly time series
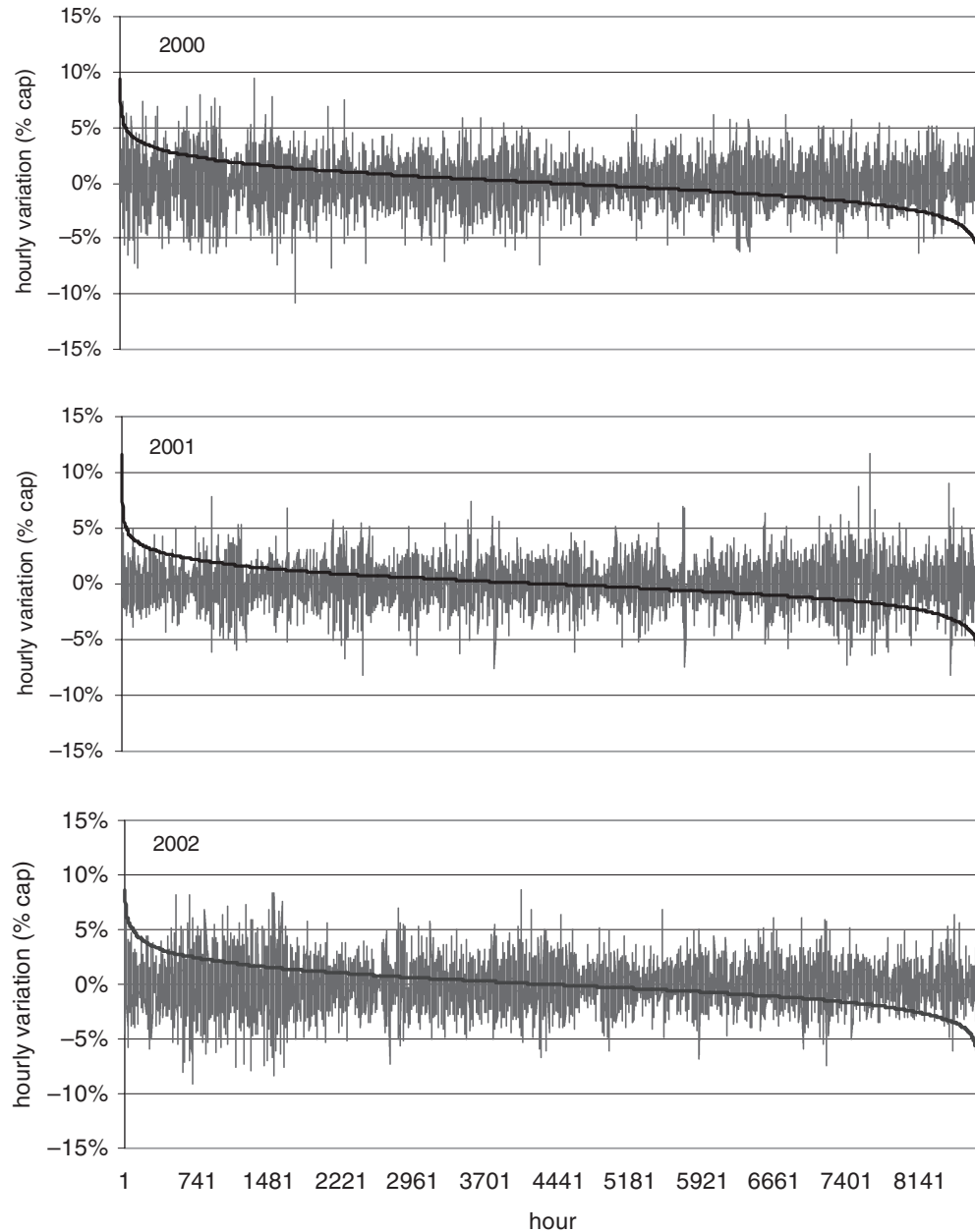
Figure 12. Hourly variations from Nordic wind power production, chronological time series and duration curve, years 2000–2002

will reduce to 70%–80% of the single-site value.[24] For the data set of Denmark the reduction is to 70% of the single-site value. For the data sets of Finland, Norway and Sweden there is more reduction, to about 60% of the single-site value. For the Nordic area the reduction is to about half of the single-site value ($\sigma = 14 \cdot 5\%$). For the more concentrated Nordic data set the reduction in standard deviation is to 60% of the single-site value.

The standard deviation of the time series of fluctuations ΔP will decrease even faster, from about 10% for a single turbine to less than a third (3%) for an area such as West Denmark.[23] For these data, Finland and
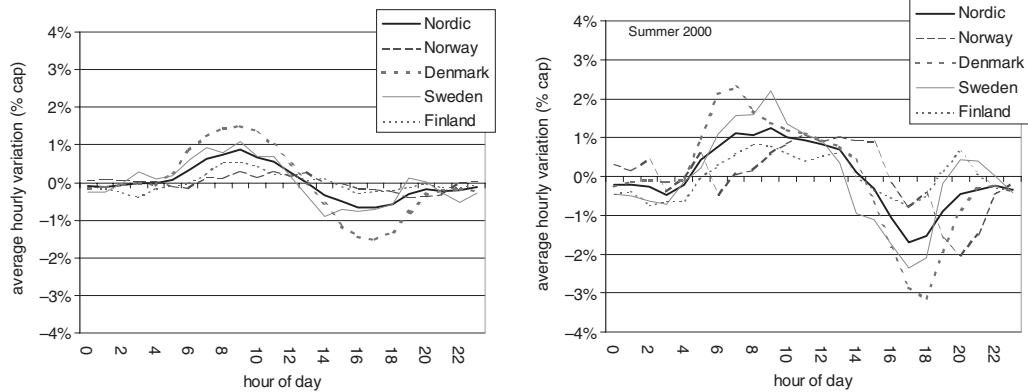
Figure 13. Diurnal dependence of hourly variations. All data and summer 2000

Denmark have the standard deviation of the time series of fluctuations ΔP lower than 3% and Nordic data lower than 2% of capacity.

Diurnal variations in output can help indicate when significant changes in output are most likely to occur.[19] The average hourly variations of wind power production are zero—there are as many up- as down-variations. However, when plotting the average hourly variation according to the time of day, the average is no longer zero for all hours of the day. There are more upward changes during the morning hours and more downward changes during the afternoon hours, as can be seen in Figure 13. This is more pronounced during summer, as is the diurnal variation of the production (see earlier). Also the maximum variations in the data set occur in the morning hours for the upward changes and in the evening hours for the downward changes. The maximum variations are less in summer according to these data; this is probably due to lower production levels in summer months.

Variations for Longer Time Scales

For longer time scales, i.e. 4–12 h variations, short-term prediction tools for wind power give valuable information on the foreseeable production levels and expected variations of wind power production.

From the Nordic data set the maximum 4 h variations are about ±50% of capacity for one country (for Denmark ±60% and for Finland ±40%). This has also been reported for a longer following period from Germany.[15] For the Nordic area it is ±35% of capacity according to this 3 year data set.

The maximum 12 h variation for the Nordic area is ±50% of capacity (for Denmark ±80% and for Finland ±70%). Taking larger areas, e.g. Northern Europe, and more years of data, a ±30% change in production 12 h ahead occurs about once a year.[11]

Representative Data for Large-scale Wind Power Production

To study the impacts of large-scale wind power production, the data should be representative in both time and space. Depending on what impact we are looking at, we should take an average year's production, or a low- or high-wind year, to see the extreme situations for system planning purposes. This means taking production from a representative time period to study. Depending on what impact we are studying, the wind power production time series should be representative for the area in question. For example, large-scale wind power impacts on the power system operation should involve the production from a large area, with a proper smoothing effect present in the data. This means taking production data from a representative space.
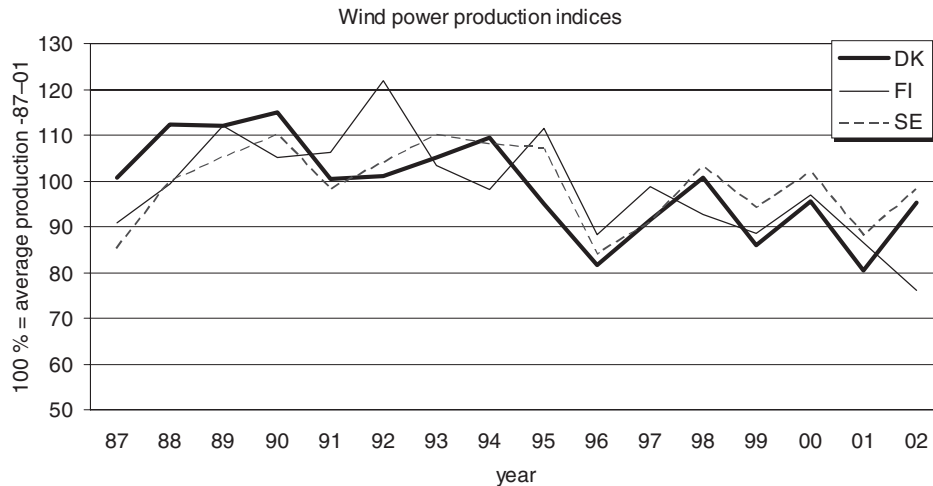
Figure 14. Yearly wind resource in 1987–2002 according to production statistics of wind energy in Nordic countries (DK = Denmark, FI = Finland, SE = Sweden)

Checking out the representativeness of the time period studied is quite straightforward when long-term wind power data exist. This is done in the following subsection. For checking the representativeness in geographical smoothing, in the second subsection some basic parameters from the previous section are picked up to form a guideline in this respect.

Representativeness of the study years

Here we look at the years in question: 2000–2002. Wind power production indices from national wind power production statistics are presented in Figure 14.[3,4,41] The wind power production index is a measure of one year's production compared with the long-term average production. A value of 100% means that the yearly production was equal to the long-term average. In Figure 14 it can be seen that the yearly production varies between 80% and 120%. In Finland the coastal areas South and West experience somewhat different wind resource variations; this is why the production indices are calculated for four sites.[4] The production indices for Finland are here calculated as weighted averages of these indices, using the large-scale wind power capacity distribution assumed in this study. For Norway this analysis was not done owing to a lack of long-term data. However, the Norwegian wind power production seems to experience the same trends as for the other Nordic countries, even if not as strongly.

Year 2000 was close to average (95% in Denmark, 97% in Finland and 102% in Sweden) and year 2001 was clearly less windy than average (80% in Denmark, 87% in Finland and 88% in Sweden). Year 2002 was close to average in Denmark (95%) and Sweden (98%) and a very-low-wind year in Finland (76%).

The production index can be used in determining the long-term average wind power production from only one year of realized production data, by dividing the year's production by the year's index value. Using the average production in 2000–2002 compared with the average production index for 2000–2002, we get roughly 24%–26% of capacity as the long-term average wind power production for Denmark, Sweden and Finland.

As a total period, 2000–2002 will give a production that is less than average: 90% of average production in Denmark, 87% in Finland and 96% in Sweden. However, as the data contain also high-wind months, e.g. the first part of year 2000 (monthly production indices in Reference 3, 4 and 41), there are also representative periods of high-wind situations in the data.

Representativeness of the geographical spreading of data

Based on the detailed statistical analyses, it can be estimated how well the data represent large-scale wind power production. The data used for wind power fluctuations are critical in the study of wind power impacts on power system operation. So as not to upscale the fluctuations when upscaling installed wind power in the system, the statistical characteristics for large-scale production should be looked for in any simulated or meteorological data-based wind power time series.[23] When enough turbines from a large enough area are combined, the smoothing effect reaches saturation and the time series can be upscaled with representative hourly variations.

As the Danish data are real large-scale wind power data from thousands of wind turbines, the comparisons made can be used as a basis to estimate how well the data sets constructed for Norway, Sweden and Finland represent large-scale wind power production.

Finland and Norway are considerably larger areas than Denmark, so also the smoothing effect should be stronger there. For Sweden there is the possibility of concentrating most of the wind power capacity south of Stockholm, which means that Sweden should get closer to the same smoothing effect as in Denmark.

Summing up the statistical properties for an hourly time series of large-scale wind power production, the following results were found.

- The standard deviation of the hourly production series should be less than the average production, slightly so for an area such as Denmark (300×200 km^2) and considerably so for a larger area: Finland 18%/22%, Norway 20%/34%, Sweden 18%/24%, Nordic 15%/25% (standard deviation/average, as % of capacity).
- The maximum hourly production should be less than 100%, 85%–95% depending on how large the area in question is: Denmark 93%, Finland 91%, Norway 93%, Sweden 95%, Nordic 87%.
- The duration of calms should be non-existent or limited: production below 1% of capacity 5% of the time in Denmark, 1%–2% of the time in Finland and Sweden, <1% of the time in Norway; minimum production in Nordic data set 1·2% of capacity.
- The standard deviation of the hourly variation series should be less than 3% of capacity: Denmark 2·9%, Finland 2·6%, Norway 3·9%, Sweden 3·5%, Nordic 1·7%.
- The hourly variations should be within ±20% of capacity, or even less if the area is larger than the size of Denmark: Denmark −23% to 20%, Finland −18% to 16%, Norway −21% to 27%, Sweden −20% to 22%, Nordic −11% to 12%.

When looking at the basic statistics for the production time series, there is no clear signal that the Norwegian and Swedish data would be unrepresentative, as taking even a few time series from the countries from different locations of the area gives a basic smoothing effect in the range of production. The analysis on the hourly variations, especially the standard deviation of hourly variations, reveals the caveats for the Swedish and Norwegian data sets.

For studies of wind power impacts on power system operation the variations of wind power production are crucial. To take a closer look at the representativeness of the variations in the time series, the smoothing effect measured as the reduction in standard deviation is studied in more detail. The smoothing effect is more pronounced with more turbines and more separation. The smoothing effect of a specified area has a limit; that is, the time series will not get smoother if more and more turbines are added from the same area. For Germany, for example, it has been estimated that 30 sites will be enough to get low variations, measured as the standard deviation of the production time series.[24] After saturation the only way to increase the smoothing will be to increase the area—which has a limit somewhere too. To quantify the smoothing effect, first the standard deviation is looked at. For combined time series the variance σ^2 is

$$\sigma^2_{\text{ensemble}} = \frac{1}{N^2} \sum_{x=1}^{N} \sum_{y=1}^{N} \sigma_x \sigma_y r_{x,y} \tag{5}$$

where N is the number of time series forming the ensemble time series, σ is the standard deviation and $r_{x,y}$ is the cross-correlation. Now, if the time series are uncorrelated, $r_{x,y}$ is close to zero and there remains only the

variances of the original time series. With a further assumption of being the same for all original time series, σ_{ensemble} is reduced to

$$\sigma^2_{\text{ensemble}} = \frac{1}{N^2}\sum_{x=1}^{N}\sigma_x^2 = \frac{1}{N}\sigma_x^2, \qquad \sigma_{\text{ensemble}} = \frac{1}{\sqrt{N}}\sigma_x \qquad (6)$$

If, on the other hand, the time series are perfectly correlated, $r_{x,y}$ is 1 and, again assuming the standard deviations of the original time series equally large, σ_{ensemble} becomes

$$\sigma^2_{\text{ensemble}} = \frac{1}{N^2}\sum_{x=1}^{N}\sum_{y=1}^{N}\sigma_x\sigma_y = \sigma_x^2, \qquad \sigma_{\text{ensemble}} = \sigma_x \qquad (7)$$

Now, as we have time series that are correlated, some more and some less, the standard deviation will lie somewhere in the middle of these extremes:[25]

$$\sigma_{\text{ensemble}} = N^{-k}\sigma_x, \quad k = -\frac{1}{2} \quad \text{to} \quad 0 \qquad (8)$$

Assuming the number of data sets N is growing with the size of the area and fitting the function in (8) to the Danish data of hourly variations gives $k = -0.2437$ and $\sigma_x = 0.1275$ (almost 13% of capacity), with a reasonably good fit of the data ($R^2 = 0.83$). Giving more weight to the data points with larger N, a curve fit of $y = 0.11x^{-0.24}$ is used here in Figure 15, this dotted line also follows more the points with lowest standard deviation values, giving an indication of how the reduction is with proper geographical spreading of the turbines in the area.

When looking at the trend of decreasing standard deviation with increasing number of wind farms in a larger area in Figure 15, the conclusion is that the Norwegian and Swedish data sets will exaggerate the hourly variations if upscaled. There will be a slight overestimation of variability for the Finnish data when upscaling the data to large-scale wind power production. Combining the four data sets to form a Nordic data set shows a continuing smoothing effect in Figure 15. It has thus been considered representative for the study of large-scale wind power.

Even for Denmark there can be some caveats as to how well the data represent future wind power production. In the future there will be fewer turbines and sites, but better production from MW-scale high turbines, especially offshore. When a substantial share of wind energy comes from large offshore wind farms, this will
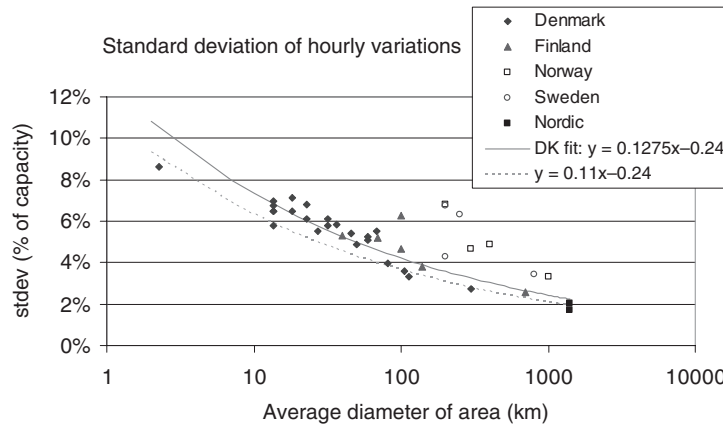

Figure 15. Reduction in variability of wind power production: reduction in standard deviation of hourly variations taken from different areas, year 2001 data. Fit for Danish data gives the full line ($y = 0.1275x^{-0.24}$). The dotted line follows the least variable time series, showing the effect of good geographical dispersion within the area

have an impact on the production, bringing about a less dispersed and thus more variable production, but also higher duration, as there are fewer calms than onshore.[37]

Summary and Conclusions

Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output.

In this study the focus is on the hourly time scale impacts on the power system, based on real wind power production data. Example years 2000–2002 were studied. As a total period, 2000–2002 will give a production that is less than average: 90% of the average production in Denmark, 87% in Finland and 96% in Sweden.

Average production in the Nordic countries is highest in Norway, 31%–34% of installed capacity, and about 22%–24% of capacity in the other countries during the example years. The seasonal variation was clearly present in the data sets: more production in winter than in summer. Wind power production in Denmark and Sweden experiences a more pronounced diurnal variation, whereas the sites in the Northern parts of Finland, Sweden and Norway do not experience any detectable diurnal variation.

From the combined production in the Nordic countries it can be seen that, as 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. Production above 50% of rated capacity is rare in summer and production above 75% is rare in winter. The lowest hourly production was 1·2% of capacity. The production was below 5% of capacity about 2% of the time.

Correlation of hourly wind power production is strong (above 0·7) for distances less than 100 km and becomes weaker (below 0·5) for distances above 200–500 km. The large-scale wind power production of the countries is correlated between Denmark and Sweden and weakly correlated between the other countries. No correlation between the hourly variations of wind power production was seen in the data sets for the countries.

The hourly variations of large-scale wind power production are 91%–94% of the time within ±5% of capacity and 99% of the time between ±10% of capacity. For the total Nordic time series the hourly variations are about 98% of the time within ±5% of capacity. Taking only the time periods when the initial production level is more than the average production, the larger variations occur about twice as often (relatively).

To be able to upscale wind power production data to represent large-scale production data, the smoothing effect should be present in the time series. When enough turbines from a large enough area are combined, the smoothing effect reaches saturation and the time series can be upscaled with representative hourly variations.

From the available hourly time series for Denmark, guidelines for the statistical properties of large-scale wind power were made. An hourly time series of large-scale wind power production should have the standard deviation of the hourly production series less than 20% of capacity, the maximum hourly production less than 100% (85%–95% depending on how large the area in question is), the duration of calms limited or non-existent, the standard deviation of the hourly variation series less than 3% of capacity and the hourly variations within ±20% of capacity, or even less if the area is larger than the size of Denmark (300×300 km^2). The clearest indication of reduced variability in the time series was found to be the standard deviation of the hourly variation time series.

According to these criteria, the data set for Finland is quite representative for large-scale wind power production and its hourly variations. The data sets for Norway and Sweden can be used to present wind power production, but for the hourly variations they are not representative. This is mainly revealed by the range and standard deviation of hourly variations of the production time series, which is not as smooth as a large-scale wind power production from thousands of turbines would be. Combining the four data sets to form a Nordic data set shows a continuing smoothing effect, so it has been considered representative for the study of large-scale wind power.
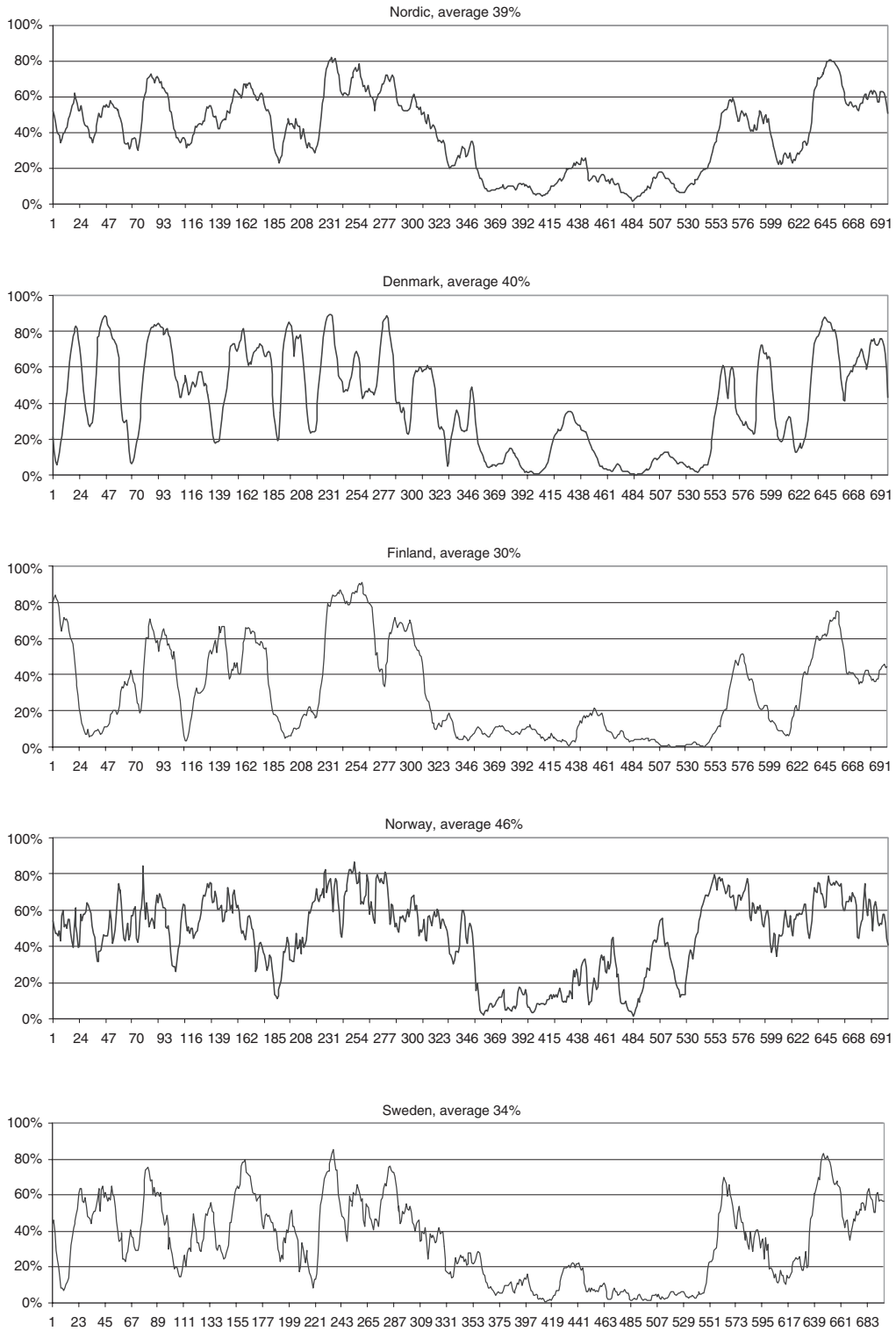
Acknowledgements

Figure 16. Hourly wind power production in February 2000. The production is given as % of installed capacity (y-axis). The average production during the month is denoted above the curve

References

1. Eltra. [Online]. Available: http://www.eltra.dk/ [1 September 2003].
2. Elkraft. [Online]. Available: http://www.elkraft.dk/ [1 September 2003].
3. Carlstedt N-E. Driftuppföljning av vindkraftverk, årsrapport 2002. *Elforsk Report 03:12, STEM Report 12:2003*. [Online]. 2003. Available: http://www.elforsk.se/varme/varm-vind_drift.html. [15.11.2004]
4. Windicator. *Windpower Monthly, 2003*, Vol. 19, No. 4.
5. Laakso T. The statistics of wind power in Finland. *Yearly Report 2002* (in Finnish). [Online]. 2003. Available: http://www.vtt.fi/pro/pro2/tuulitilastot/windstat.htm.
6. Landberg L. The availability and variability of the European wind resource. *International Journal of Solar Energy* 1997; **18**: 313–320.
7. Giebel G. On the Benefits of Distributed Generation of Wind Energy in Europe. *Fortschr.-Ber. VDI*, *Reihe 6*, *Nr 444*. [Online]. VDI: Düsseldorf, 2001. Available: http://www.drgiebel.de/thesis.htm.
8. Van Wijk AJM. Modelling wind power production in the Netherlands. *Wind Engineering* 1990; Vol. 14, No. 2, pp. 122–140.
9. Hurley T, Watson R. An assessment of the expected variability and load following capability of a large penetration of wind power in Ireland. *Proceedings of Global Wind Power Conference GWPC'02*, Paris, 2002.
10. Balea L, Siebert N, Kariniotakis G, Peirano E. Quantification of capacity credit and reserve requirements from the large scale integration of wind energy in the French power system. *Proceedings of Global Wind Power Conference GWPC'04*, Chicago, IL, 2004.
11. Giebel G. Equalizing effects of the wind energy production in Northern Europe determined from Reanalysis data. *Risø-R-1182(EN)* [Online]. 2000. Available: http://www.risoe.dk/rispubl/index.htm.
12. Holttinen H, Peltola E, Koreneff G. *Seasonal and Long-term Variations of Wind Power Production in Finland* (*VTT Research Notes 1800*) (in Finnish). VTT: Espoo, 1996.
13. Tammelin B, Nurmi J. An assessment of variability of wind power production in Finland. *Proceedings of European Wind Energy Conference EWEC'01*, Copenhagen, 2001, pp. 1078–1081.
14. Van Zuylen EJ, Ramaekers LAM, van Wijk AJM, Verschelling JA. Wind power fluctuations on a national scale. *Proceedings of European Wind Energy Conference EWEC'96*, Gothenburg, 1996, pp. 986–989.
15. ISET. *Wind Energy Report Germany*. Institut für Solare Energieversorgungstechnik: Kassel, 2002.
16. Ensslin C, Hoppe-Kilpper M, Rohrig K. Wind power integration in power plant scheduling schemes. *Proceedings of EWEC Special Topic Conference*, Kassel, 2000.
17. Ernst B. Analysis of wind power ancillary services characteristics with German 250 MW wind data. *NREL Report TP-500-26969* [Online]. 1999. Available: http://www.nrel.gov/publications/.
18. Parsons BK, Wan Y, Kirby B. Wind farm power fluctuations, ancillary services, and system operating impact analysis activities in the United States. *NREL Report CP-500-30547* [Online]. Available: http://www.nrel.gov/publications/.
19. Poore RZ, Randall G. Characterizing and predicting ten minute and hourly fluctuations in wind power plant output to support integrating wind energy into a utility system. *Proceedings of AWEA Windpower'01 Conference*, 2001.
20. Milligan M. Wind power plants and system operation in the hourly time domain. *NREL/CP-500-33955* [Online]. 2003. Available: http://www.nrel.gov/publications/.
21. Hirst E. Integrating wind output with bulk power operations and wholesale electricity markets. *Wind Energy* 2002; **5**: 19–36.
22. Smith JC, DeMeo EA, Parsons B, Milligan M. Wind power impacts on electric power system operating costs: summary and perspective on work to date. *Proceedings of Global Wind Power Conference GWPC'04*, Chicago, IL, 2004.
23. Milborrow D. PIU Working Paper on Penalties for Intermittent Sources of Energy. [Online]. 2001. Available: http://www.number10.gov.uk/output/Page3703.asp.
24. Focken U, Lange M, Waldl H-P. Previento—a wind power prediction system with an innovative upscaling algorithm. *Proceedings of European Wind Energy Conference EWEC'01*, Copenhagen, 2001, pp. 826–829.
25. Persaud S, Fox B, Flynn D. Modelling the impact of wind power fluctuations on the load following capability of an isolated thermal power system. *Wind Engineering* 2000; **24**: 399–415.
26. DTI. Quantifying the system costs of additional renewables in 2020. *A Report Commissioned by the UK Department of Trade and Industry* [Online]. 2003. Available: http://www2.dti.gov.uk/energy/developep/support.shtml [14 March 2003].
27. Holttinen H. Impact of hourly wind power variations on the system operation in the Nordic countries. *Wind Energy* 2005; **8**, 23 p. (In print.)
28. Nørgaard P, Holttinen H. A multi-turbine power curve. *Proceedings of Nordic Wind Power Conference*, Gothenburg [Online]. 2004. Available: http://www.wilmar.risoe.dk/.
29. Holttinen H. Hourly wind power variations and their impact on the Nordic power system operation. *Licenciate Thesis*, Technical University of Helsinki [Online]. 2003. Available: http://www.vtt.fi/renewables/windenergy/windinenergysystems.htm.
30. Lumituuli. [Online]. Available: http://www.lumituuli.fi [1 September 2003].
31. Swedish Meteorological Institute (SMHI). Wind speed measurement time series. 2003 (courtesy of Hans Bergström).

32. Kjeller Vindteknikk. Wind speed measurement time series. 2002 (courtesy of Lars Tallhaug).
33. Andøy Energi. Wind speed measurement time series. 2002 (courtesy of Kåre Gjøvik).
34. Holttinen H, Peltola E. Experiences of using WAsP and on-site measurements for siting a wind farm. *Proceedings of European Wind Energy Conference EWEC'93*, Lübeck-Travemünde, 1993; 673–676.
35. Nørgård P, Giebel G, Holttinen H, Söder L, Petterteig A. Fluctuations and predictability of wind and hydro power. *EU Project WILMAR Deliverable D2.1. Report Risø-R-1234(EN)* [Online]. 2004. Available: http://www.wilmar.risoe.dk/.
36. Alm LK, Tallhaug L. Wind power contribution to power adequacy. *IFE Report IFE/KR/F-93/132*, Halden, 1993 (in Norwegian).
37. Pryor SC, Barthelmie RJ. Persistence of offshore winds: implications for power quality. *Proceedings of European Wind Energy Conference EWEC'01*, Copenhagen, 2001 pp. 717–270.
38. Nordel. Non-dispatchable production in the Nordel system. Nordel's Grid Group, May 2000. http://www.nordel.org/Content/Default.asp?PageID=163.
39. Kristoffersen JR, Christiansen P, Hedevang A. The wind farm main controller and the remote control system in the Horns Rev offshore wind farm. *Proceedings of Global Wind Power Conference GWPC'02* Paris, 2002.
40. Milligan M, Factor T. Optimizing the geographic distribution of wind plants in Iowa for maximum economic benefit and reliability. *Wind Engineering* 2000; **24**: 271–290.
41. Naturlig Energi. [Online]. Available: http://www.naturlig-energi.dk.