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Wind and load variability in the Nordic countries

Hannele Holttinen | Simo Rissanen | Xiaoli Larsen | Anne Line Løvholm

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Hannele Holttinen & Simo Rissanen
VTT Technical Research Centre of Finland

Xiaoli Larsen
DTU

Anne Line Løvholm
Kjeller Vindteknikk

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VTT
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FI-02044 VTT
Tfn +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

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Wind and load variability in the Nordic countries

Tuulivoiman ja sähkönkulutuksen vaihtelut Pohjoismaissa. **Hannele Holttinen, Simo Rissanen, Xiaoli Larsen & Anne Line Løvholm.** Espoo 2013. VTT Technology 96. 98 p. + app. 33 p.

Abstract

This publication analysed the variability of wind production and load in Denmark, Finland, Sweden, and the Nordic region as a whole, based on real data measured from large-scale wind power during 2009–2011. The Nordic-wide wind power time series was scaled up such that Sweden had same amount of wind power production than Denmark, and Finland and Norway only 50% of the wind power production in Denmark.

Wind power production in Denmark and Sweden is somewhat correlated (coefficient 0.7) but less correlation is found between the other countries. The variations from one hour to the next are only weakly correlated between all countries, even between Denmark and Sweden. Largest variations occur when the production is approximately 30–70% of installed capacity and variability is low during periods of light winds. The variability in shorter time scales was less than the hourly variations. During the three years analysed in this publication there were few storm incidents and they did not produce dramatic wind power ramps in the Nordic region.

Wind and load variations are not correlated between the countries, which is beneficial from the viewpoint of wind integration. The smoothing effect is shown as reduction of variability from a single country to Nordic-wide wind power. The impact of wind power on the variability that the system experiences is evaluated by analysing the variability of net load with different wind power penetration levels. The Nordic-wide wind power production increases the highest hourly ramps by 2.4% (up) and -3.6% (down) of installed wind power capacity when there is 20% wind power penetration and by 2.7% (up) and -4.7% (down) for 30% wind penetration. These results assess the impacts of variability only. The next step will be assessing the uncertainty from forecast errors.

The timing of ramp events, and occurrence of high-wind and low-load are studied. With current wind penetration, low production levels (2–5% of installed wind power) can occur in a single country during peak loads, but in the Nordic region the production during peak loads does not fall to such low levels (minimum 14% during 10 highest peaks). The low wind periods occur primarily in the summertime. The longest period with wind generation below 5% of installed capacity in the wintertime for three years of data was 30 hours. The maximum penetration level, during one hour, can reach high levels already with a 20% (yearly) penetration level. At 30% penetration on yearly level the maximum hourly wind share was 160% in Denmark, 130–140% in Finland and Sweden and 110% in Nordic region

Keywords wind variability, wind integration, smoothing effect, ramping

Tuulivoiman ja sähkönkulutuksen vaihtelut Pohjoismaissa

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Tiivistelmä

Tässä julkaisussa tarkastellaan tuulivoimatuotannon ja sähkönkulutuksen vaihteluita Suomessa, Tanskassa, Ruotsissa ja koko Pohjoismaiden alueella. Analyysit perustuvat pääosin mitattuihin tuulivoiman ja sähkönkulutuksen tuntiaikasarjoihin. Pohjoismainen tuulivoiman tuotantoaikasarja skaalattiin eri tuulivoimaosuuksille siten, että Ruotsissa ja Tanskassa oli sama määrä tuulivoimatuotantoa ja Suomessa ja Norjassa vain puolet tästä.

Tuulivoimatuotanto Tanskassa ja Ruotsissa korreloi jonkin verran (korrelaatiokerroin 0,7), mutta muiden maiden tuulivoimatuotanto korreloi vähemmän. Tuulivoiman tuntivaihtelut korreloivat vain heikosti eri maiden välillä. Suurimmat vaihtelut syntyvät, kun tuotanto on noin 30–70 % asennetusta kapasiteetista. 15 minuutin vaihtelut ovat pienempiä kuin tuntivaihtelut. Analysoidussa kolmen vuoden datassa oli vain muutama myrsky, eikä niistä aiheutunut Pohjoismaiden tasolla suuria ramppeja tuotantoon.

Tuulivoiman ja sähkönkulutuksen vaihtelut eivät korreloi, mikä helpottaa tuulivoiman integrointia järjestelmään. Tuulivoimavaihteluissa näkyy selvä tasaantuminen, kun tarkastellaan alueellista, yhden maan laajuista ja Pohjoismaiden laajuista tuulivoimatuotantoa. Tuulivoimavaihteluiden vaikutuksia sähköjärjestelmään on arvioitu tarkastelemalla nettokuormaa – sähkönkulutus miinus tuulivoimatuotanto – eri tuulivoimaosuuksilla. Pohjoismaiden tasolla suurimmat tuntivaihtelut lisääntyvät 2,4 % (ylös) ja –3,6 % (alas) suhteessa installoituun tuulivoimakapasiteettiin, kun tuulivoimaa on 20 % sähkönkulutuksesta. Tuulivoimaosuudella 30 % vaihtelut lisääntyvät 2,7 % (ylös) ja –4,7 % (alas). Kun tarkastellaan vaihteluiden lisääntymistä pelkästään Suomen alueella, tuulivoiman vaikutus on huomattavasti suurempi, 4,6 % (ylös) ja –7,6 % (alas). Tämä tarkastelu ottaa huomioon vain tuntivaihtelut, ja jatkotyön aiheena on selvittää tuulivoiman ennusvirheiden vaikutukset säätöön.

Tuulivoiman saatavuus huippukuorman aikaan voi joinakin vuosina olla pientä, 2–5 % yhden maan alueella. Pohjoismaiden alueella pienin tuulivoimateho kymmenen suurimman kuorman aikana oli 14 % asennetusta kapasiteetista, kolmen vuoden datasta. Pisimmät pienen tuotannon ajanjaksot osuivat kesälle (pisin 70 tuntia alle 5 % kapasiteetista), talviaikaan pisin oli 30 tuntia.

Tuulivoimaosuus yhden tunnin aikana voi ylittää 100 % siinä vaiheessa, kun tuulivoimalla tuotetaan 20 % vuotuisesta sähköntarpeesta. Kun tuulivoimaosuus on 30 % vuotuisesta tarpeesta, suurin tunnittainen tuulivoimaosuus oli 160 % Tanskassa, 130–140 % Suomessa ja Ruotsissa ja 110 % koko Pohjoismaiden alueella. Aikasarjoista on myös analysoitu suurimpien vaihteluiden ajoittumista.

Avainsanat wind variability, wind integration, smoothing effect, ramping

Preface

This work presents analyses for wind power variability in the Nordic countries, conducted as part of the research project Icewind which belongs to Toppforskningsinitiativet research initiative. The work conducted in Finland has been co-financed by Smart Grids and Energy Markets research programme SGEM work package Managing variable generation.

The authors wish to thank all the data providers, without which this work would not have been possible: Energy Technologies in Finland, The transmission system operator Energinet.dk in Denmark, system operator Svenska Kraftnät and Vattenfall in Sweden. The web pages of the system operators have been developed to contain a lot of data on the power system load and power production. This helps research in obtaining relevant data for these kinds of analyses and is greatly acknowledged.

The publication is mainly written at VTT Technical Research Centre of Finland. The Norwegian data has been compiled at Kjeller Vindteknikk. The analyses of 15-minute data for Denmark have been conducted at DTU, as well as analyses on the frequency of storms in the Nordic countries. The VTT team acknowledges Samuli Sillanpää, who contributed to an earlier version of this publication before moving to Helsinki University. The authors also like to acknowledge David Weir, NVE Norway for comments.

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Appendix A: Wind power production and load time series from years 2009 and 2011

Appendix B: Wind power production variation time series from years 2009 and 2011

Appendix C: Consumption data correction

1. Introduction

This publication analyses wind power production variability in the Nordic countries, compares the variability to load variability and analyses the total variability of combined load and wind. The analyses are based on data for large scale wind power production and load in Denmark, Finland, Sweden, and the Nordic region as a whole during 2009–2011.

Analyses on the variability of wind power production and load can be used to assess the impacts of increasing shares of wind power to the power system. This is valuable information, for example, for analysing the adequacy of short term balancing reserves in the system. In addition to variability, the uncertainty of forecast errors will determine the reserve needs. This question will be further assessed as a follow up to this publication, which focuses on the variability from the time series of wind power production.

The variability of wind power production is high for a single wind turbine and wind farm. However, this is not relevant when considering the impacts of large scale wind power on the power system as a whole. For this reason the focus is on system implications within a single country and the Nordic region with different wind penetration levels.

The Nordic countries have a synchronous power system that is balanced in a coordinated fashion. The impact of wind power variability is analysed from a system-wide perspective by considering the variability of load and wind power production together, instead of treating wind power variability in isolation. The impacts on balancing the power system depend on the share of wind power of all production and on how widely wind power is distributed. Scenarios with different shares of wind power and area sizes are presented.

Variability of wind power has been extensively studied, but studies based on real, measured large scale wind power production are still rare. This publication builds upon previous work regarding the Nordic system (Holttinen 2004) but now with considerably more representative data, as well as more recent international collaboration under IEA Wind Implementing Agreement Task 25 (Holttinen et al. 2011).

The publication is structured as follows. Chapter 2 describes the data sets used, Chapter 3 analyses the variability of wind power production and the smoothing effect in the Nordic countries. Chapter 4 analyses the load variability in the Nordic countries and Chapter 5 the combined variability of wind and load at different shares of wind power. Chapter 6 discusses the results and conclusions.

2. Data used in the analyses

The analysis in this publication is based on three years of data, 2009–2011, from Denmark, Finland, Norway and Sweden. It covers hundreds of sites in Sweden (Svenska Kraftnät 16.5.2012) and Denmark (Energinet.dk 16.5.2012), and 30 sites in Finland (provided by Finnish Energy Industries). For Norway measured wind power production data was not available and the data for 10 sites in Norway was compiled from meso-scale model wind data.

Hourly data of wind power production was obtained from the following sources (maps for the sites are in Figure 1 – Figure 4):

- Denmark: system operator Energinet.dk web pages (www.energinet.dk). The data is based on measurements that are upscaled to present the total wind power production from more than 5000 turbines in Denmark. 2009 data is scaled to 6.72 TWh and 2010 data is scaled to 7.8 TWh annual production to match yearly statistics. 2011 data is unscaled.
- Finland: hourly data collected from most existing wind farms by Energy Industries as part of their electricity statistics, and the sum of this data was available for this study. The data consists of 140 MW of wind power, 105 turbines at 33 sites at the beginning of 2009, and 194 MW of wind power, 120 turbines at 36 sites at the end of 2011.
- Norway: The data for 10 sites in Norway was compiled from meso-scale model wind data, turbine specific power curves and the yearly production for each of the wind farms (public available data from Norwegian Water Resources end Energy Directorate www.nve.no). For the WRF model run at Kjeller Vindteknikk (KVT) the horizontal resolution is 4 km * 4 km and the temporal resolution for the result is 1 hour. The modelled wind power production was validated with production measurement from 2 existing wind farms. This data was used only when calculating the Nordic timeseries, and is not reported as such, as it is not from measured data like the other countries.
- Sweden: system operator Svenska Kraftnät web pages (www.svk.se). The data is from 1359–2036 wind turbines, increasing in the time period 2009–2011.

In addition, 15-minute wind power production data from 2009–2011 was available for Western Denmark (provided by Energinet.dk).

Denmark has been the pioneer of wind integration and already has experience from a large share of wind power in the system. The installed wind power capacity at the end of year 2011 was about 3870 MW in Denmark (estimated division between east and west installed capacity was West Denmark 2849 MW and East Denmark 1022 MW), 2900 MW in Sweden, 520 MW in Norway and 200 MW in Finland (EWEA 2011).

Since the Nordic wind power production is currently heavily dominated by Denmark (Table 1) the Swedish production has been scaled up to the same level, and the production of Finland and Norway to half of Denmark. The share from Finland and Norway could be larger, but the input data time series from these countries are not as good as for Sweden and Denmark, as they have less sites and smoothing effect incorporated in the data.

Currently, approximately 28% of the electricity consumption is produced by wind power in Denmark, 4% in Sweden, and 1% in Norway and Finland. The Nordic wide wind penetration level in 2011 was 4% (this would be 6% if scaled data for Sweden, Finland and Norway is used). For all countries the installed capacity has increased during the years of study. Production data is therefore presented relative to the installed wind power capacity in most analyses (Equation 1).

$$\%\text{ of capacity} = 100 * \frac{Production\ [MW]}{Installed\ capacity\ [MW]} \tag{1}$$

For Finland the timing of new capacity build-up is known so it is straightforward to produce a time series relative to the currently installed capacity for the data for 30 sites. For Sweden and Denmark the data was converted to be relative to the current capacity assuming a linear growth of capacity during the year, and using the installed capacity in the beginning and at the end of the year (Table 1). Information on the total installed wind capacity in Sweden differs somewhat based on the source (EWEA 2010, 2011 and 2012; Svenska Kraftnät 16.5.2012; IEA Wind 2010–2012). Svenska Kraftnät advised to use the wind statistics on Energimyndigheten's web pages (www.energimyndigheten.se) to best align with the production time series.

Table 1. Installed wind power capacity in the Nordic countries at the end of years 2008–2011. For Finland the source for installed capacity is Wind energy statistics in Finland 14.6.2012 and the numbers in parenthesis show the amount of data available for this study.

Year	Denmark (EWEA 2012, IEA Wind) [MW]	Finland [MW]	Norway (EWEA) [MW]	Sweden (Energi-myndigheten) [MW]	Nordic [MW]
2008	3161	142 (140)	428	1085	4801
2009	3482	146 (141)	431	1448	5503
2010	3749	196 (175)	441	2019	6383
2011	3871	199 (194)	520	2769	7352

The hourly time series were used when comparing the variability of wind power production between the countries, and as starting points when upscaling the wind data to future higher penetration levels.

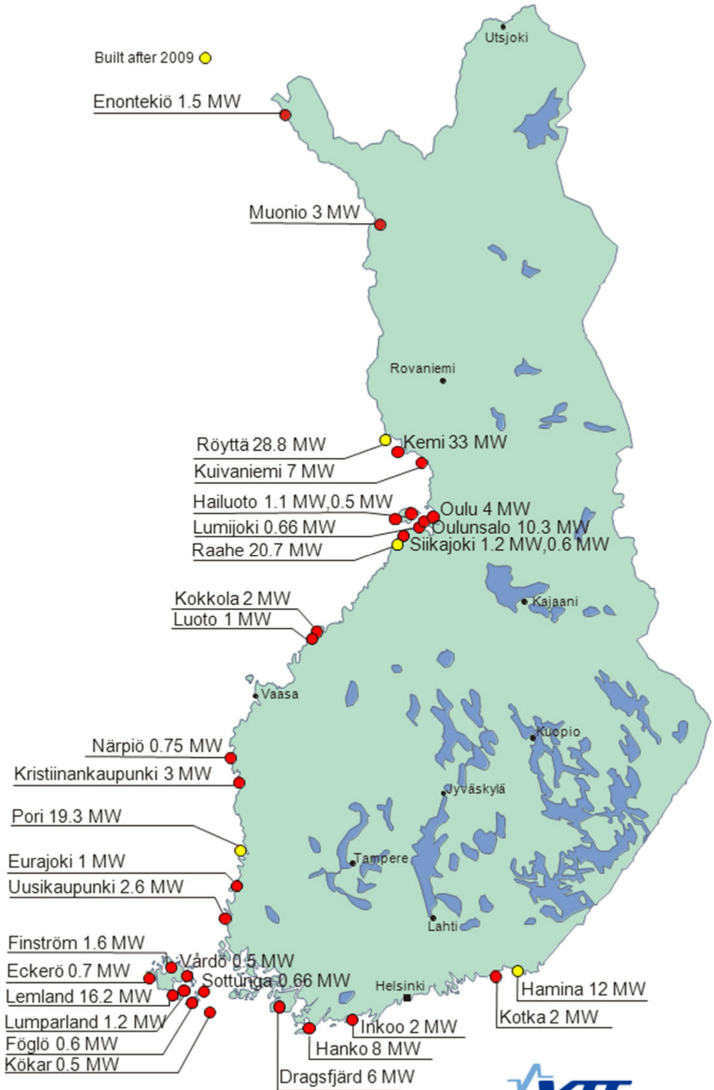

Figure 1. Map of the Finnish sites of which data has been used in this study.

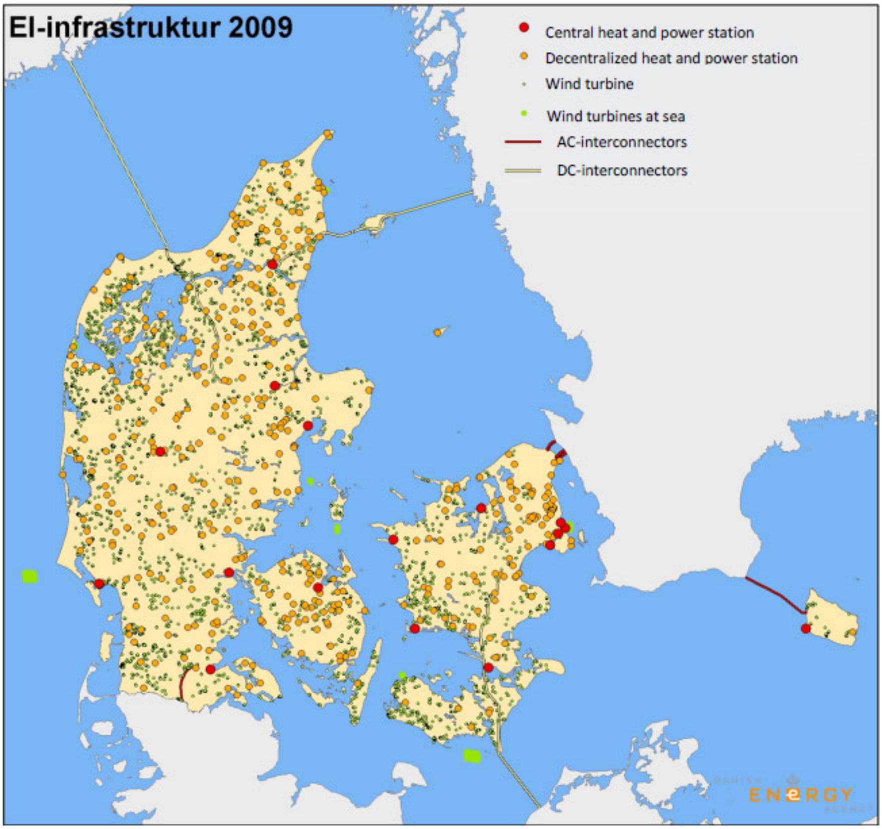

Figure 2. Green dots present wind power plants in Denmark, where wind power is widely dispersed to hundreds of sites (Center for Politiske Studier 2009).

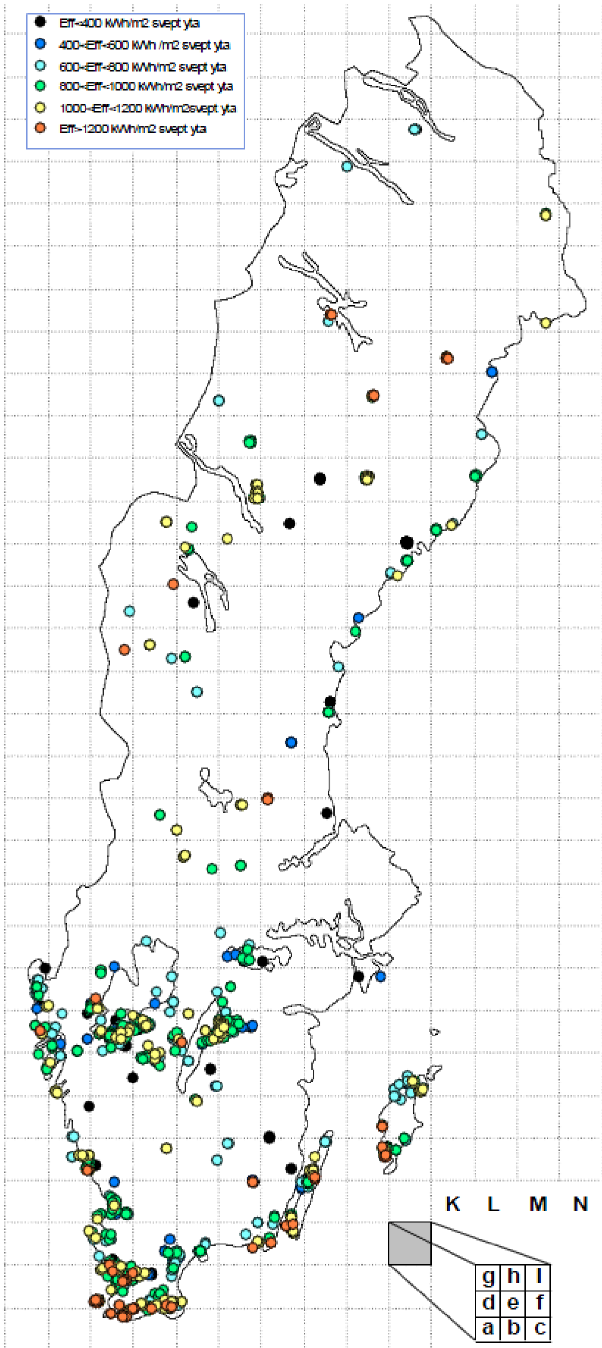

Figure 3. Map of the Swedish sites. The production during 2011 was largest for the orange colored sites, with yellow, green and blue ones following (Carlstedt 2011).

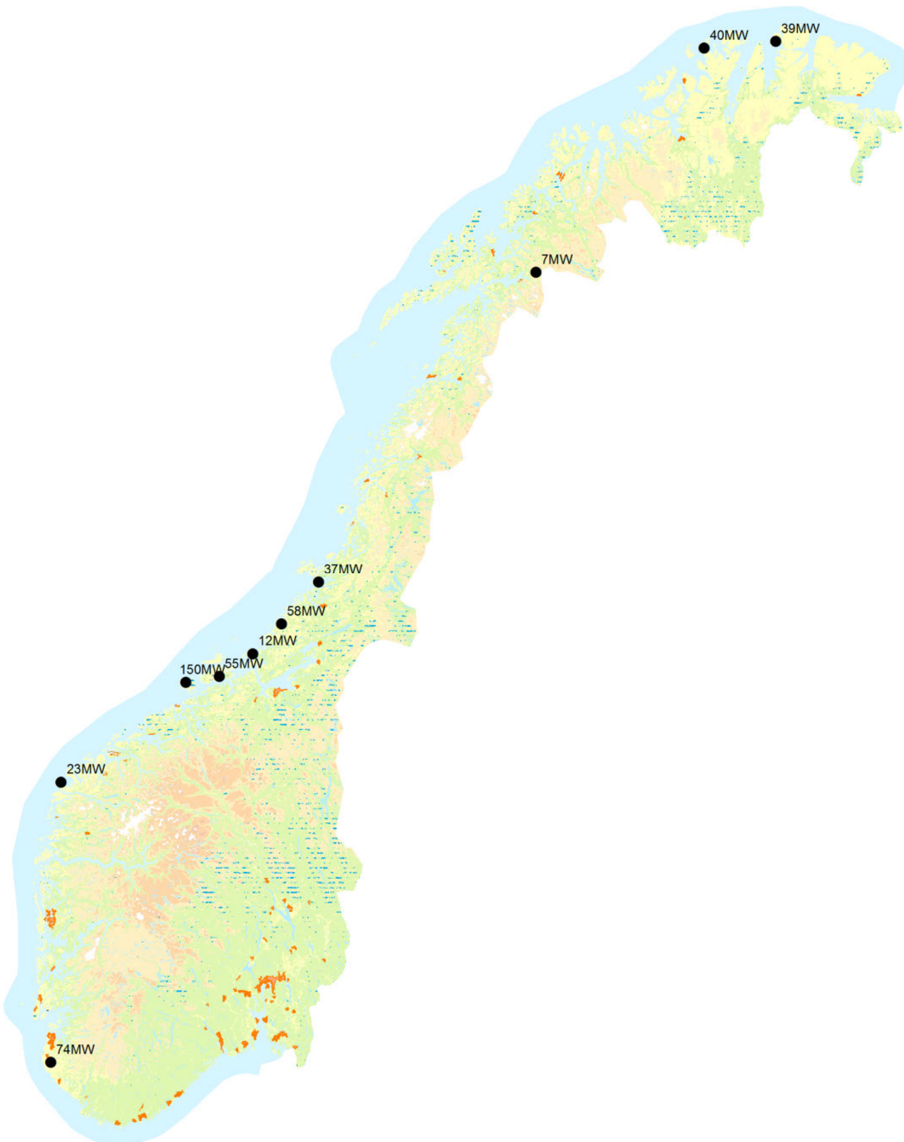

Figure 4. Map of the Norwegian sites. For the 150 MW wind power plant only half of the capacity was used, to better represent future distributed wind power plants.

Hourly load data for the Nordic countries was obtained from Nord Pool Spot (16.5.2012, www.nordpoolspot.com). The data was corrected by removing some spikes in order to make sure that the analyses of variability would not be too affected by any potential outliers in the initial data. Load data is presented both as MWh/h and as relative to peak load during each year (Equation 2).

$$\%\ of\ peak\ load\ =\ 100 * \frac{Load}{Maximum\ load} \tag{2}$$

The data covers also Western Denmark, which belongs to a different synchronous power system (Central Europe) than the other Nordic countries and Eastern Denmark (Nordic system). Also Western Denmark has access to the balancing market of the Nordic countries over the HVDC links. The balancing market is called the Regulating Power Market and is operated by the system operators (TSOs) during the operating hour (for bids that can be activated in 15 minutes).

The hourly variability is calculated as the difference between two consecutive hourly production or load values – we do not have access to minimum or maximum values inside the hour, so the average power during the hour is the basis for the analyses.

3. Variability of wind power production

Wind power production varies according to wind variations at the location of the turbines. For a single turbine and single wind farm site the variability is high. This variability is not so relevant when considering the impacts of wind power on the power system as a whole. In this publication the focus is on regional and Nordic-wide wind power production and its variability. However, for a distribution system operator, also the variability from a smaller area may be of interest. In the following, analyses and discussion of both the hourly wind power production and its hourly variability are presented.

The sum of the total wind power production in the Nordic countries is currently heavily dominated by Denmark. To look at possible future Nordic wide production, the Swedish wind power production was scaled up to a similar level as the Danish wind power production, and the wind power production from Finland and Norway to half of that of Danish wind power production.

3.1 Production time series

The data available for this study is shown as time series in Figure 5 – Figure 8. The time series show the hourly wind power production for each country during 2010 and duration curves for the years 2009–2011. Duration curves show the production for all 8760 hours of the year in descending order. From the duration curves it can be seen that the annual production has increased every year as new capacity has been built (Table 1).

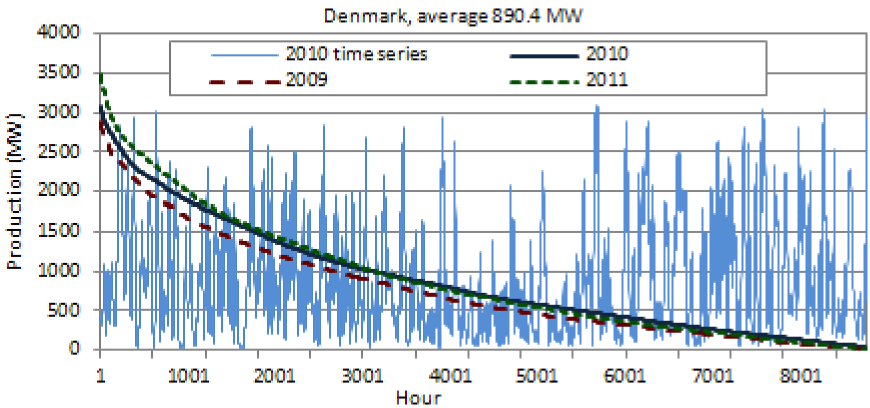

Figure 5. Wind power production in Denmark 2010. Production time series were scaled from 7.2 TWh to 7.8 TWh to match the yearly production and total installed capacity reported from Denmark. Installed capacity was 3480 MW at the beginning of the year and 3802 MW at the end of the year.

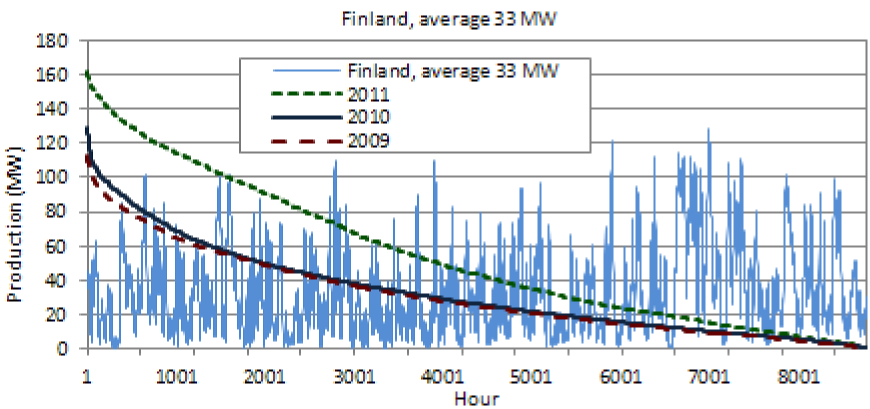

Figure 6. Wind power production in Finland year 2010. Installed capacity was 141 MW at the beginning of the year and 164 MW at the end of the year.

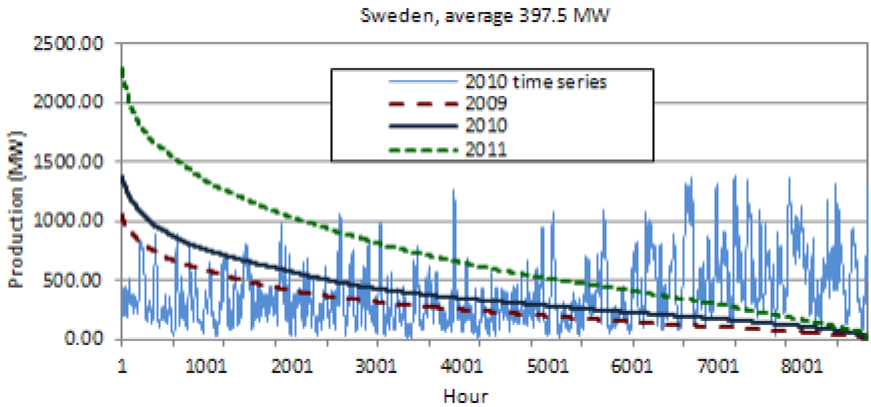

Figure 7. Wind power production Sweden 2010. Installed capacity was 1448 MW at the beginning of the year and 2019 MW at the end of the year.

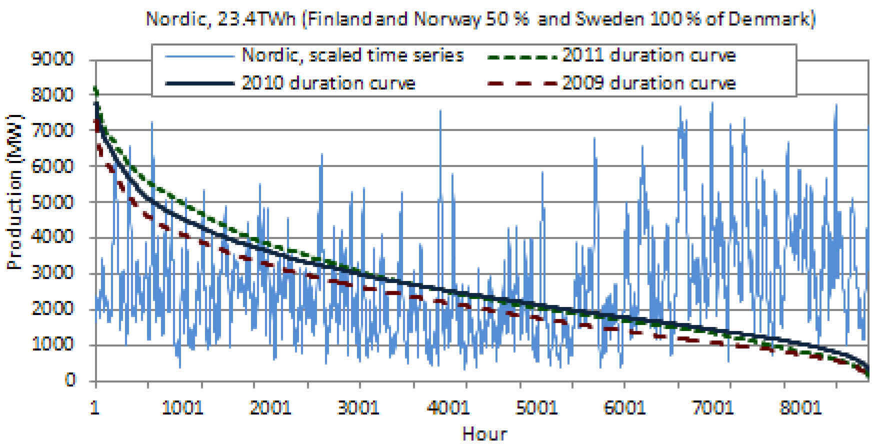

Figure 8. Wind power production in the Nordic countries 2010 – with Sweden and Finland scaled to 100% and 50% of the production in Denmark respectively. Scaled installed capacity was 8647 MW at the beginning of the year and 10548 MW at the end of the year.

Variability of wind power will smooth out when production from different sites are combined. Figures 8–10 show the duration curves of production from areas with increasing sizes (single site, regional, country, Nordic). The smoothing effect of production is clearly visible: the maximum power from large-scale wind power will never reach 100% of installed capacity and occurrences of 0% production will be rarer as a larger area is covered by the wind power plants. At the same time the duration curves become flatter. Same impact is shown in Figure 11 for wind power generation aggregated in the two control areas Jutland and Zealand in Denmark, compared to wind power in the whole Denmark.

Smoothing effect of variations will be stronger if the production is not well-correlated – or exhibits a negative correlation. The correlation coefficients of hourly wind power production between the countries are presented in Table 2. Wind power production in Denmark and Sweden is correlated. This is explained by noting that a large share of the Swedish capacity is located along the Sweden's southern coast, close to Denmark. Finland, Sweden and Norway show a weaker correlation between each other, and correlation between Finland and Denmark, and Norway and Denmark is almost non-existent. However, the correlations calculated for Finland and Norway vary significantly on a yearly basis, especially for 2011 which was more windy than average.

Table 2. Correlation coefficients of hourly production (% of capacity).

	2009	2010	2011
Finland-Sweden	0.48	0.42	0.62
Finland-Denmark	0.18	0.04	0.30
Finland-Norway	0.42	0.35	0.47
Denmark-Sweden	0.71	0.65	0.71
Denmark-Norway	0.17	0.10	0.31
Sweden-Norway	0.37	0.30	0.53

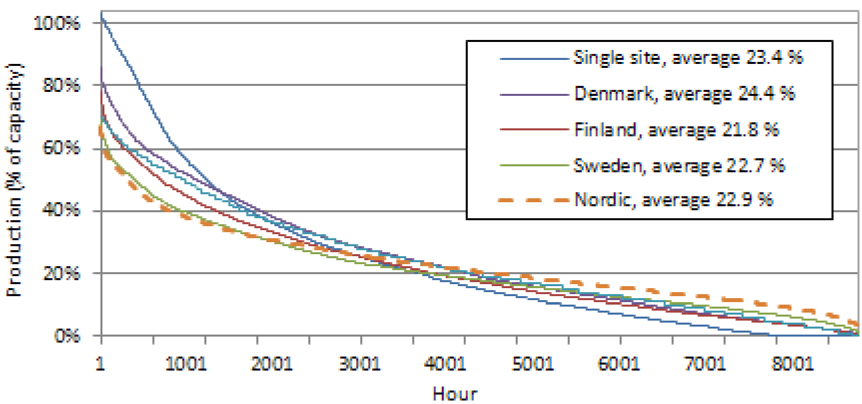

Figure 9. Smoothing effect when increasing the area size from a single site to a whole country and further to Nordic wide wind power, year 2010.

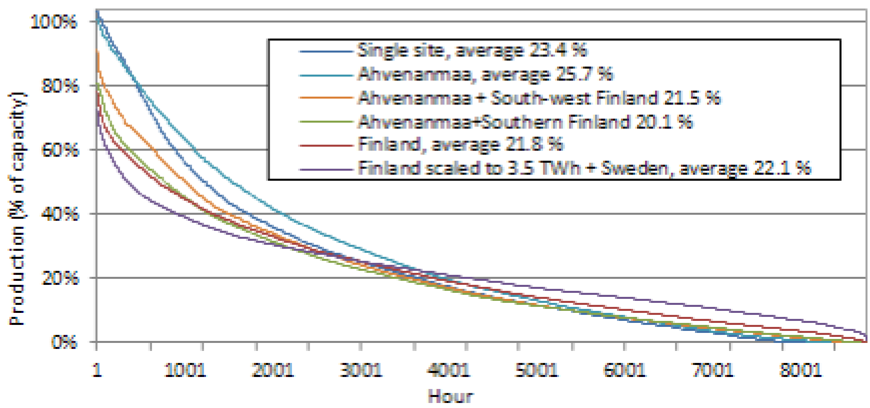

Figure 10. Smoothing effect (2010) when starting with a single site and increasing the area size within a single country and further to two countries, while assuming the same amount of wind power in both countries.

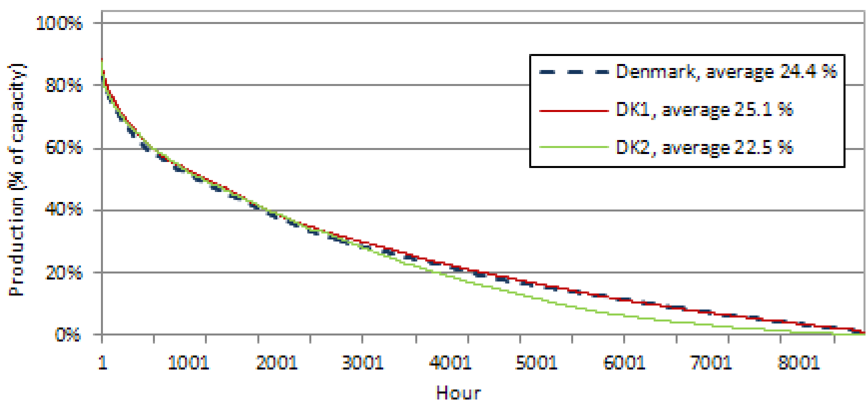

Figure 11. Smoothing effect in Denmark, year 2010. DK1 is Jutland and DK2 is Zealand.

3.1.1 Statistics of hourly wind power production

Tables 3–5 show the basic statistics of hourly wind power production from all countries during the years 2009–2011. A single site from Finland was used as a reference point. Year 2011 was more windy than average, as can be seen from both the average and standard deviation (variability).

The smoothing effect of production variations can be seen in Tables 3–5:

- Standard deviation of hourly production decreases from the single site value of close to 25%, to closer to 20% in Denmark. In Finland it was 17–21%, in Sweden 15–18% and in Nordic countries 12–16%.

- Maximum hourly wind power production from a single site exceeds 100% of installed capacity, but for a single country is less than 90% of installed capacity. In larger countries like Finland and Sweden, it was 75–84% of installed capacity. Maximum production for the Nordic region was 67–77%.
- Minimum hourly wind power production can still be 0% for a single country. Minimum production in the Nordic region can still be less than 1% of the sum of installed capacities in all countries (in year 2010 minimum was 2.8%).

The range of hourly production from large scale wind power is still wide – up to 90% of installed capacity in one country and 75% for the Nordic region.

The Swedish data set is significantly smoother than that of Denmark or Finland. Maximum wind power production in Sweden is only 76% of installed capacity and the standard deviation is lower than for the other countries.

The figures differ somewhat between the years. A higher average power production also increases the standard deviation. According to wind production index information, years 2009–2010 were less than average and year 2011 more or close to average for all countries (Finland 83–74–98%. Sweden 94–90–116%, Denmark 88–84–100%).The largest differences for yearly numbers can be seen for Finland: in 2011 average production was 28% and in other years 22%. In Finland also new wind farms built during 2009 and 2010 contributed to increasing the average production in 2011. In Denmark and Sweden the average production ranged from 23 to 24%.

Compared to previous work, analyses made for years 2000–2001 using less data, the variability in this data set is already smaller, especially for Sweden but also for Finland and even for Denmark (Holttinen 2005). In 2000–2002 the maximum wind power production was above 91% for all countries (for Sweden 95% with 6 sites only).

Table 3. Basic statistics of wind power production in the Nordic countries in 2009. Wind power production figures are presented relative to the installed capacity. Single site data is shown for comparison (from Finland). Nordic time series is dominated by Denmark (6.72 TWh from total 9.51 TWh) and does not include data from Norway. The Nordic scaled data set has one third from Denmark, third from Sweden and third from Norway and Finland combined.

	Single site	Denmark	Finland	Sweden	Nordic	Nordic scaled to 20.1 TWh
Largest distance NS-WE (km)	0.355–0.03	300–300	1000–400	1300–400	1700–1200	1800–1300
Mean	23.0%	23%	22.1%	22.6%	22.9%	22.6%
Median	13.8%	16.9%	17.5%	18.5%	17.9%	19.9%
Standard deviation	24.8%	19.6%	17.3%	16.2%	17.3%	13.4%
Max	103.0%	88.4%	80.4%	76.0%	84.5%	76.3%
Min	0.0%	0.03%	0.01%	0.3%	0.4%	0.3%
Range	103.0%	88.3%	80.4%	75.3%	84.1%	76.0%

Table 4. Basic statistics of wind power production in the Nordic countries in 2010, wind power production time series is presented as % of capacity.

	Single site	Denmark	Finland	Sweden	Nordic	Nordic scaled to 23.4 TWh
Largest distance NS-WE (km)	0.355–0.03	300–300	1000–400	1300–400	1700–1200	1800–1300
Mean	23.4%	24.4%	21.6%	22.7%	23.9%	22.8%
Median	15%	19.1%	17.3%	19.2%	19.7%	20.7%
Standard deviation	24.5%	19%	16.6%	14.5%	16.0%	11.9%
Max	103.3%	85.9%	78.1%	74.6%	77.0%	67.0%
Min	0.0%	0.8%	0.004%	0.5%	1.8%	2.8%
Range	103.3%	85.1%	78.1%	74.1%	75.3%	64.2%

Table 5. Basic statistics of wind power production in the Nordic countries in 2011, wind power production time series is presented as % of capacity.

	Denmark	Finland	Sweden	Nordic	Nordic scaled to 23.7 TWh
Largest distance NS–WE (km)	300–300	1000–400	1300–400	1700–1200	1800–1300
Mean	23.7%	28.0%	29.5%	25.9%	26.8%
Median	17.6%	22.3%	25.2%	20.5%	23.1%
Standard deviation	20.1%	21.4%	18.7%	17.9%	15.7%
Max	89.8%	83.6%	84.3%	86.7%	77.2%
Min	0.2%	0.02%	0.6%	0.7%	1.3%
Range	89.6%	83.6%	83.6%	86.0%	75.9%

3.1.2 Seasonal distribution of production

Wind power production is higher during autumn and winter in all countries and the Nordic region. Correspondingly, low production levels of less than 10% of installed capacity are most probable in summertime.

Frequency distributions of hourly production (Figure 12 – Figure 15) were calculated using three years of data: 2009–2011. Data was grouped into bins around 0, 5, 10, 15% of capacity etc. The distributions were calculated for all data during the period, and also individually for each season. In summer, the production is more often concentrated at the lower levels of less that 15% of capacity. Winters and autumns have more very high production situations than spring and summer.

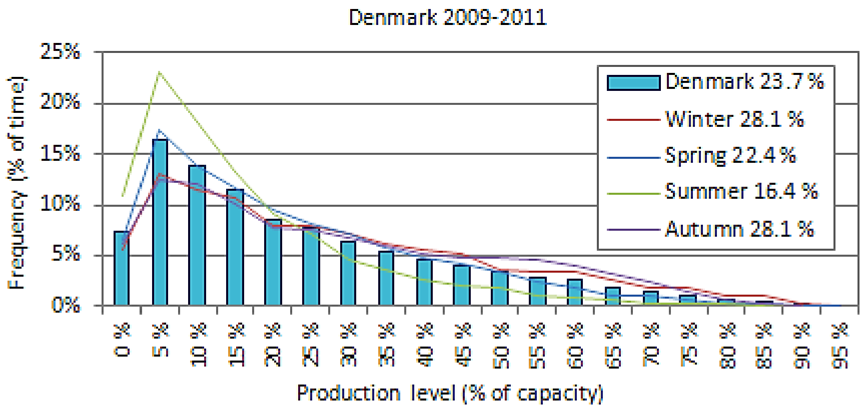

Figure 12. Frequency distributions of wind power production in Denmark during 2009–2011 and during different seasons. Low production levels are more probable during summer and high levels during winter. Average production during each season is denoted in the legend text.

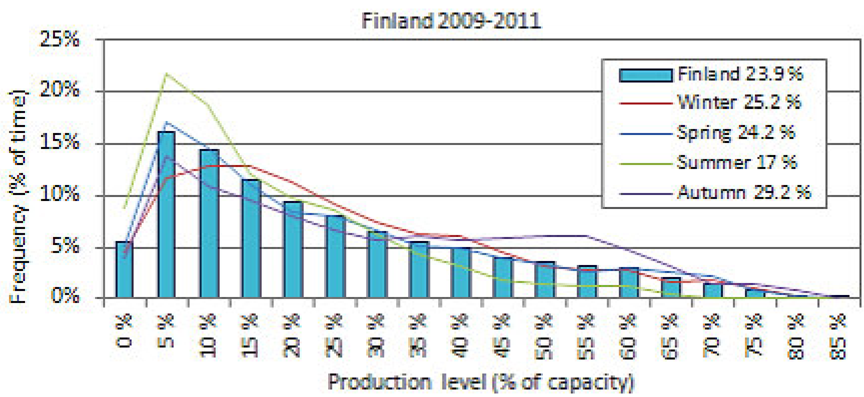

Figure 13. Frequency distributions of wind power production in Finland during 2009–2011.

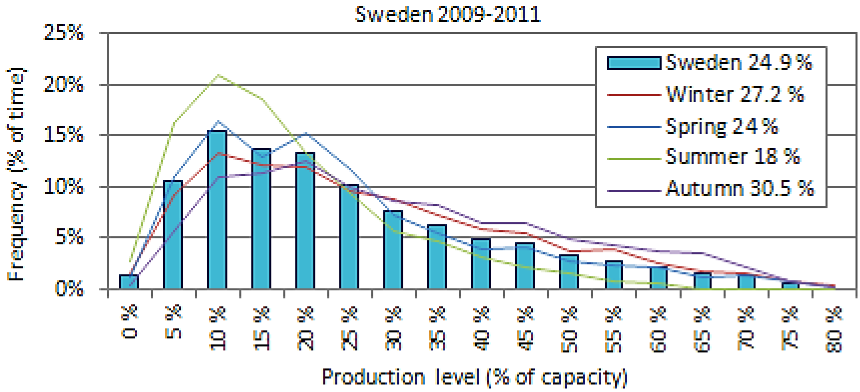

Figure 14. Frequency distributions of wind power production in Sweden during 2009–2011.

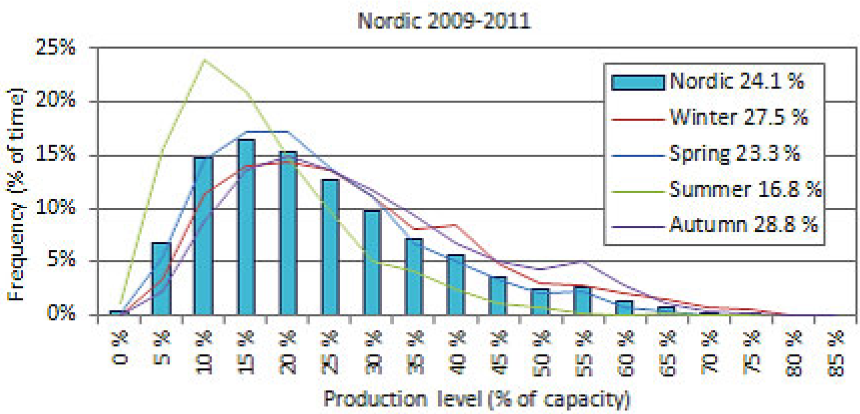

Figure 15. Frequency distributions of wind power production in the Nordic region during 2009–2011.

3.1.3 Diurnal pattern of hourly production

Wind power production can follow a pattern that reflects the hour of the day – in many places the production tends to be higher in the afternoons. This can clearly be seen in Denmark but less in Northern parts of Scandinavia (Figure 16 – Figure 23).

Diurnal patterns of wind power production are especially clear in Denmark where the production is at the highest level in the afternoons from 1 to 5 pm. The pattern is more pronounced during summer and spring, when the diurnal variation affects Finland and Sweden as well. However, in the wintertime it is almost non-existent in all Nordic countries (Figure 20).

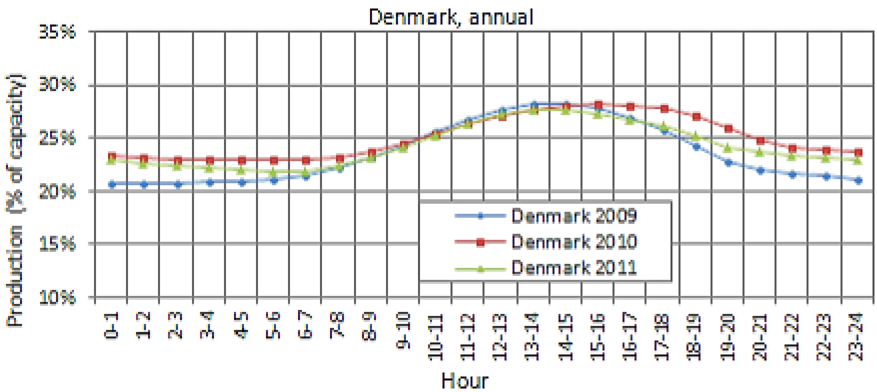

Figure 16. Diurnal pattern of wind power production in Denmark.

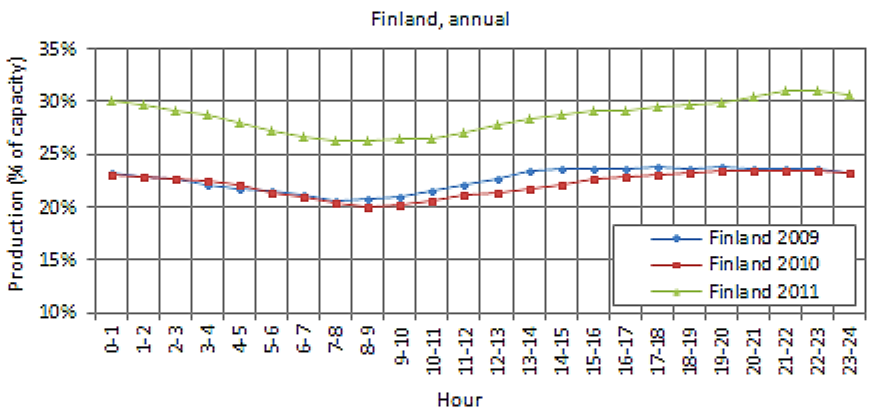

Figure 17. Diurnal pattern of wind power production in Finland.

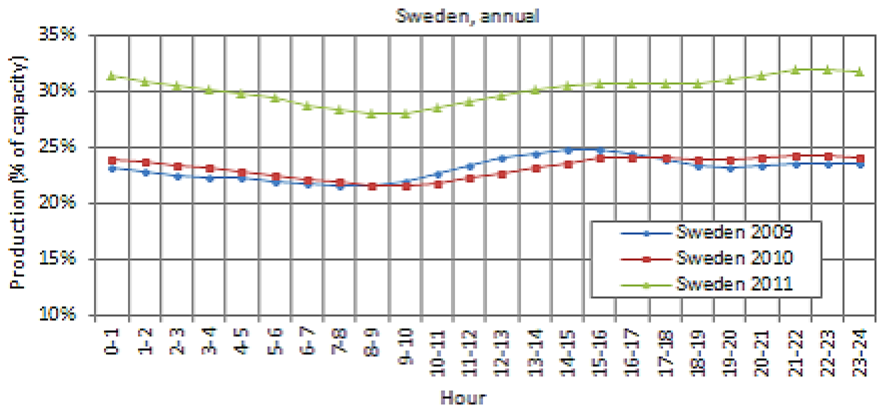

Figure 18. Diurnal pattern of wind power production in Sweden.

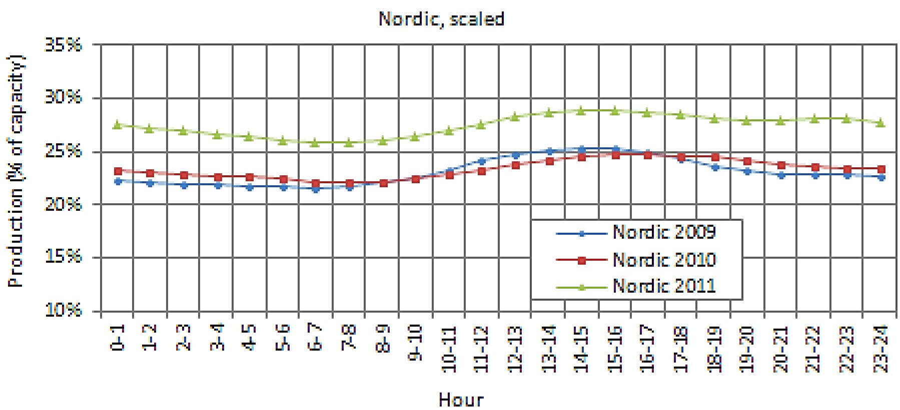

Figure 19. Diurnal pattern of wind power production in Nordic countries.

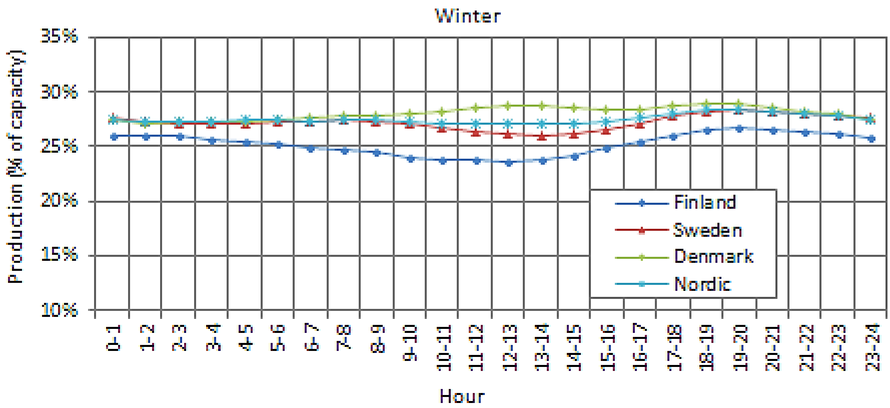

Figure 20. Diurnal pattern of wind power production in winter, years 2009–2011.

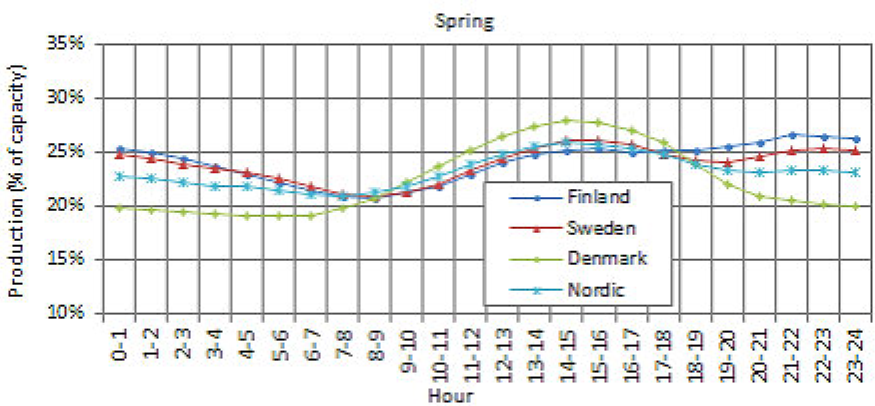

Figure 21. Diurnal pattern of wind power production in spring, years 2009–2011.

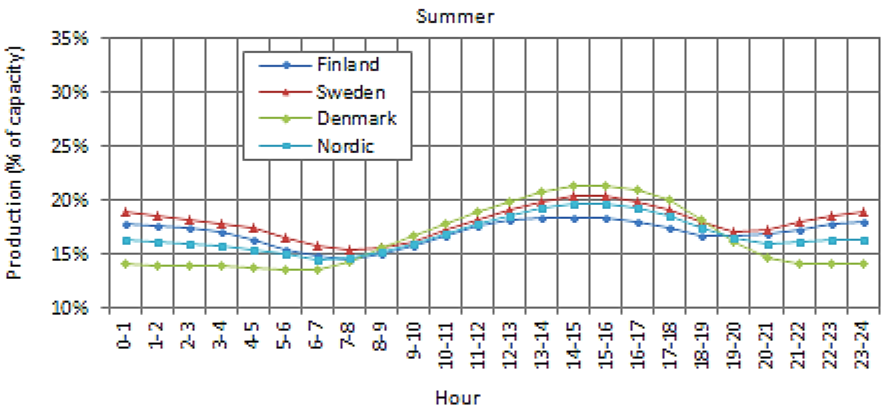

Figure 22. Diurnal pattern of wind power production in summer, years 2009–2011.

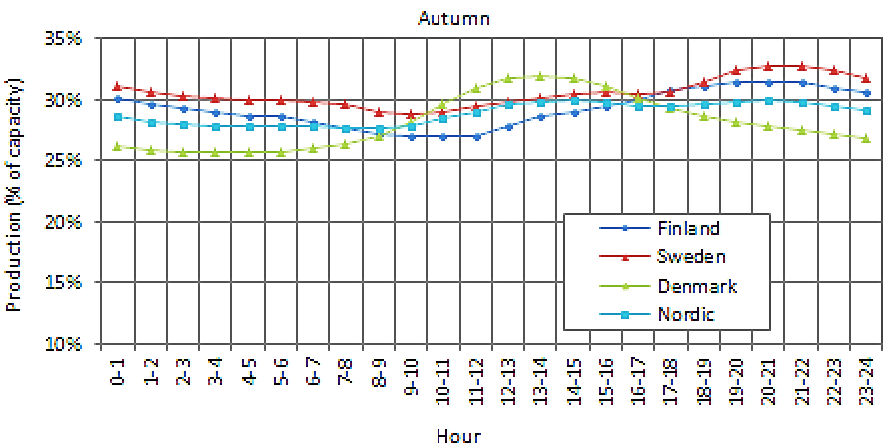

Figure 23. Diurnal pattern of wind power production in autumn, years 2009–2011.

3.2 Time series of hourly step changes in production

After analysing the hourly wind power production, the next step is to investigate how much the production can vary in one hour, or several hours. The production changes of consecutive hours was analysed in order to find out to what extent the production varies on an hourly scale, from one hourly average value to the next.

The time series of hourly step changes during 2010 are presented in Figure 24–Figure 27. Due to wider distribution of sites, the variations in both up or down directions are smaller in Sweden than in Finland or Denmark. This is due to a larger area of Sweden compared to Denmark. In Finland the variability is larger than in Denmark even though the area is larger, because there are fewer sites represented in the data. For example during 2010, the maximum 1 hour up variation was 18% in Denmark and Finland, 11% in Sweden, and 8% in the Nordic region. The smoothing effect can also be seen by comparing the duration curves of hourly variations within each country and the Nordic region, and it is especially clear at the tails of the distributions. In Sweden and the Nordic region the variability from one hour to the next is most of the time within ± 5% of installed capacity. In Denmark it is most of the time within ± 10% of capacity.

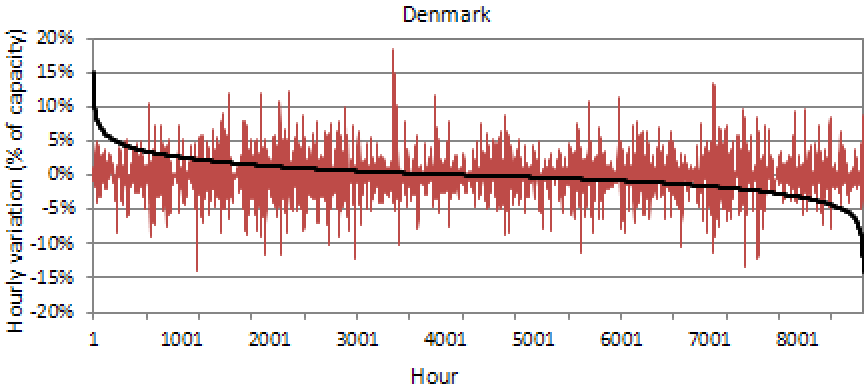

Figure 24. Hourly variation (difference of average power between two consecutive hours) of wind power production in Denmark 2010, as time series and duration curve.

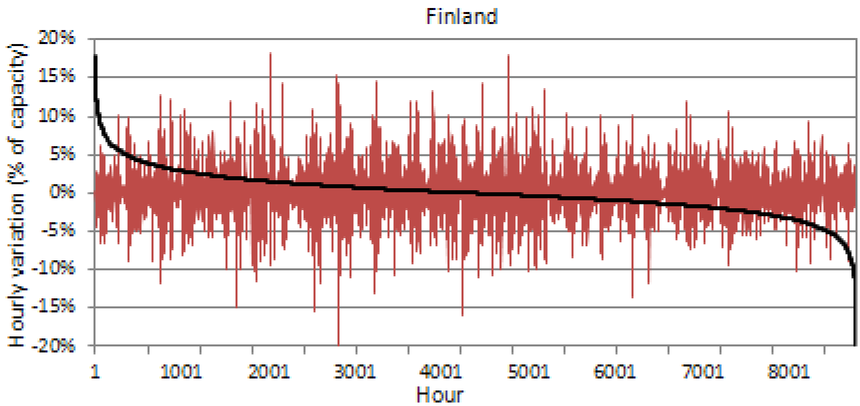

Figure 25. Hourly variation of wind power production in Finland 2010.

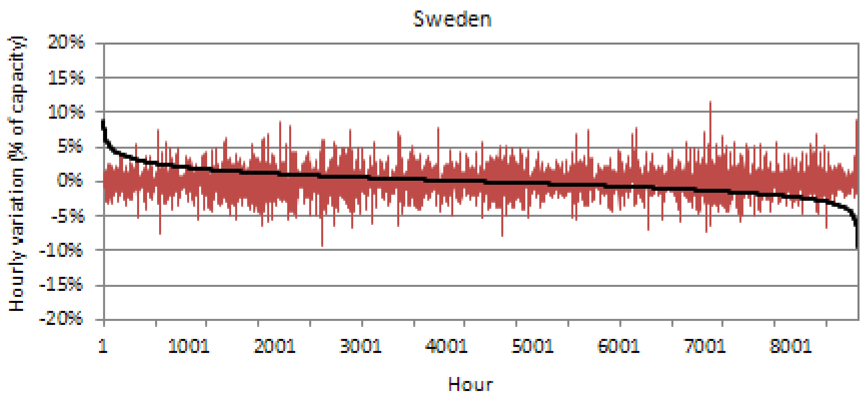

Figure 26. Hourly variation of wind power production in Sweden 2010.

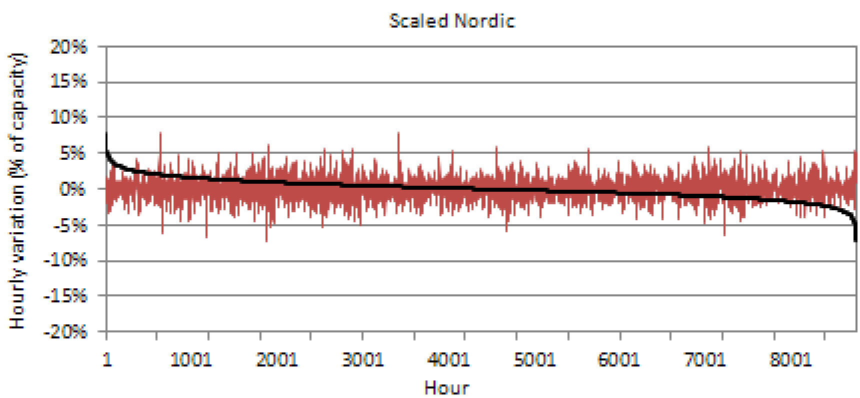

Figure 27. Hourly variation of wind power production in the Nordic countries 2010. Finland and Norway have been scaled to 50% and Sweden to 100% of Denmark.

For all regions the variability is similar during the three years (Appendix B and Figure 30). The variability of wind power production is always smoothed when distributing the production into larger areas. This can be seen when comparing the results of a single site to a larger region and to a country. The duration curves for hourly variations show that increasing the area size decreases the variability (Figure 28, Figure 29). This can be seen especially in the tails that show the larger variations up and down.

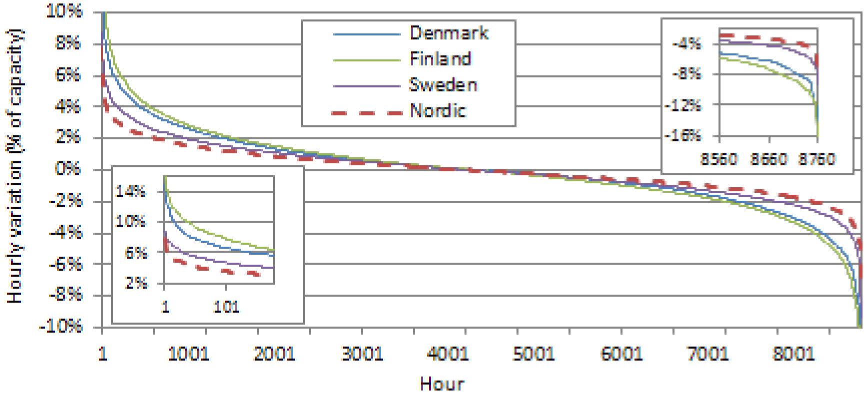

Figure 28. Duration curves of hourly variation of production in 2010. Finland has been scaled to 50% and Sweden to 100% of Denmark.

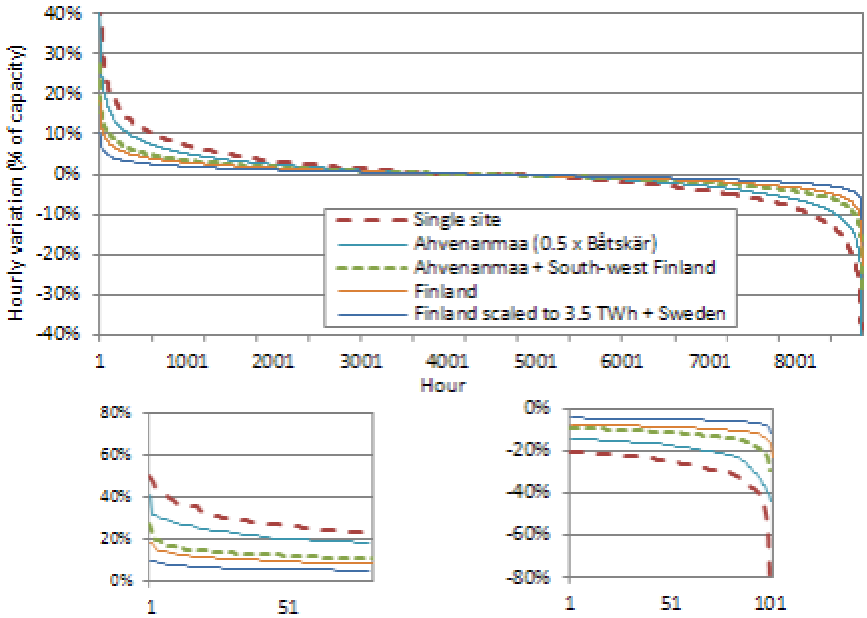

Figure 29. Duration curves of hourly variation in 2010.

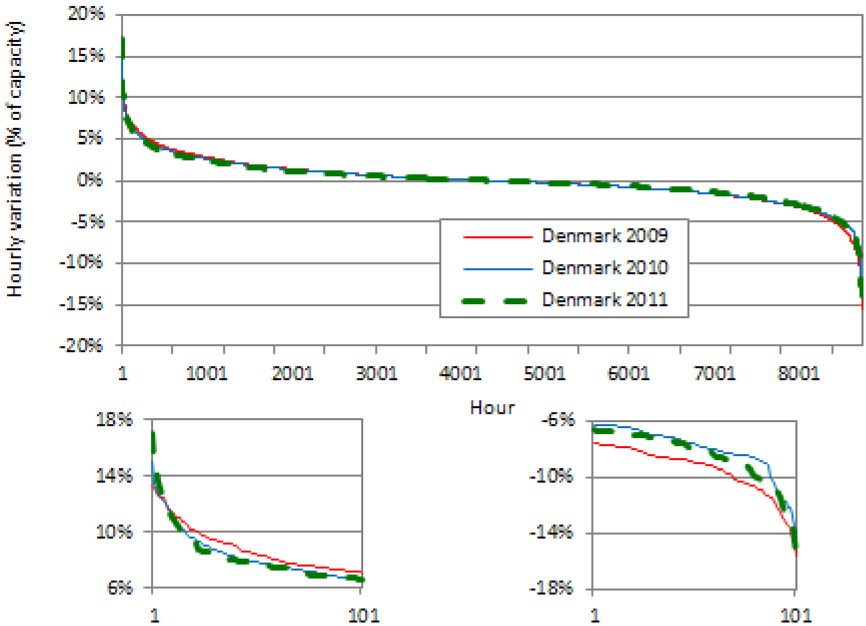

Figure 30. Duration curves of hourly variation in Denmark, years 2009, 2010 and 2011.

3.2.1 Statistics of hourly variability

Tables 6–8 show the basic statistics of hourly variability from all countries during the years 2009–2011, together with a single site in Finland and the Nordic region (again, Finland and Norway have been upscaled to 50% of Denmark and Sweden to 100% of Denmark).

The smoothing effect can be seen from the statistical values:

- Average variability in the upwards or downwards direction is about 6% of installed capacity for a single site, 2% in Denmark and Finland, roughly 1.5% in Sweden and 1% in Nordic countries. Year 2011 data shows lower variability in Denmark and higher in Finland.
- Standard deviation decreases from the value of a single site of approximately 8%, to approximately 2.5% in Denmark, 2% in Sweden and 1.5% for the Nordic region.
- Maximum hourly wind power variation is 18% of capacity in Denmark, 23% in Finland, 11% in Sweden and 8% in Nordic countries.

Again we note that the Swedish data set is significantly smoother than that of Denmark or Finland.

Table 6. Hourly wind power variations in 2009, presented as % of installed capacity. Positive (negative) mean is the average increase (decrease) in the production of two successive hours. The size of a region is measured as the largest distance from North to South and from West to East.

	Single site	Denmark	Finland	Sweden	Nordic	Nordic, scaled to 20.1 TWh
Largest distance NS-WE (km)	0.355–0	300–300	1000–400	1300–400	1700–1200	1800–1300
Positive mean	6.1%	1.9%	2.1%	1.4%	1.5%	1.1%
Negative mean	-6%	-1.8%	-2%	-1.3%	-1.5%	-1.1%
Standard deviation	8.9%	2.7%	2.9%	1.8%	2.1%	1.5%
Max	81.4%	13.3%	22.7%	9.9%	10.6%	8.4%
Min	-66%	-15.5%	-18.6%	-10.2%	-12.0%	-7.8%

Table 7. Hourly wind power variations 2010, presented as % of installed capacity.

	Single site	Denmark	Finland	Sweden	Nordic	Nordic, scaled to 23.4 TWh
Largest distance NS-WE (km)	0.355–0	300–300	1000–400	1300–400	1700–1200	1800–1300
Positive mean	5.4%	1.8%	2%	1.3%	1.4%	1.1%
Negative mean	-5.3%	-1.7%	-1.9%	-1.2%	-1.3%	-1.0%
Standard deviation	7.5%	2.5%	2.8%	1.6%	1.8%	1.4%
Max	53%	18.4%	18.1%	10.7%	14.3%	7.8%
Min	-81.8%	-14%	-22.5%	-8.7%	-9.9%	-7.3%

Table 8. Hourly wind power variations 2011, presented as % of installed capacity.

	Denmark	Finland	Sweden	Nordic	Nordic, scaled to 23.7 TWh
Largest distance NS-WE (km)	300–300	1000–400	1300–400	1700–1200	1800–1300
Positive mean	1.6%	2.4%	1.5%	1.3%	1.1%
Negative mean	-1.6%	-2.3%	-1.5%	-1.2%	-1.1%
Standard deviation	2.4%	3.3%	2%	1.7%	1.5%
Max	17%	22.6%	10.7%	10.1%	7.6%
Min	-16%	-20.1%	-10.3%	-10.6%	-8.2%

The smoothing effect will be stronger if the production within the area is only weakly correlated – or has a negative correlation. Compared with the correlation of production, production variability is significantly less correlated between all countries. It is almost non-existent between Finland and the other countries, and approximately 0.25 between Sweden and Denmark (Table 9). In this light, it is rare that variations in the same direction will occur during the same hour in different countries.

Table 9. Correlation of hourly wind power variations.

	2009	**2010**	**2011**
Finland–Sweden	0.09	0.09	0.14
Finland–Denmark	-0.01	-0.01	0.03
Finland–Norway	0.02	-0.01	0.0
Denmark–Sweden	0.28	0.23	0.23
Denmark–Norway	0.01	0.02	0.02
Sweden–Norway	0.03	0.03	0.05

The smoothing effect can be clearly seen from the standard deviation of variations time series. Standard deviation measures the amount of variability from the mean value. The standard deviations have been plotted with the area size in Figure 31. The area size is calculated as estimated mean distance (Söder et al. 2012) where the wind power stations are assumed to be evenly spread out over a region which can be modeled as a rectangle. The mean distance between the wind power stations is then assumed to be the mean distance between two random points in the corresponding rectangle. The mean distance between the two points is calculated as

$$Mean\ distance = \frac{1}{15}\left[\frac{a^3}{b^2}+\frac{b^3}{a^2}+d\left(3-\frac{a^2}{b^2}-\frac{a^2}{b^2}\right)+\frac{5}{2}\left(\frac{b^2}{a}ln\frac{a+b}{b}+\frac{a^2}{b}ln\frac{b+d}{a}\right)\right] \qquad (3)$$

where $d = \sqrt{a^2+b^2}$

$a = Largest\ distance\ in\ \text{north} - \text{south direction}$

$b = Largest\ distance\ in\ \text{east} - \text{west direction}$

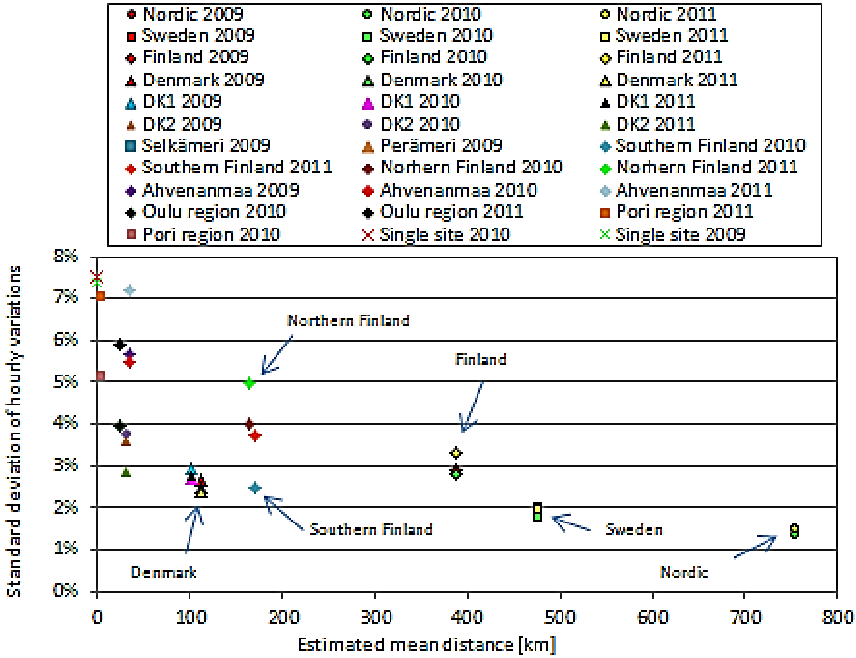

Figure 31. Smoothing effect within the Nordic region, presented as decreasing standard deviation of the time series of hourly variations, when the size increases.

3.2.2 Variability dependence on production level

There are no observed patterns of wind power production in the Nordic countries that would result in variability of wind power depending on the season or time of day. However, there is clear dependence on the current production level. At small winds, the variability is small, and is also lower at high winds when the turbines operate at rated power (usually from 15 m/s to 20…25 m/s).

This dependence was analysed by binning the absolute values of hourly variations according to the current production level (using a bin width of 5%). Figures 31–35 show the average values within each bin for 2010 data (2009 and 2011 figures, see Appendix).

The highest variability occurred when the production level was between 35–70% in Denmark, 30–50% in Finland and 30–70% in Sweden. In Finland the last bin (for 80–90% production level) shows a high variability due to only 2 data points.

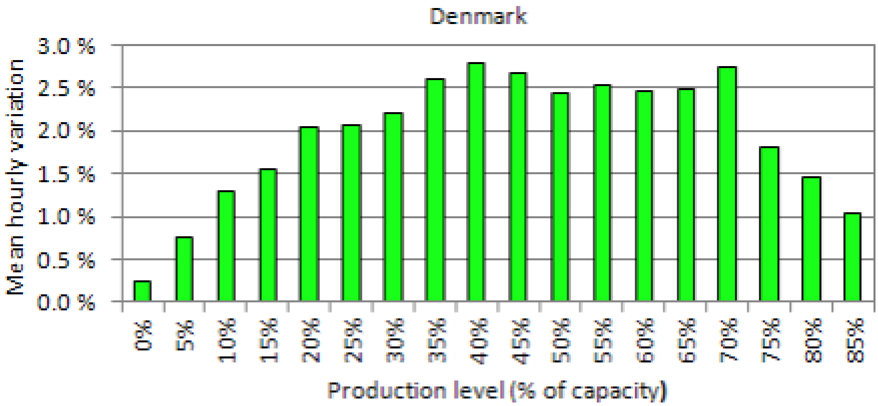

Figure 32. Average absolute variation during different production levels in Denmark, year 2010.

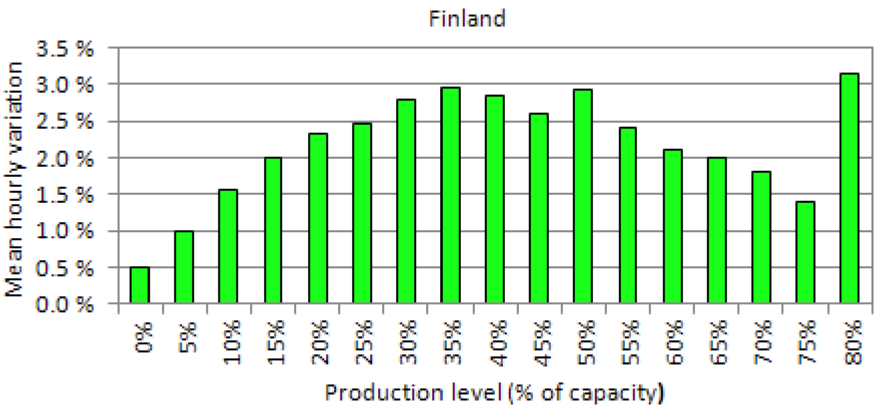

Figure 33. Average absolute variation during different production levels in Finland, year 2010. The high variability within the last bin 80–90% is due to only 2 data points.

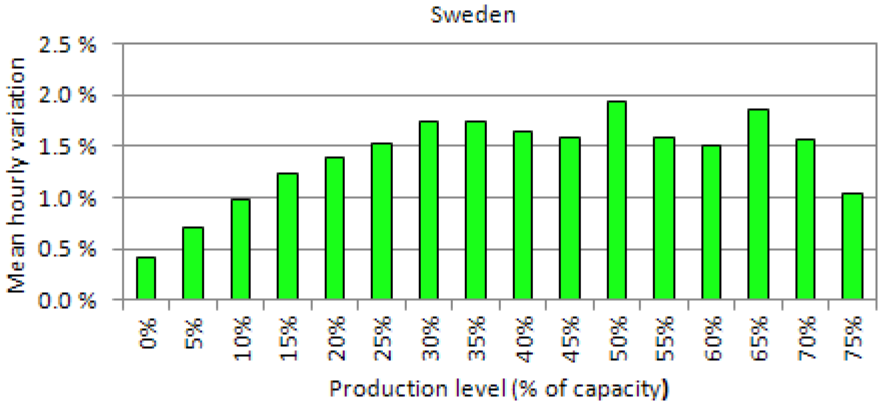

Figure 34. Average absolute variation during different production levels in Sweden, year 2010.

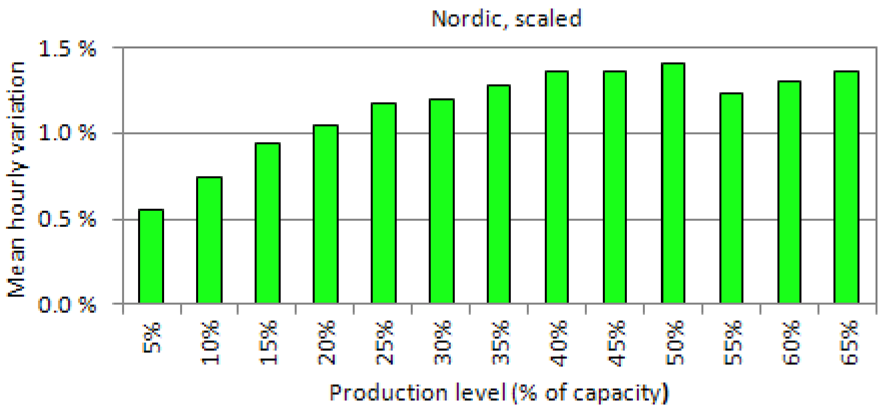

Figure 35. Average absolute variation during different production levels in Nordic countries, year 2010.

3.2.3 Variability during shorter time scales

The level of variability between two consecutive time points depends on the duration between them. The variability tends to decrease when measured over shorter time periods. For example, average 15 minute variations in Western Denmark were ± 0.57% with a standard deviation of 1.0% during 2009 which is significantly less than the corresponding 60 minute values for Western Demark of 2% and 2.7%.

Basically, the longer the time period, the higher the wind variability can be. For example, extending the time period to 4 hours leads to notable increases in the average, and especially extreme, variations. The changes are apparent when examining the tails of the duration curves.

The results for large scale wind power are presented in Figure 36 for West Denmark and in Figure 37 and Table 10 for the whole of Denmark. There were also10 minute data available for some limited number of wind power plants (Figure 38 and Figure 39). Even if the variability as such is at higher level than in the data for large scale wind power, due to less smoothing effect in the data, the decreased variability effect due to shorter time scale can be clearly seen.

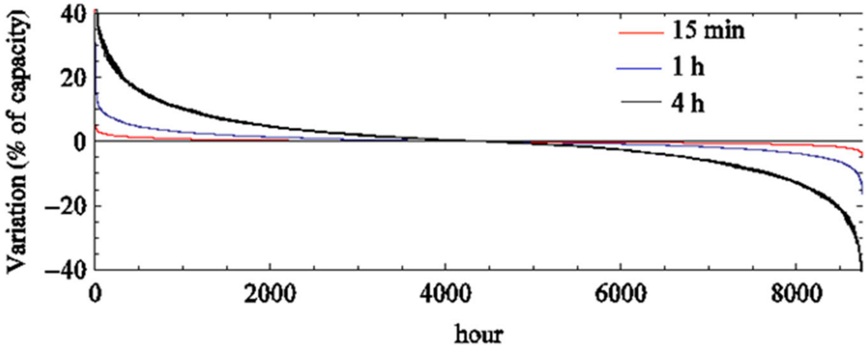

Figure 36. Duration curves of 15 minute, 1 hour and 4 hour variation in Western Denmark during 2009.

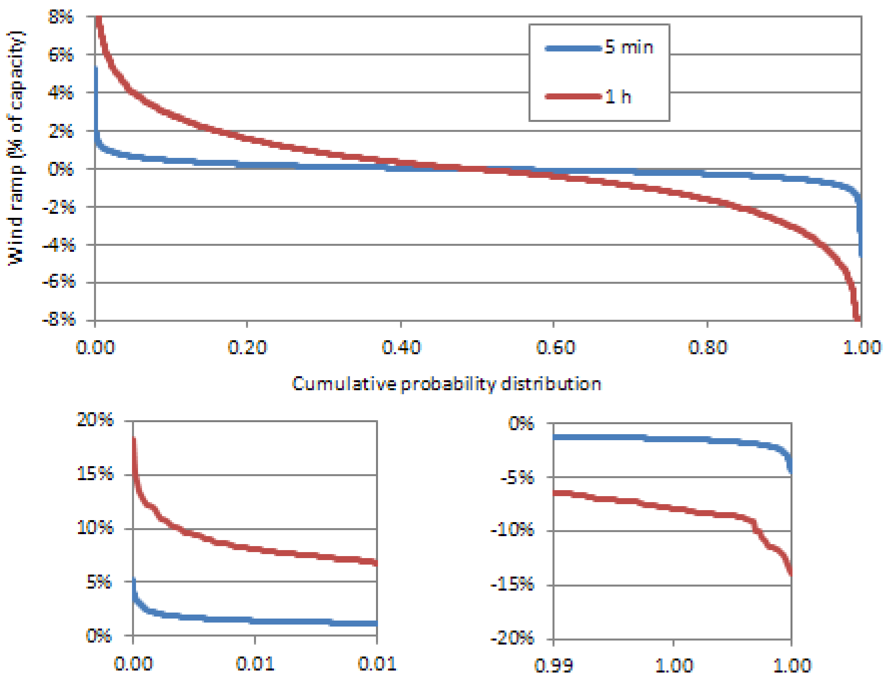

Figure 37. Duration curve of 5 min and 1 h variations in Denmark 2010.

Table 10. 5 min variations in Denmark, year 2010.

	Denmark
Largest distance NS-WE	300–300
Positive mean	0.3%
Negative mean	-0.3%
Standard deviation	0.4%

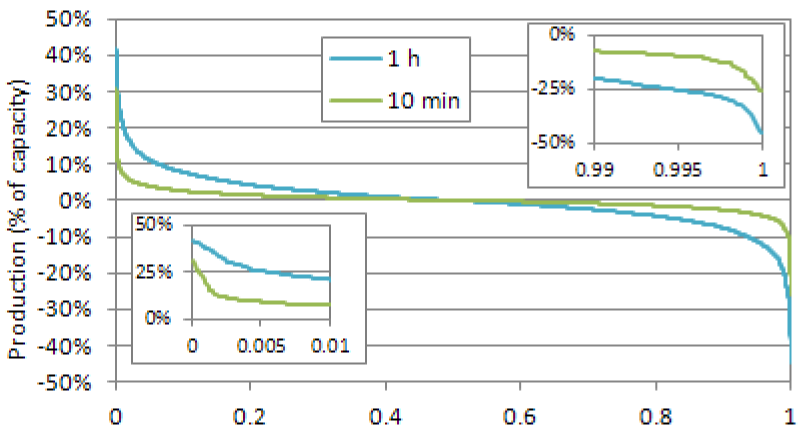

Figure 38. Duration curves of 10 minute and 1 hour variation in 3 wind farms in Sweden and Denmark during 2011.

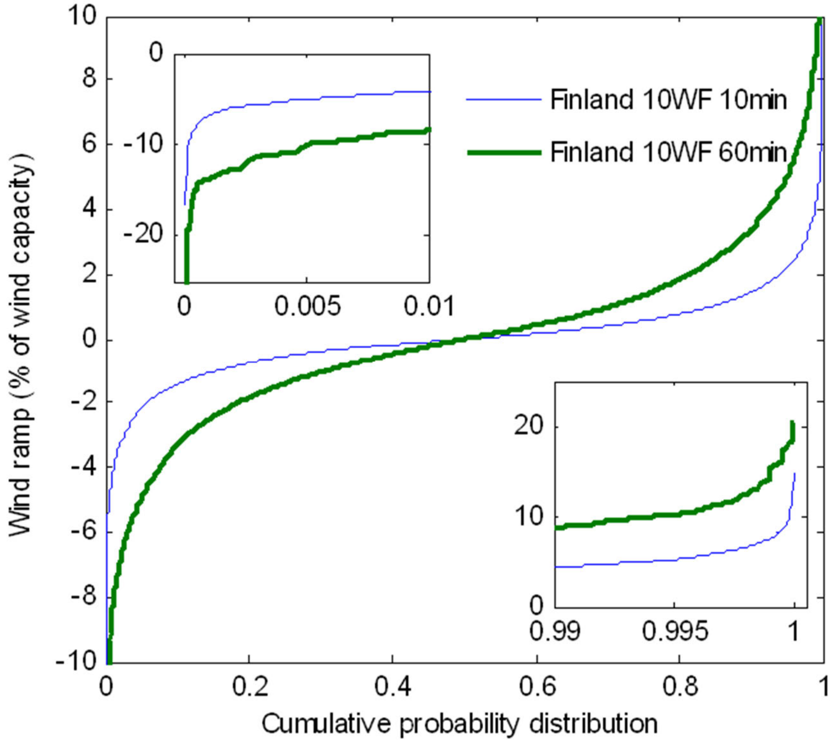

Figure 39. Comparison of wind power variability in Finland 2010 (10 wind farms) when using time steps of 10 minutes and one hour.

3.2.4 Four hour variability

Basically, the longer the time period, the higher the wind variability can be. When looking at variability in 4 or 12 hours, it is important to note that short term forecasts are crucial in order to be able to take into account how much the wind power production will vary. Most of this variability will be seen in day-ahead electricity markets, for example, and it shows that even in larger area like the Nordic countries, there will still be considerable changes in available wind power during low and high wind days.

The statistics are presented in Table 11. Time series of 4 hour variations, together with duration curves, are presented in Figure 43 – Figure 46 and the duration curves in comparison of hourly variability in Figure 40 – Figure 42.

Both the range and the average variability experience smoothing effect from one country to Nordic wide wind power, and the 4 hour variability is 2–3 times higher than hourly variability (Figure 47).

Table 11. 4 hour variations 2010, relative to installed capacity.

	Denmark	Finland	Sweden	Nordic	Nordic, scaled to 23.4 TWh
Largest distance NS-WE	300–300	1000–400	1300–400	1800–1300	1800–1300
Positive mean	5.9%	5.6%	4.3%	4.3%	3.3%
Negative mean	-5.7%	-5.2%	-4.0%	-4.1%	-3.1%
Standard deviation	8.1%	7.5%	5.5%	5.8%	4.2%
Max	42.0%	44.4%	29.1%	30.2%	23.3%
Min	-41.7%	-52.3%	-27.7%	-24.2%	-16.3%

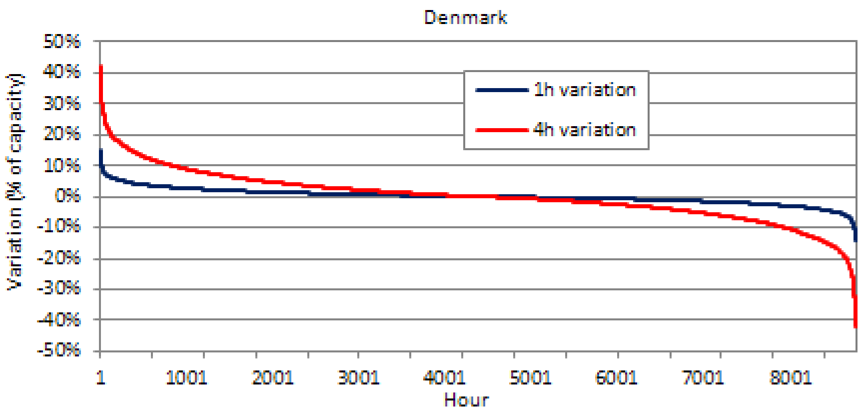

Figure 40. Duration curves of 1 hour and 4 hour variation in Denmark 2010.

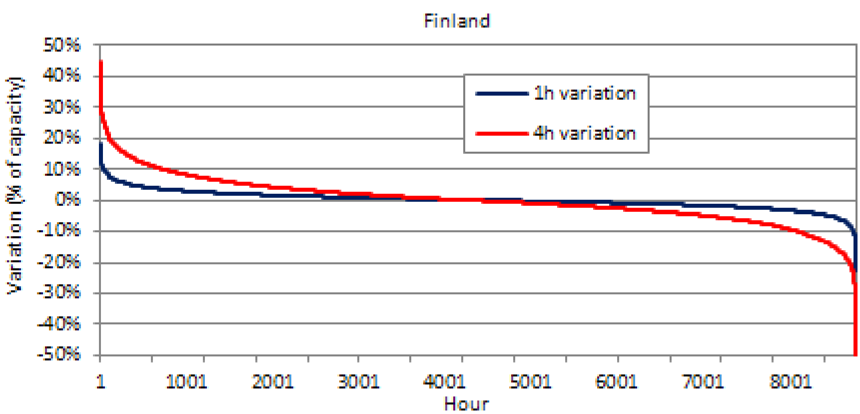

Figure 41. Duration curves of 1 hour and 4 hour variation in Finland 2010.

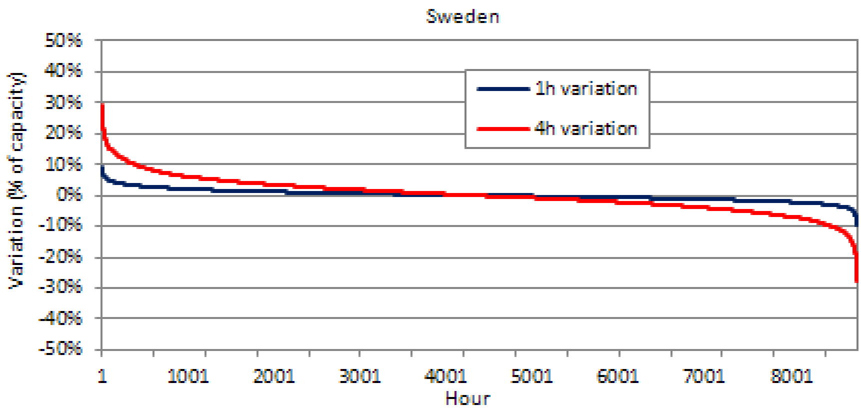

Figure 42. Duration curves of 1 hour and 4 hour variation in Sweden 2010.

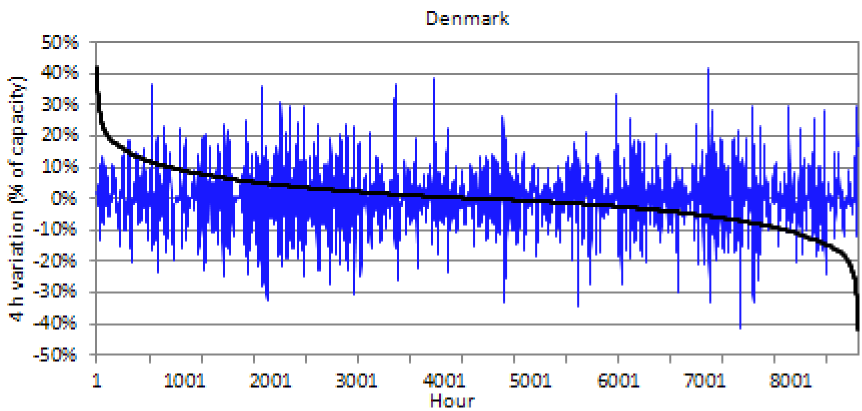

Figure 43. Time series and duration curve of 4 h production variation in Denmark 2010.

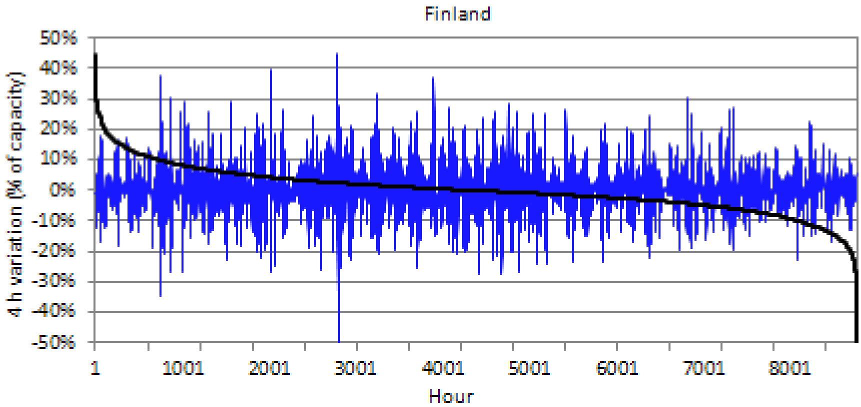

Figure 44. Time series and duration curve of 4 h production variation in Finland 2010.

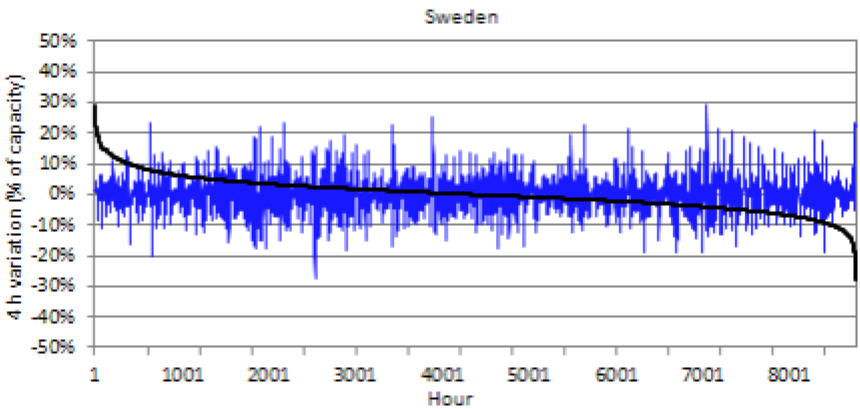

Figure 45. Time series and duration curve of 4 h production variation in Sweden 2010.

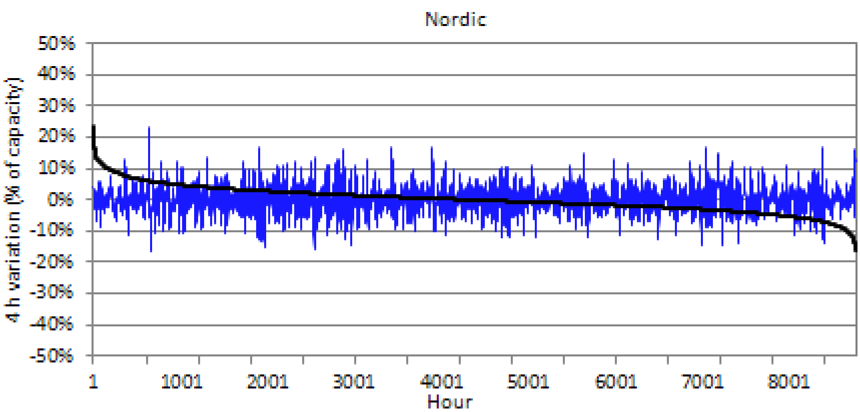

Figure 46. Time series and duration curve of 4 h production variation in Nordic countries 2010.

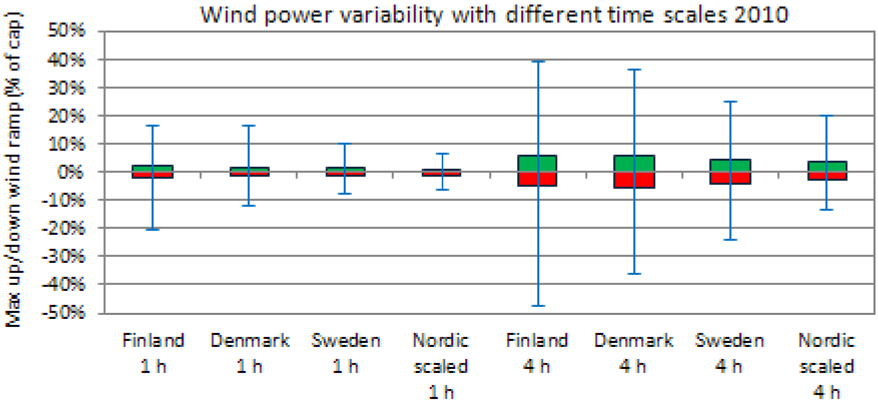

Figure 47. Average 1 hour and 4 hour wind power up-ramps (green bars) and down-ramps (red) during 2010. Range of variations is shown with blue error bars.

3.2.5 Extreme variability – case of a storm

In extreme storm conditions turbines stop from full power to protect the wind turbine. Typical storm limit for a turbine is 25 m/s for 10 minutes. These events are quite rare: usually 1–2 times in 1–3 years depending on the location of the turbine.

Large storm fronts take four to six hours to pass over an area of several hundred kilometres. Aggregation of wind power capacity usually turns a sudden interruption of power that a single wind farm experiences into a multi-hour downward ramp for a large region: for example the 8th January 2005 Gudrun storm caused the wind power production of West Denmark to decrease from 90% of capacity to 10% (2000 MW) in 6 hours.

Short term forecasts of wind power are critical in managing these situations. To prevent large ramps, large wind power plants may be required to operate at partial loads during storm events. The impact can also be reduced by adjusting the controls of wind turbines: preventing all turbines within a wind park from shutting down during the same minute and by reducing the output more slowly as wind speed exceeds the cut-out limit.

Years 2009 and 2010 did not see many storm incidents, but in Norway two of the most significant extratropical cyclones in recent memory occurred in 2011: Berit struck at the end of November 2011 and Dagmar/Tapani struck at Chrismas in 2011. In Denmark 11.11.2010 Horns Rev offshore wind farm was shut down because of a storm (Cutululis et al. 2011).

To analyse storm events we need data also for the wind speeds to make sure the aggregate down ramp from wind power plants actually results from some turbines shut down from full power instead of calming wind. In the absence of measurements, this can be examined through modeled wind fields. Various global data are available, e.g. NCEP/NCAR reanalysis data, ERA-Interim, CFSR data, with horizontal resolution ranging from 38 km to 200 km. In order to examine mesoscale variability and spatial correlation, outputs from mesoscale models can be used. Both DTU and Kjeller Vindteknikk are currently running the mesoscale model WRF and making more detailed analyses on storms that pass one or several of the Nordic countries, and their spatial correlation. In this publication we had available the geostrophic wind speeds from NCEP/NCAR reanalysis data, 6 hour temporal resolution and about 200 km horizontal resolution, which is quite rough resolution.

Just looking at largest down ramps from wind power production data in Denmark, there were a total of 91 ramps exceeding 30% of installed capacity in 4 hours. Only 6 of the ramps in wind power production data coincided with the 30 most windy days.

The first example shown for wind power production data is the case of two storms 26th and 27th December, 2011. The wind power production from different regions in Finland are depicted in Figure 48. The wind power production in the Northern part of the coast line dropped totally, but in two phases in the first hours of 26th December. However, the total wind power production in Finland only saw a decrease of 20% of installed capacity. In Sweden the ramps were even less dramatic (Figure 49). The geostrophic winds (the winds high enough above ground level that the surface roughness and obstacles do not interfere) showed several storm level wind situations during that week (Figure 48–Figure 49). The variations of wind power production in Finland are depicted in Figure 50.

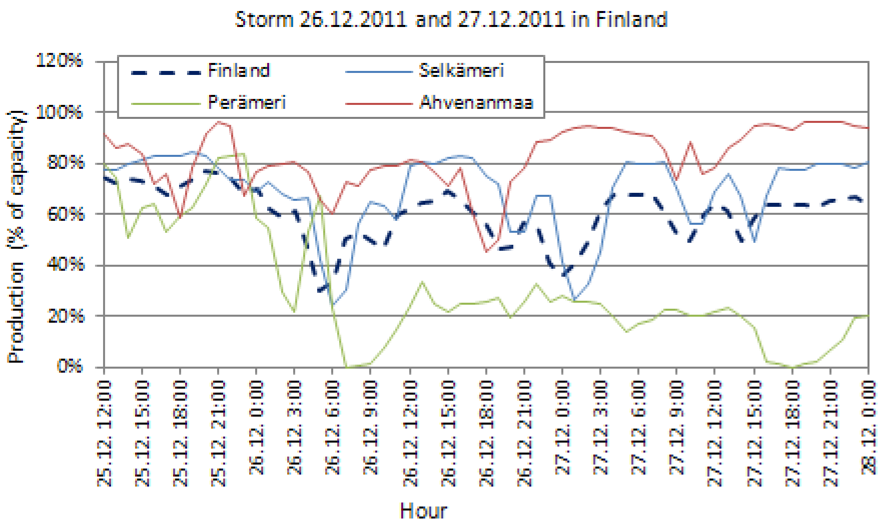

Figure 48. Wind power production in Finland 26.12.–27.12.2011, during two extreme storms in 26 and 27th Dec when part of the turbines were shut down due to storm limit.

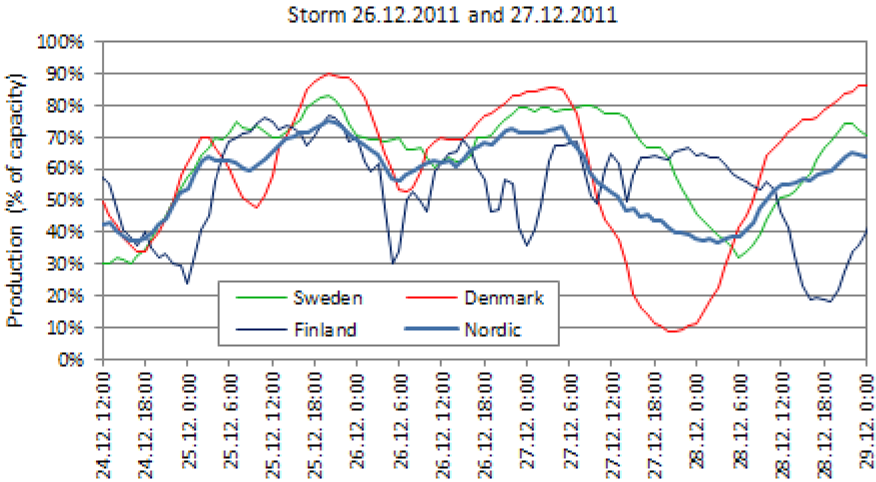

Figure 49. Wind power production in Finland, Sweden and Denmark 24.12.–29.12.2011. Largest 5 hour down ramp in Denmark was 37% of capacity (29.12. 16:00–20:00), in Finland 32% of capacity (26.12. 1:00–5:00) and in Sweden 17% of capacity (27.12. 20:00–28.12 0:00).

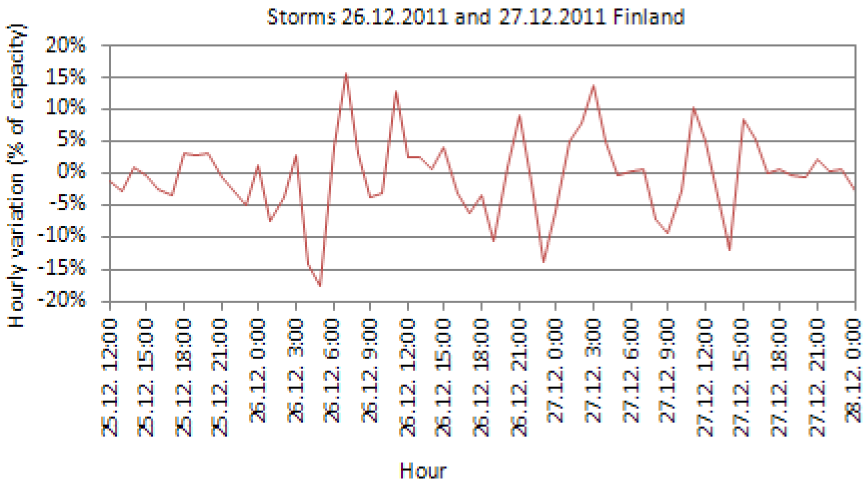

Figure 50. Hourly variation of wind power production in Finland during the storm 26–27th Dec.

The second case is the storm Berit in Norway. This storm hit the middle part of Norway hard, and there were ramps of about 30% of installed capacity in Norway Nov 25th down and Nov 26th up. Sweden data did not experience ramps and the storm in Finland and Denmark was on the following day (little Berit on 27th), so the impact on wind power production does not coincide Nordic wide.

The third case is the storm in Denmark 11.11.2010 (Figure 51). This storm did not have a large impact on the wind power production in Sweden or Finland (Figure 52). Largest 5 hour down ramp in Denmark was 34% of capacity (11.11. 21:00–12.11. 02:00), in Finland 17% of capacity (10.11. 11:00–16:00) and in Sweden 15% of capacity (12.11. 01:00–06:00).

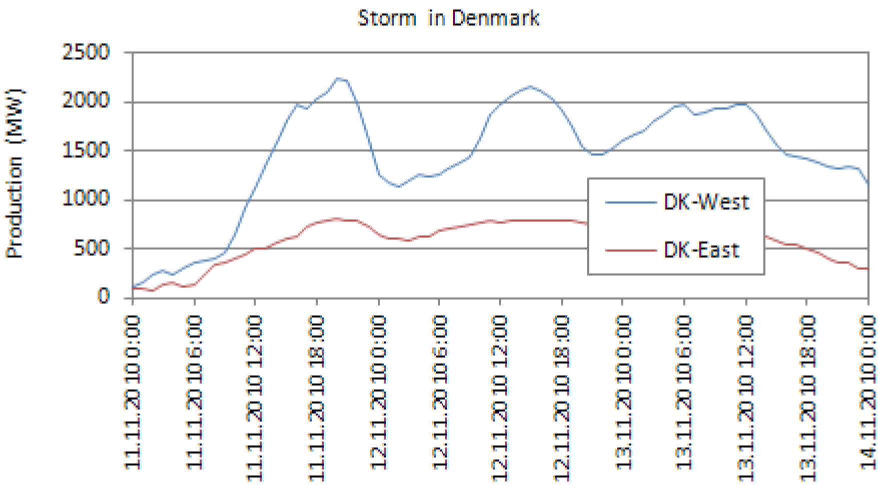

Figure 51. Wind power production in Denmark 11.11.–14.11.2010.

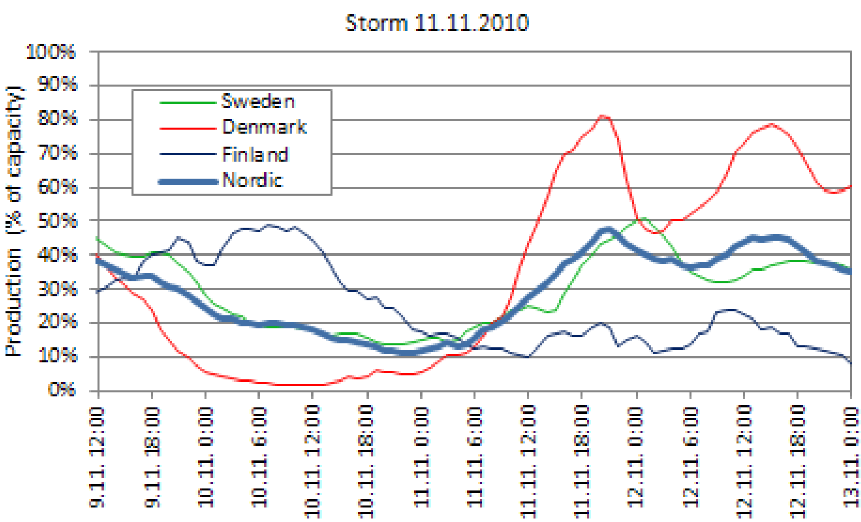

Figure 52. Wind power production in Finland, Sweden and Denmark 9.11.–13.11.2010.

Some cases from Denmark data was spotted February, 2011. 4th February, maximum 4 h down ramp in Denmark was 36% of capacity (4.2.2011 12:00–16:00). There was a ramp in Sweden occurring close to that (16% of capacity 15:00–19:00), but the highest ramp in Finland 17% did not occur in those hours (Figure 53). In Figure 54 we can see ramp down events on 7th February 18:00 – 24:00, but the strongest ramp down events during this case were due to winds calming down on 9th February (Fi 28%, Se 24% ja Dk 22%).

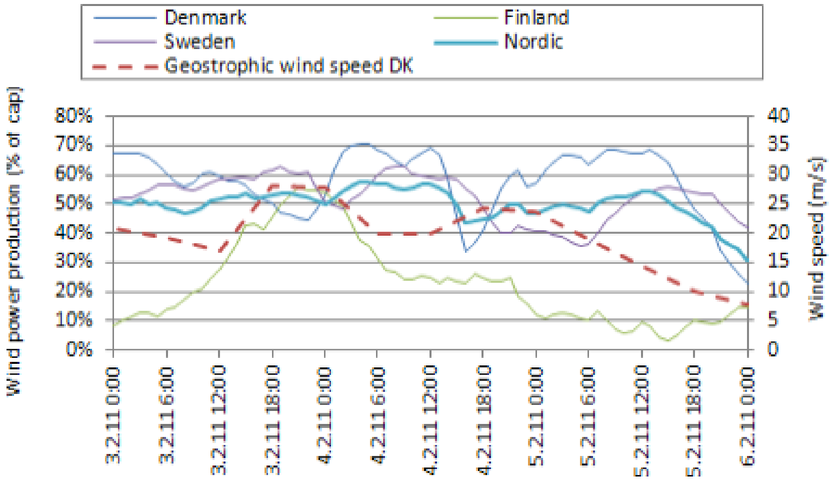

Figure 53. Wind power production in the Nordic countries during storm event 4th February.

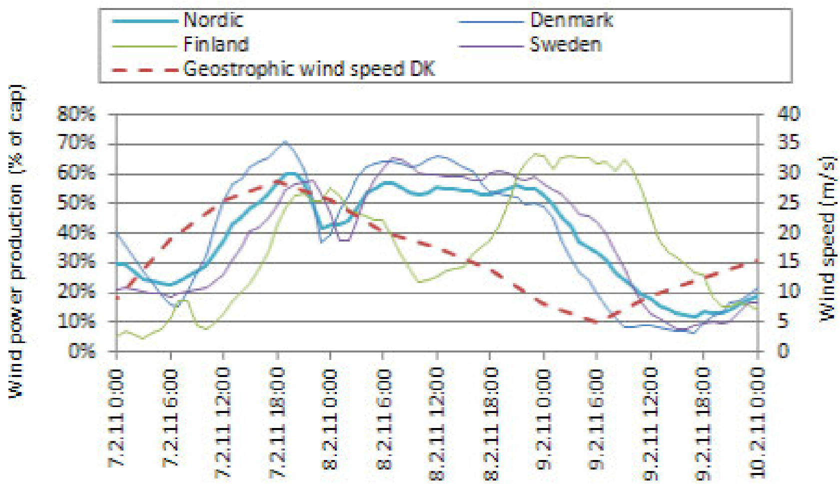

Figure 54. Maximum 4 h down ramp in Denmark was 34% of capacity (7.2.2011 19:00–23:00) and SE 20% (7.2. 22:00–8.2. 02:00).

The model wind data was analysed as to find larger area storms that would extend to all Denmark. The wind power production data was analysed from these dates, and maximum 1 and 4 hour ramps are presented in Table 12. All ramp rates for the countries are less than 37% in 4 hours and 18% for one hour, and the extreme ramp rates in individual countries did not coincide with other countries. The conclusion from these analyses are that during the 3 years 2009–2011 there were no extreme storms in the Nordic region that would have impacted the wind power production dramatically over all countries.

Table 12. Maximum down ramps during days when geostrophic winds have been high in larger areas covering all Denmark. The ramps in Finland and Sweden are also presented during the days.

Date	1h Denmark	4h Denmark	1h Finland	4h Finland	1h SE	4h SE
11.1.09	1%	1.6%	3.3%	2.1%	3.1%	3.3%
12.1.09	3.7%	12.8%	8.9%	11.4%	4.5%	10%
3.10.09	5%	9.4%	2.9%	0.3%	4.6%	6.9%
4.10.09	3.9%	13.2%	5.8%	8.1%	2.2%	6.5%
23.11.09	6.7%	23.9%	7.8%	19.1%	5.8%	13.5%
27.1.10	9.1%	16.9%	1.9%	0.3%	3.8%	4.2%
11.11.10	12.2%	15.1%	5.6%	8%	1.4%	0.5%
11.12.10	5.5%	18.6%	1.9%	3.6%	2.1%	3.4%
31.12.10	4.8%	12%	1.8%	4%	1.8%	5.1%
1.1.11	7.2%	14.2%	4%	8.5%	7.5%	13.7%
3.2.11	3.6%	10.2%	1.9%	0.5%	4.6%	6.5%
4.2.11	12.8%	35.8%	6.2%	17%	5.5%	15.6%
7.2.11	14.5%	34.3%	8.2%	7.5%	4.2%	2.4%
8.2.11	3.9%	28.4%	6.1%	20.7%	9.1%	20.5%
10.3.11	1.6%	1.5%	9.8%	22.5%	3.7%	11.5%
12.9.11	1%	0.7%	7.9%	9.2%	2.8%	6.5%
17.10.11	2%	4.7%	5.5%	9.4%	3.1%	10.9%
26.11.11	5.9%	6.2%	8.4%	28.5%	1.7%	5%
27.11.11	12%	34.5%	10.1%	26.3%	3.2%	5.6%
1.12.11	10.3%	26.6%	7.1%	13.1%	4.2%	12%
3.12.11	8.7%	19.6%	12.6%	29.6%	2.9%	5.3%
8.12.11	8.9%	14.5%	4.3%	7.9%	1.1%	0.6%
9.12.11	3.3%	9.8%	6.9%	13.3%	3.4%	11.2%
10.12.11	6.1%	8.9%	4.9%	12.8%	3.3%	10%
13.12.11	7%	19.4%	4.4%	4.9%	2.9%	2.9%
14.12.11	11.2%	29.1%	4.1%	11.2%	4.8%	15.3%
25.12.11	5.8%	15.6%	5.6%	8.3%	4.3%	8%
26.12.11	6.9%	24.2%	17.4%	32.1%	3.9%	12.2%
28.12.11	0%	-2.4%	9.8%	30.5%	4.4%	16.6%
29.12.11	11.4%	36.7%	5.8%	11.8%	3.6%	11%

4. Load variability

Power systems are designed to manage variable electricity consumption, the load. When wind power is added to a power system, it becomes relevant to study how much variability the power system experiences before the addition of extra variability imposed by wind power.

4.1 Load time series

Of the Nordic countries, Sweden and Norway have the largest consumption and Denmark the lowest. Hourly time series from year 2010 are shown in Figure 55 and the total Nordic consumption during the years 2009–2011 in Figure 56.

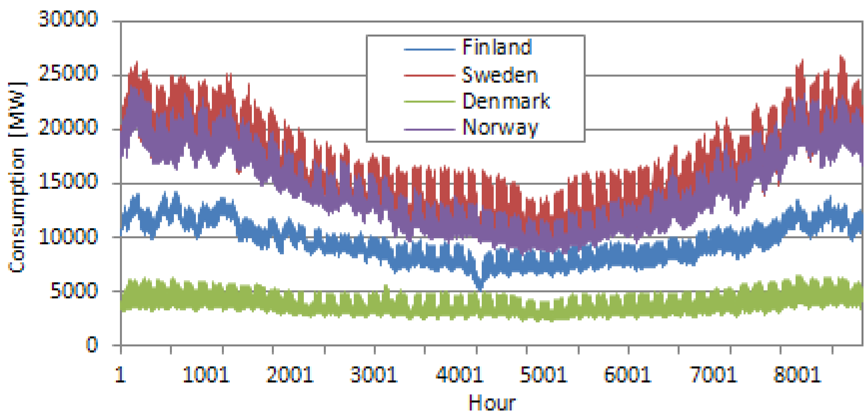

Figure 55. Hourly time series of electricity consumption in the Nordic countries in 2010.

In Sweden, Norway and Finland the load is clearly temperature dependent. Loads in wintertime are higher than in summer and due to electrical heating depend on how cold the weather is. In Norway for example, 2009 and especially 2010 were winters with abnormally long cold periods and this was very important to the loads for these winters. 2011 was a relatively mild winter in Norway.

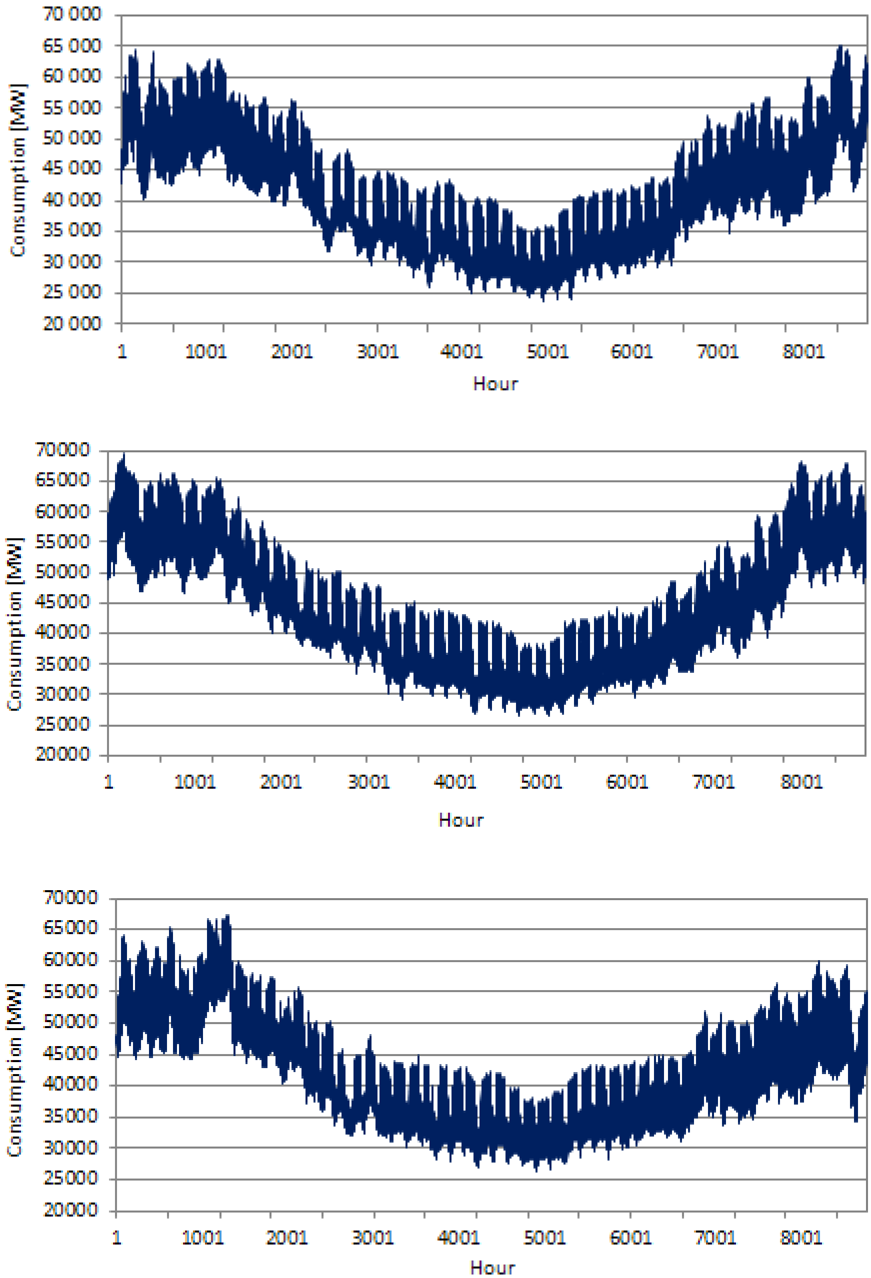

Figure 56. Example of differences in load time series from year to year – hourly time series of total electricity consumption in the Nordic countries in 2009–2011.

Table 13. Basic statistics of load time series (MW), year 2010.

	Denmark	Finland	Norway	Sweden	Nordic
Mean	4047	9718	14971	16729	45465
Standard deviation	901	1795	3812	3952	10173
Peak load	6498	14320	23994	26800	69675
Minimum load	2196	5009	8392	9222	26389
Range	4302	9311	15602	17578	43286

4.1.1 Diurnal patterns

Load has a clear diurnal and weekly pattern – low at nights and high at daytime, and lower during Saturdays and Sundays, as can be seen in Figure 57–Figure 61 for different seasons. The figures do not take into account the different load level during weekends.

In Denmark the seasonal dependence of load is lower and there is less energy intensive industry that would give a base load for all hours. This makes the daily variations in Denmark almost as high as for the other countries even if the total consumption is low.

Typical daily variation, from night time low to afternoon peak is about 2000 MW in Denmark and Finland, and 4000 MW in Sweden and Norway. In the Nordic region this variation is approximately 12 000 MW. This shows that the typical daily pattern is quite similar in the 4 countries and that the variation will not smooth out very much when increasing the area from a single country to the Nordic region.

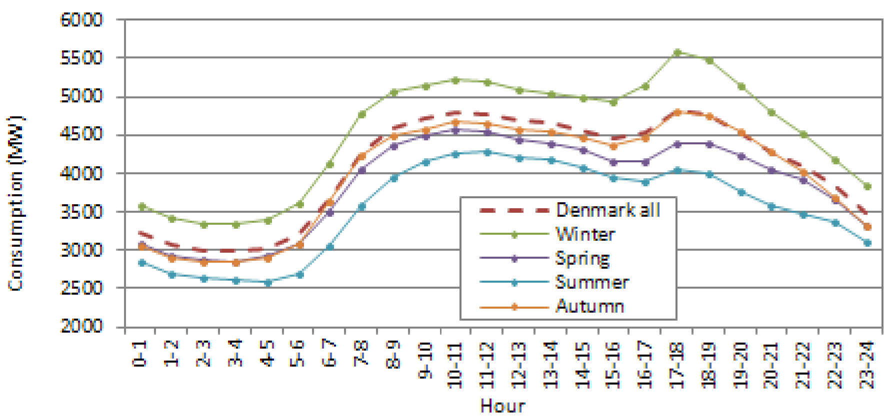

Figure 57. Diurnal pattern of consumption in Denmark 2009–2011.

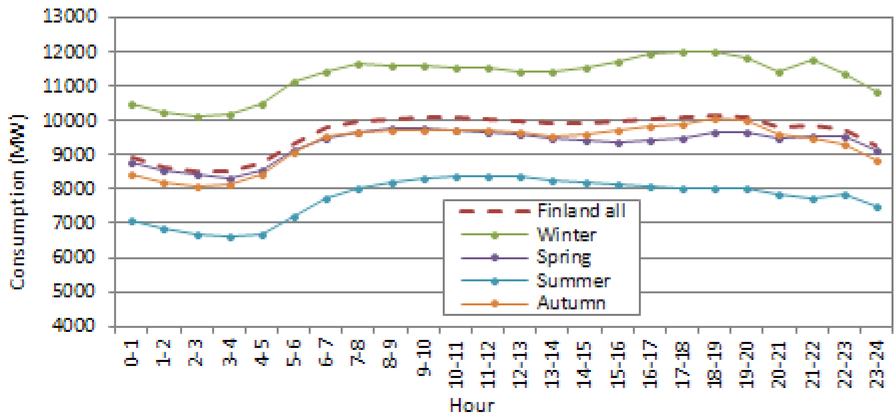

Figure 58. Diurnal pattern of consumption in Finland 2009–2011.

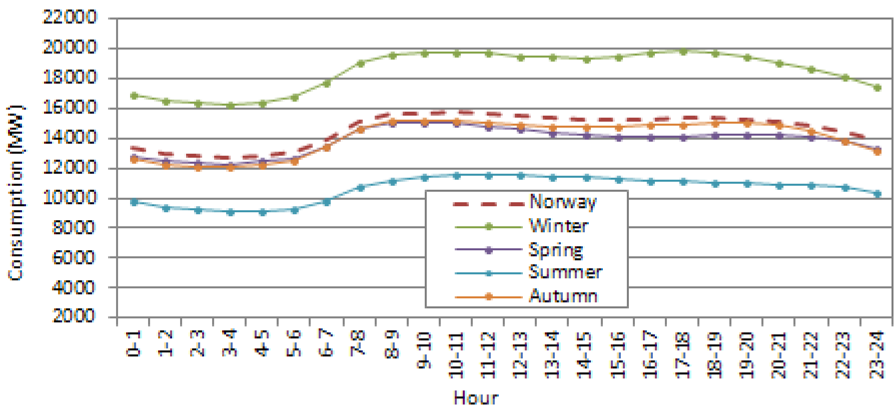

Figure 59. Diurnal pattern of consumption Norway 2009–2011.

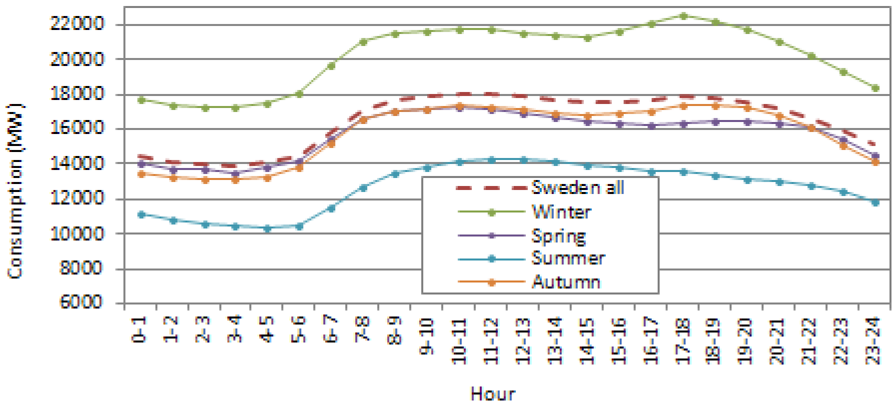

Figure 60. Diurnal patter of consumption Sweden 2009–2011.

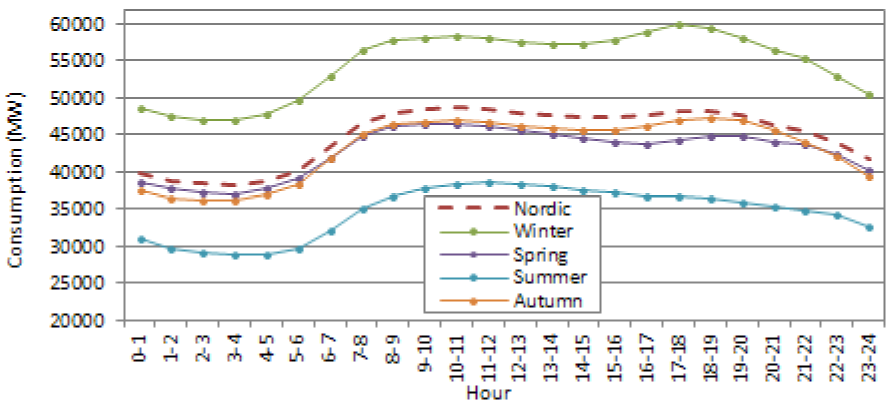

Figure 61. Diurnal patter of consumption the Nordic countries 2009–2011.

4.2 Hourly step changes in load

Power systems are designed to manage variable electricity consumption, the load. When wind power is added to a power system, it is relevant to study how much variability the power system experiences before the addition of extra variability imposed by wind power.

Hourly variability of load is presented in Figure 62 – Figure 67 and Table 14–Table 15. Common morning load rises result in hourly increases of 700–900 MW in Denmark, 600–1000 MW in Finland, 1200–2000 MW in Norway and 1500–2200 MW in Sweden (the higher numbers occur wintertime).

These graphs were also used to remove some outlying spikes in the data to make sure that the impacts of wind power would not be underestimated. From

Denmark and Sweden 2010 time series 5 hours were corrected and from Finland and Norway 2010 1 hour were corrected (in every time series 1 hour was missing because of daylight savings time change in autumn). Corrected time series can be seen in Figure 63 – Figure 67. Complete list of corrected values from years 2009–2011 are presented in Appendix B.

The variations in load are quite strongly correlated in the Nordic countries, especially between Sweden and Denmark (Table 16).

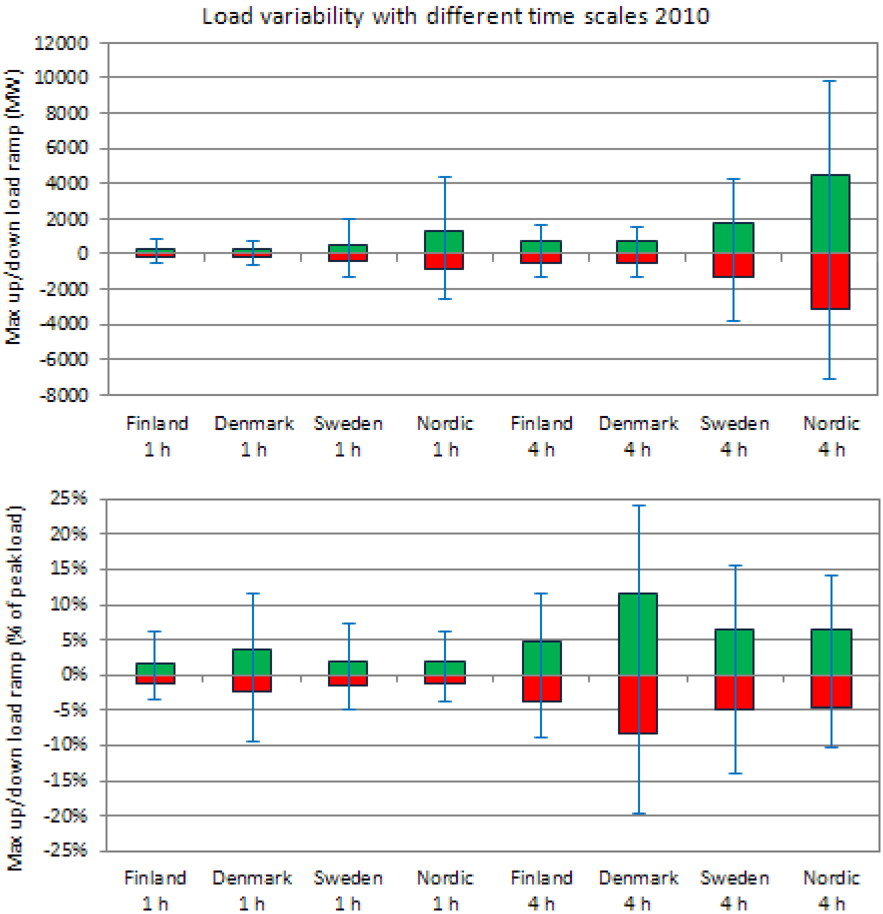

Figure 62. Average 1 hour and 4 hour load up-ramps (green bars) and down-ramps (red) during 2010. Range of variations is shown with blue error bars. Upper graph shows absolute MW values and lower graph relative to peak load.

Table 14. Hourly variations of load in 2010 (MW).

	Denmark	Finland	Norway	Sweden	Nordic
Positive mean	226.8	231.4	398	519	1322
Negative mean	-160	-176.3	-258	-376	-880
Standard deviation	253.4	276.3	454	613	1467
Max	973	1097	2304	2467	5667
Min	-777	-655	-1345	-1709	-3480

Table 15. Hourly variations of load in 2010 (% of peak load).

	Denmark	Finland	Norway	Sweden	Nordic
Positive mean	3.5%	1.6%	1.7%	1.9%	1.9%
Negative mean	-2.5%	-1.2%	-1.1%	-1.4%	-1.3%
Standard Deviation	3.9%	1.9%	1.9%	2.3%	2.1%
Max	11.7%	5.8%	5.7%	6.9%	6.3%
Min	15%	7.7%	9.6%	9.2%	8.1%

Table 16. Correlation of 1 h load variations.

	2009	2010	2011
Finland-Sweden	0.66	0.65	0.68
Finland-Denmark	0.60	0.59	0.63
Denmark-Sweden	0.91	0.90	0.89
Norway-Sweden	0.90	0.90	0.90
Norway-Denmark	0.87	0.87	0.86
Norway-Finland	0.60	0.58	0.62

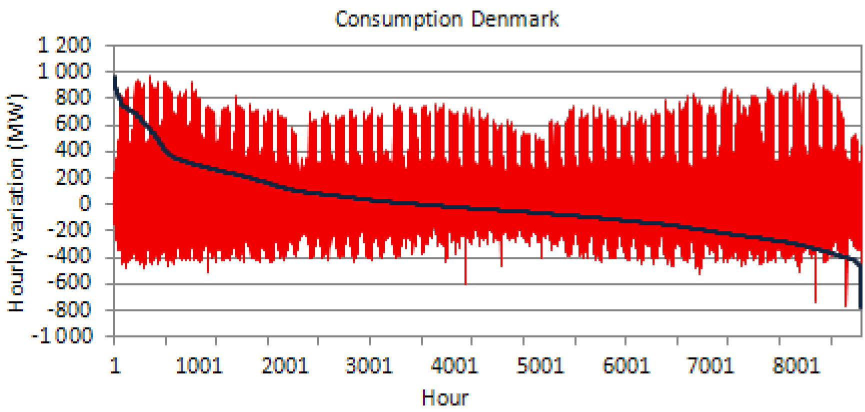

Figure 63. Hourly variations of consumption in Denmark 2010, chronological time series and duration curve.

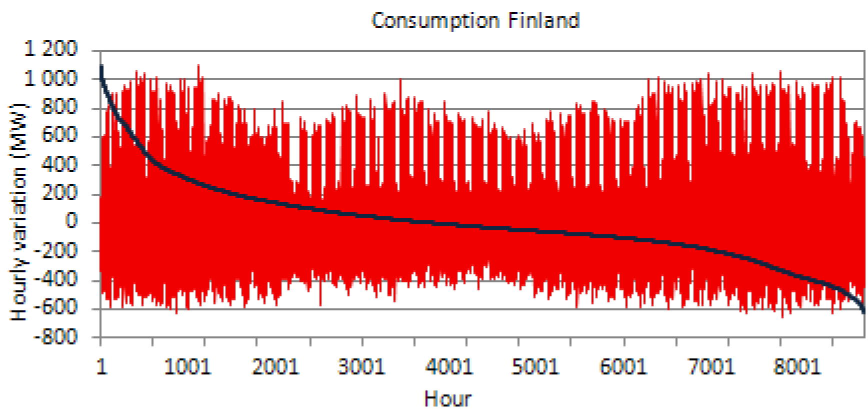

Figure 64. Hourly variations of consumption in Finland 2010.

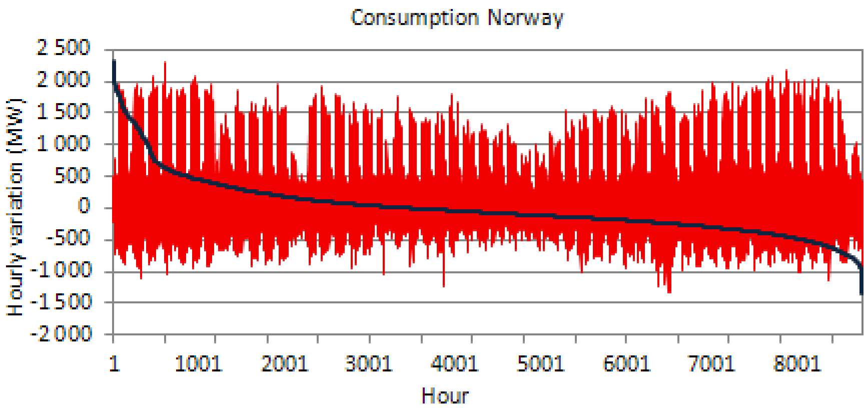

Figure 65. Hourly variations of consumption in Norway 2010.

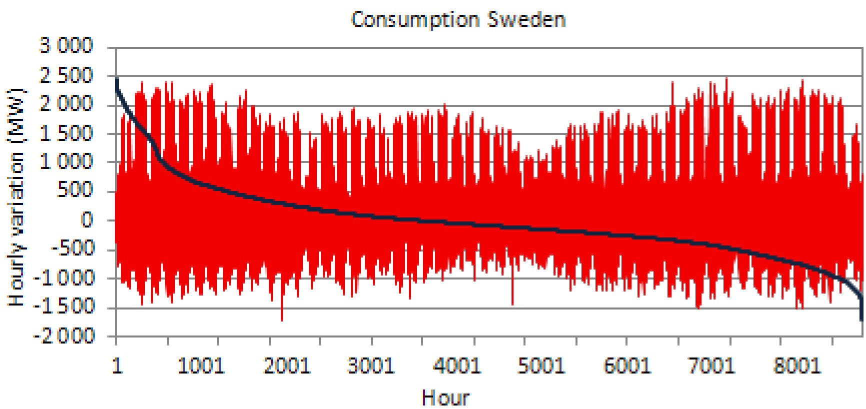

Figure 66. Hourly variations of consumption in Sweden 2010.

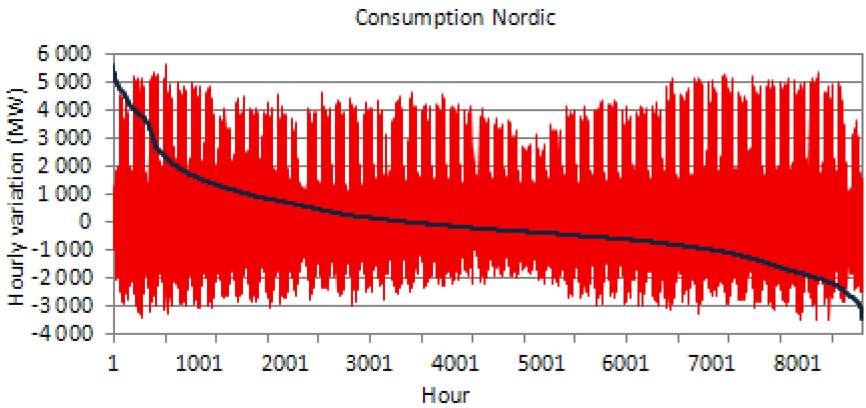

Figure 67. Hourly variations of consumption in the Nordic countries 2010.

The load can vary 2–3 times as much in 4 hours than in 1 hour. For Finland, this corresponds to 1400–2200 MW compared to 600–1000 MW, for Sweden 3400–5500 MW compared to 1100–2400 MW, for Denmark 1500–2200 MW compared to 500–900 MW, for Norway 2200–4700 MW compared to 900–2000 MW, and for the Nordic countries 8000–14000 MW compared to 2600–5100 MW (Figure 68 – Figure 72).

Both the hourly and four-hourly load changes can be predicted to a great extent from load forecasts which are more accurate than wind power predictions.

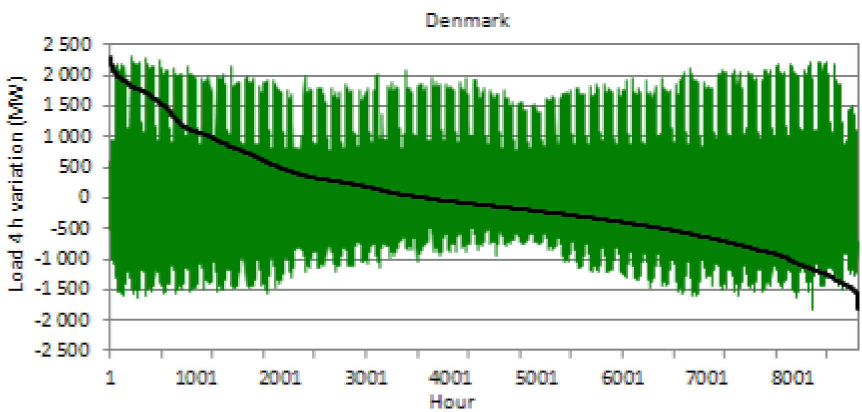

Figure 68. 4 h variations of load in Denmark 2010, time series and duration curve.

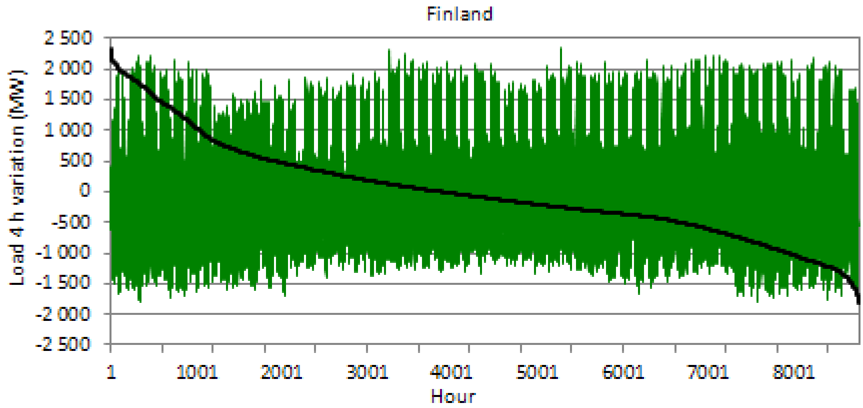

Figure 69. 4 h variations of load in Finland 2010.

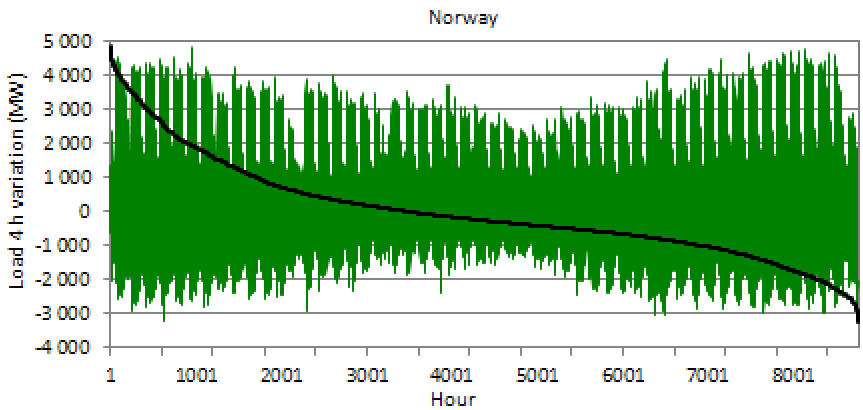

Figure 70. 4 h variations of load in Norway 2010.

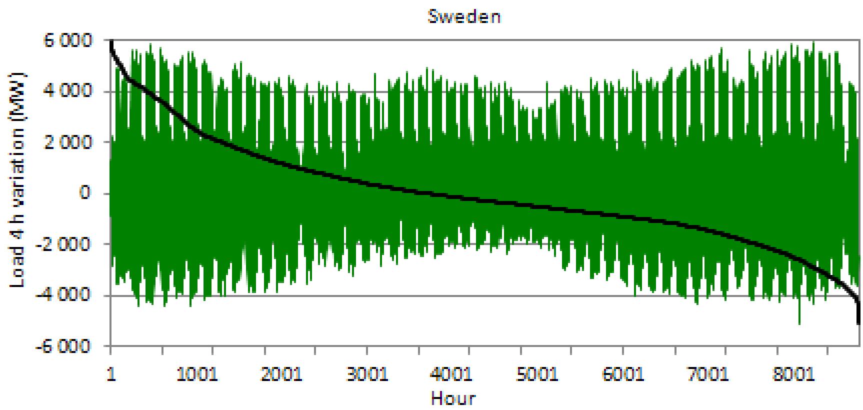

Figure 71. 4 h variations of load in Sweden 2010.

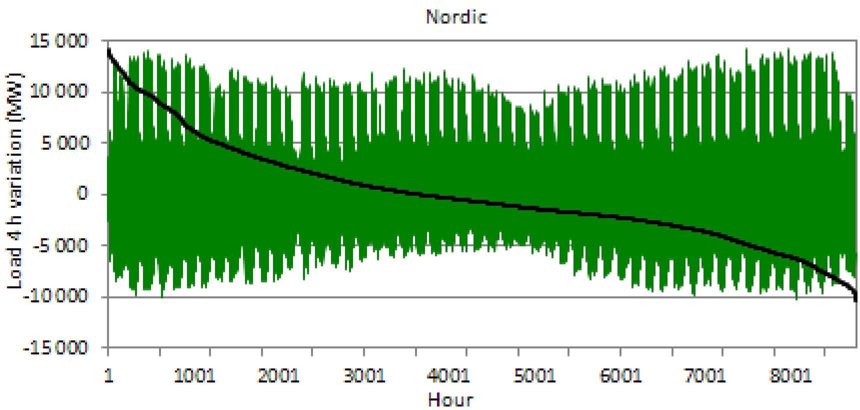

Figure 72. 4 h variation of load in the Nordic countries.

5. Combined variability of wind and load

The impact of wind power variability depends on the penetration level. In the following, the increase in production variability that the power system sees due to wind power, starting with load variability and adding wind power, is studied with increasing penetration levels in the Nordic countries during the three year time period. This increase has implications for the short term reserves in the power system.

The combined wind and load time series are also studied for two kinds of challenging events. First, high instant penetration levels of wind power are most difficult for wind integration, as has been reported by countries with experience in the area. Second, low wind power production during peak load situations has implications on capacity adequacy in power systems and will become more important in the future when increasing amounts of wind power and aging of conventional power plants will reduce the conventional capacity in power systems.

5.1 Scenarios with increasing penetration levels

The consumption, wind power production and wind power penetration levels in the Nordic countries during 2011 can be seen in Table 17. In Denmark 22.6% of the consumption was produced with wind, 4.4% in Sweden, 0.9% in Norway and 0.6% in Finland. The Nordic wide wind penetration level was 4.1%

Table 17. Consumption, wind power production and penetration levels in the Nordic countries in 2011, showing also how much the penetration level would be if the wind power production in Sweden, Finland and Norway was up-scaled according to the analyses in previous sections (Sweden 100% of Denmark, Finland and Norway both 50% of Denmark).

	DK	**FI**	**SE**	**Nordic**	**Nordic, scaled**
Wind	7.91 TWh	0.47 TWh	6.19 TWh	14.58 TWh	23.74 TWh
Consumption	34,9 TWh	81,9 TWh	139,2 TWh	379 TWh	379 TWh
Penetration	22.6%	0.6%	4.4%	4.1%	6.3%

The variability and maximum instantaneous wind power penetration are studied using penetration levels of up to 50% for Denmark and up to 30% for the other countries. Denmark has a target to cover 50% of its electricity demand with wind power – this means roughly doubling the current wind power production.

We use the same up-scaling method for the Nordic data set as was used when analysing wind variability (Section 3): Finland and Norway are up-scaled to 50% of Denmark wind power production and Sweden to 100% of Denmark. In Norway the wind power production could be larger compared to Sweden and Finland, however as the data is from a limited amount of wind farms, it was decided to limit the Norway total so that the variability would not be too much over exaggerated. For example, with Nordic 10% wind penetration the country-specific penetration levels become: Finland 7.8%, Sweden 9.1% and Denmark 37.4% and Norway 5.1%.

5.2 Increase in variability from load to net load

If wind power production and load were positively correlated, they would tend to increase and decrease at the same time, and adding wind would help the load following task of the power system. On the other hand, if the correlation were negative, wind would tend to decrease when load increases (and vice versa) and this would require more from the load following units in the system. The correlation of hourly load and wind power production in the Nordic countries is very weak (Table 18). Therefore the variations will sometimes occur in the same directions and help the system, and other times in opposite directions making load following more difficult. Even more important from the viewpoint of wind integration, is that the correlation between hourly ramps of load and wind production is essentially 0 in the Nordic countries (Table 18). Therefore it is not probable that the largest variations would occur simultaneously for both of them.

Table 18. Correlation of load and wind time series and load and wind 1 h variation time series.

	Wind – load		
	2009	**2010**	**2011**
Finland	0.11	0.04	0.07
Denmark	0.11	0.12	0.24
Sweden	0.01	0.11	0.17
Nordic	0.10	0.17	0.26
	Wind – load hourly variations		
Finland	-0.01	-0.02	-0.05
Denmark	0.08	0.06	0.08
Sweden	-0.03	-0.07	-0.06
Nordic	0.01	-0.03	-0.02

Hourly variability before and after adding wind power can be seen visually from Figure 73–Figure 76 showing time series of variations together with duration curves. As adding small amounts of wind power will not be seen in the graphs, Finland and Sweden have been plotted with a 20% wind penetration level.

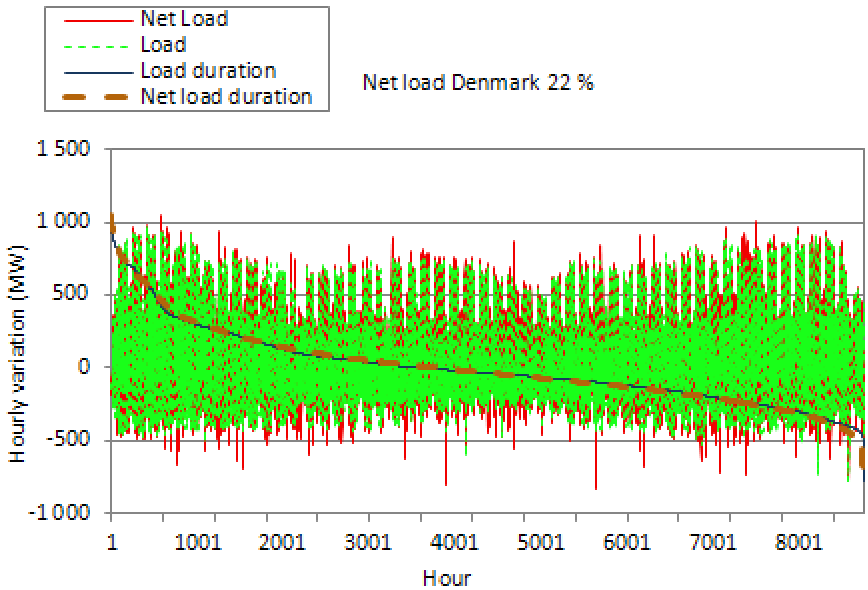

Figure 73. Net load and load in Denmark, measured data from year 2010.

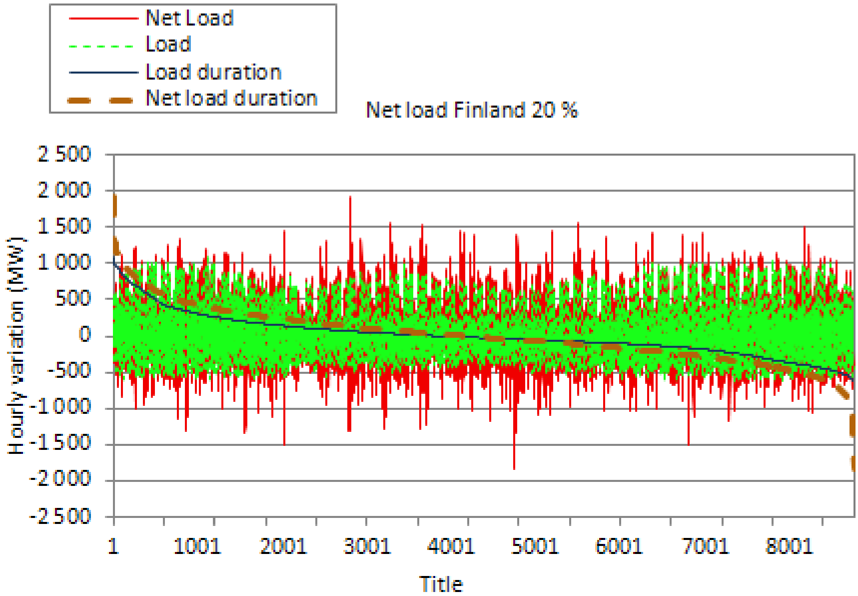

Figure 74. Load and net load in Finland, year 2010 wind data up-scaled to 20% penetration level.

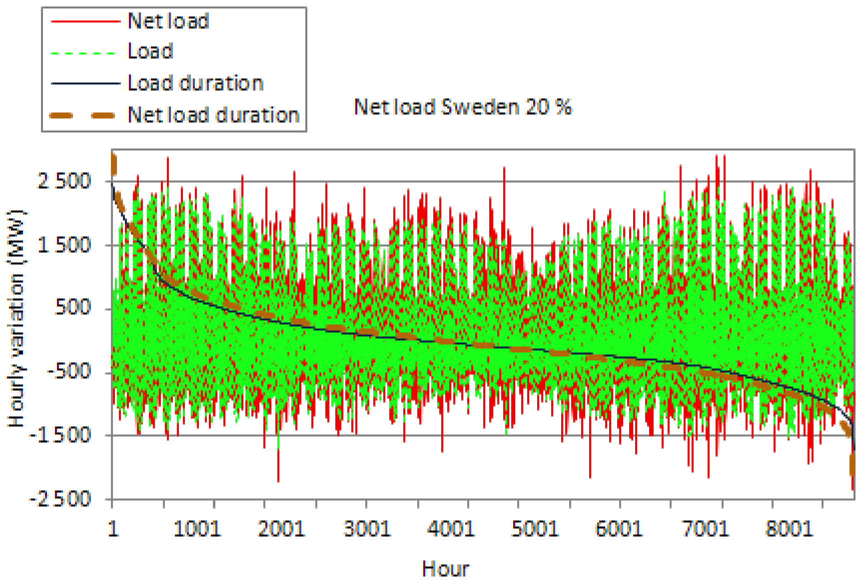

Figure 75. Load and net load in Sweden, year 2010 wind data up-scaled to 20% penetration level.

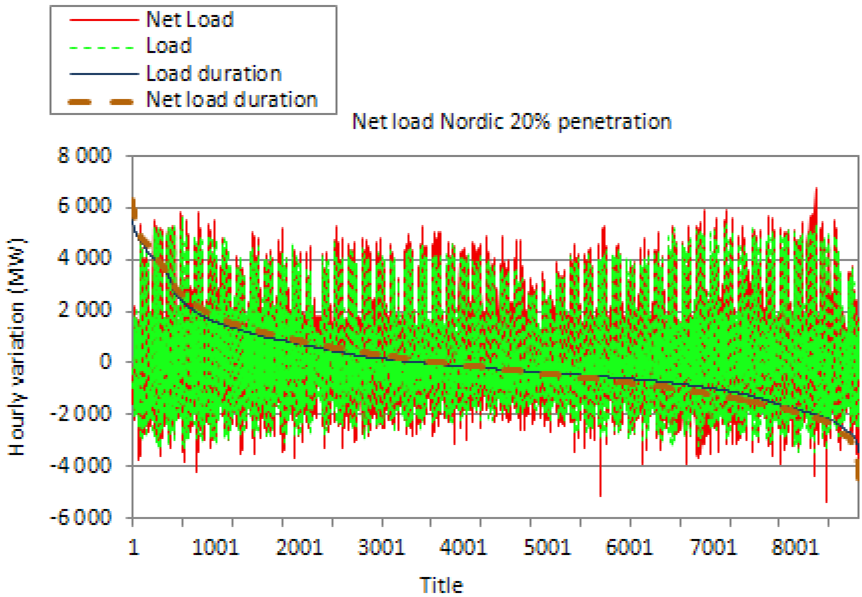

Figure 76. Load and net load in Nordic countries, year 2010 wind data up-scaled to 20% penetration level.

5.3 Implications to reserve power

How much will wind increase the variability imposed to the power system? This will directly influence the amount of short term, operating reserves and balancing power that is needed, from the regulating power market.

The impact of wind power variability to the power system depends on the penetration level. The increase in variability that the system sees due to wind power was studied with various penetration levels by comparing the variability of load and net load (net load is load-wind, i.e. the amount that needs to be produced by other means than wind). This increase in extreme variability during a year will influence the amount of operating reserves or balancing power from the regulating power market that is needed to cover extreme cases. It is also worth noting that in addition to sub-hourly variations, production forecast errors left uncorrected before the delivery will need to be handled via the regulating power market.

Wind penetration of 20% from yearly consumption means 17.0 TWh & 8920 MW of wind for Finland; 29.3 TWh & 14590 MW wind in Sweden and 79.7 TWh & 39700 MW wind in Nordic countries (for Denmark the amount of wind in 2010, 3800 MW has been used).

For load, the up-ramps are more pronounced than down-ramps. As we are working with measured data, some data points might be erroneous. This is why the absolute maximum values may be misleading, and it is more reasonable to focus on the distribution of hourly variations. The highest variations that occur only a few times per year can be seen at the tails of the distribution (Figure 77 – Figure 79).

The impact of wind power is studied by taking a statistical measure for confidence level, like standard deviation or data point that covers x% of the data (exceedance level). Looking at the tails of the distributions, where the magnitude of the highest variations that occur only a few times per year can be seen, a confidence level before and after wind power is added shows the impact of wind power variability (Holttinen et al. 2012).

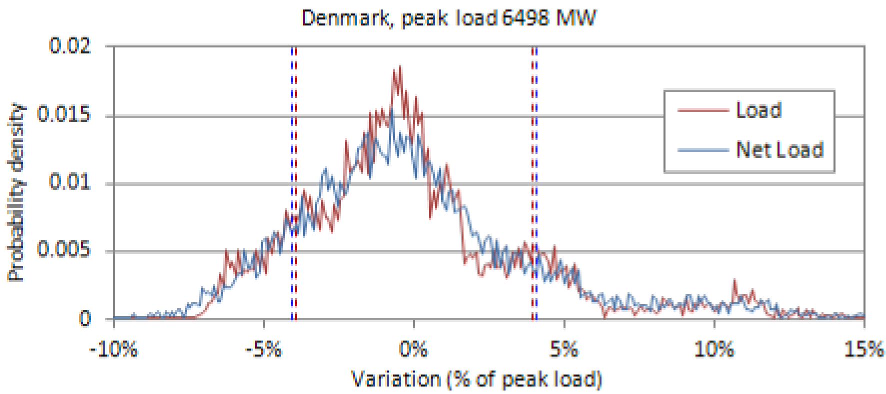

Figure 77. Variability of load and net load (load – wind), measured relative to peak load, in Denmark during 2010. The probability distributions show how often variations of different magnitudes occur. The standard deviation of the variations is shown with vertical lines. The distributions of both load and net load are asymmetrical with more pronounced up-ramps than down-ramps.

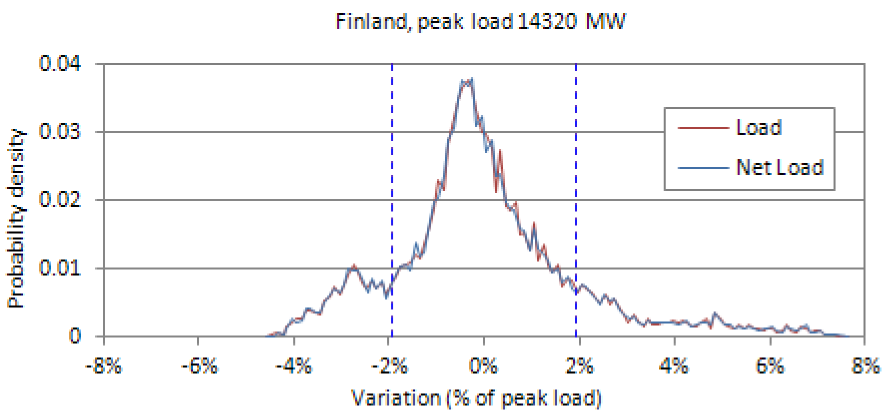

Figure 78. Variability of load and net load in Finland, year 2010.

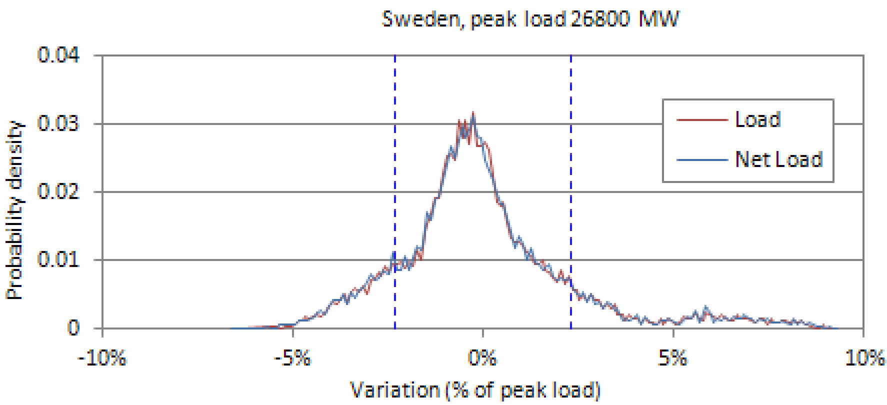

Figure 79. Variability of load and net load in Sweden, year 2010.

In Figure 80 and Table 19 the different statistical parameters are compared for load data. For the load time series, using 3 times standard deviation (3 sigma or 3σ) as the confidence level covers the down-ramps more than adequately but will be 200 MW short of the maximum up-variation in Finland and Denmark, 600 MW in Sweden and even 1200 MW in the Nordic region. Exceedance levels lead to generally higher confidence levels for the up-ramps than sigma. The 99% exceedance level covers approximately 80% of the maximum variation, and the 99.9% exceedance level approximately 90%.

For wind power production (Figure 81), both 3sigma and 99% exceedance level lead to substantially smaller values than the realized maximum variations. This shows that extreme variability can be larger than statistically estimated. It also shows that the extreme variability is very rare, as even looking at maximum variability during 99% of time stays well inside ±10% of installed capacity even in a smaller country.

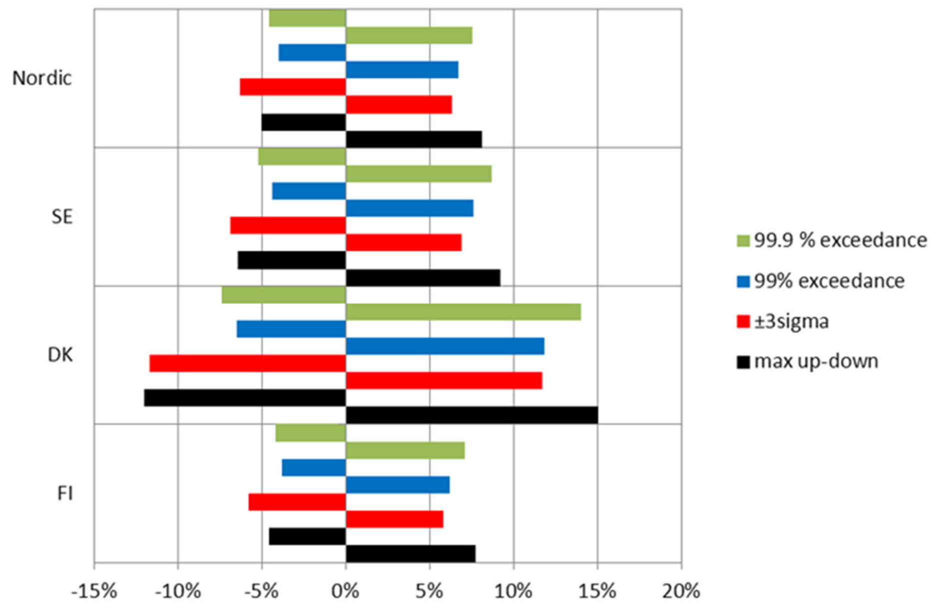

Figure 80. Load data: comparison of how statistical parameters cover the maximum variability measured in the time series.

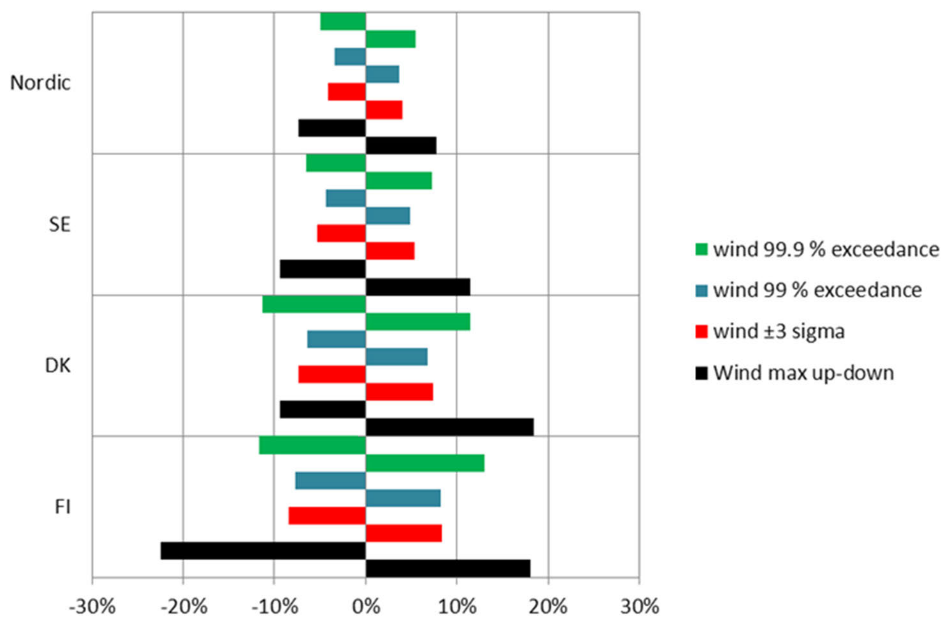

Figure 81. Wind power production data: comparison of how statistical parameters cover the maximum variability measured in the time series.

Table 19. Different statistical measures for year 2010. Load in MW and % of peak load, wind in MW and % of capacity. For Nordic time series Finland and Norway have been scaled to 50% and Sweden to 100% of the production in Denmark.

MW	Finland	Denmark	Sweden	Nordic
Load: max up-down variability	1097 -655	973 -777	2467 -1709	5667 -3480
Load 1h variation: ±3sigma	±829	±760	±1840	±4401
Load: 99% exceedence	891 -541	769 -420	2050 -1176	4702 -2758
Load: 99.9% exceedence	1015 -603	912 -480	2330 -1407	5215 3208
Wind 1h variability				
max up-down	365.2 -432	663.4 -507.3	492.6 -338.3	887.2 -809.6
±3sigma	169	269.3	207.4	480.9
99% exceedence	163.1 -153	255.3 -236.5	193.2 -165.7	426.4 -394.2
99.9% exceedence	265.7 -224.3	422.9 -415.9	296.4 -252.2	654.4 -581.5

% of peak load	Finland	Denmark	Sweden	Nordic
Load 1h variability				
max up-down	7.7% -4.6%	15% -12%	9.2% -6.4%	8.1% -5%
±3sigma	5.8%	11.7%	6.9%	6.3%
99% exceedance	6.2% -3.8%	11.8% -6.5%	7.6% -4.4%	6.7% -4%
99.9% exceedance	7.1% -4.2%	14% -7.4%	8.7% -5.2%	7.5% -4.6%
Wind 1h variability (% of capacity)				
max up-down	18.2% -22.7%	18.4% -9.4%	11.5% -9.4%	7.8% -7.3%
±3sigma	8.4%	7.4%	5.3%	4.1%
99% exceedance	8.3% -7.7%	6.8% -6.4%	4.9% -4.3%	3.7% -3.4%
99.9% exceedance	13.1% -11.7%	11.5% -11.3%	7.3% -6.5%	5.5% -4.9%

The amount that wind variability increases the overall variability during one hour for the whole Nordic area, is by 1–2% (relative to installed wind capacity) for 10% penetration, 2–3% for 20% penetration and 3–4% for 30% penetration. The results for Sweden and Denmark are somewhat less for up-regulation but more need for down-regulation. The results for Finland are much higher than for other countries, starting from 3–4% more up-regulation and -5 – -6% more down-regulation for 10% penetration level and 6–7% more up-regulation and 9–11% more down-regulation for 30% penetration level (relative to installed wind capacity). The lower amount of data can explain these results partly; however, as the relative load variations are low in Finland, wind variability will show more when combining wind and load variations. The results of increases in variability in net load, compared to load, for year 2010 are shown in Table 20 for all statistical measures and in Table 21 for 99.9% exceedance level, both as MW numbers and as relative to installed wind capacity.

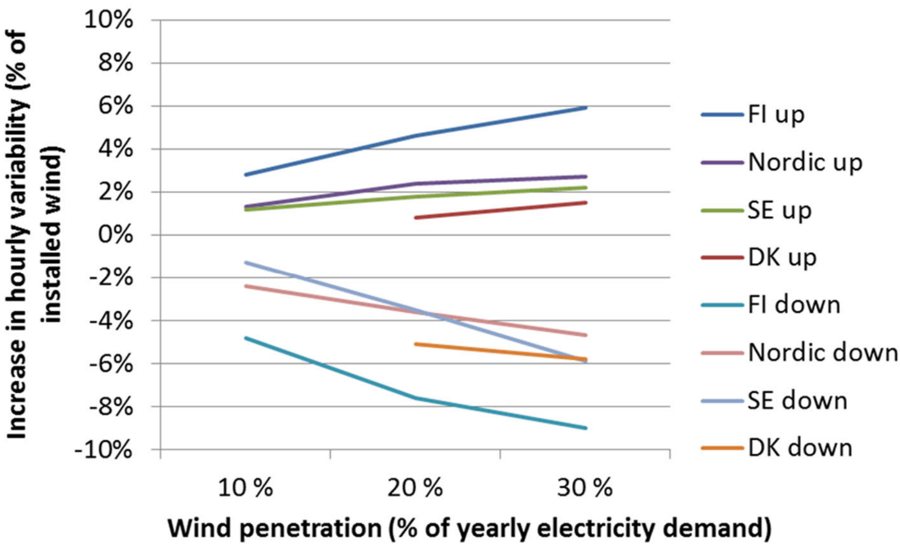

Figure 82. Increase in extreme variability for the power system due to hourly wind power variability at different penetration levels of wind.

Table 20. 1 hour time step: increase in the magnitude of large ramps, from load to net load (20% wind penetration, data from 2010).

	Finland	Denmark	Sweden	Nordic, scaled to 23.4 TWh
Increase in maximum up-down variability	831 MW -1195 MW	75 MW -48 MW	449 MW -641 MW	1117 MW -1884 MW
Increase in 99% exceedence	157 MW -296 MW	16 MW -61 MW	95 MW -200 MW	178 MW -214 MW
Increase in 99.9% exceedence	410 MW -681 MW	28 MW -184 MW	265 MW -512 MW	484 MW -729 MW

Table 21. Magnitudes of wind and net load variations in 2010 (MW) using a 99.9% exeedence level and increasing wind penetration levels (as yearly electricity demand).

MW	Wind	FI	DK	SE	Nordic
Load 99.9% exceedence	-	1015 -603	912 -480	2330 -1407	5215 -3208
Net load, increase to load	10%	125 -216	-	90 -98	133 -246
Net load, increase to load	20% (22% DK)	410 -681	28 -185	265 -512	484 -729
Net load, increase to load	30%	791 -1206	76 -288	486 -923	811 -1435
% of capacity	**Wind**	**FI**	**DK**	**SE**	**Nordic**
Net load, increase to load	10%	2.8% -4.8%	-	1.2% -1.3%	1.3% -2.4%
Net load, increase to load	20% (22% DK)	4.6% -7.6%	0.8% -5.1%	1.8% -3.5%	2.4% -3.6%
Net load, increase to load	30%	5.9% -9.0%	1.5% -5.8%	2.2% -5.9%	2.7% -4.7%

5.4 Timing of largest ramps

The timing of the load and wind ramps is further illustrated in Figure 83–Figure 90. Ramps are from hourly data, so they are the difference in average power between two consecutive hours. For all Nordic countries, largest load ramps upward occur from 6 to 9 am and largest downward around midnight. The timing of ramps in Finland in CET is not exactly the same as for the other countries due to a one hour time difference. In Denmark there is also a considerable up-ramp from 17 to 18.

For wind power, upward and downward ramps occur more randomly and cancel out each other bringing the average wind production ramps close to zero.

However, maximum ramps in both directions can still be large and occasionally happen in the opposite direction compared to load ramps. For this reason the maximum and minimum of all ramps, from 3 years of data, was included in the graphs.

In Denmark the maximum wind ramp downward during the 3 year period was -15% of wind capacity, at 6 to 7 in the morning. The maximum up-ramp of wind power occurred at 10 to 11, during the morning up-ramp of load, but the second largest up-ramp at 00–01, which is one of the down-ramping load hours. In Finland the maximum ramps during 2009–2011 (20–22% of capacity) occurred during the daytime when load ramping is not that severe. However, the maximum down ramps during the morning load rise and up-ramps during the midnight hours were larger than 15%. In Sweden, largest up ramps (10–12%) mostly occurred during the day. However, maximum up-ramp of wind power occurred in the evening hours (19–20) during load down-ramp. Largest wind down-ramps (10–11%) mostly occurred during load down-ramp hours except from a 10% maximum down-ramp at 8 to 9 in the morning.

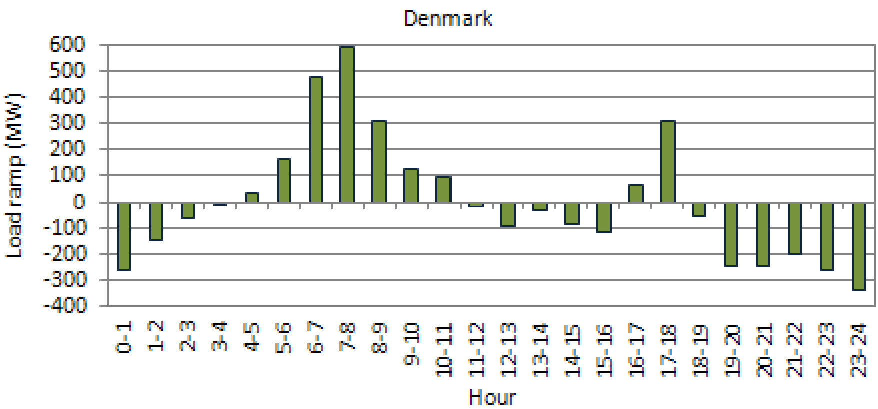

Figure 83. Average load ramps in Denmark, years 2009–2011.

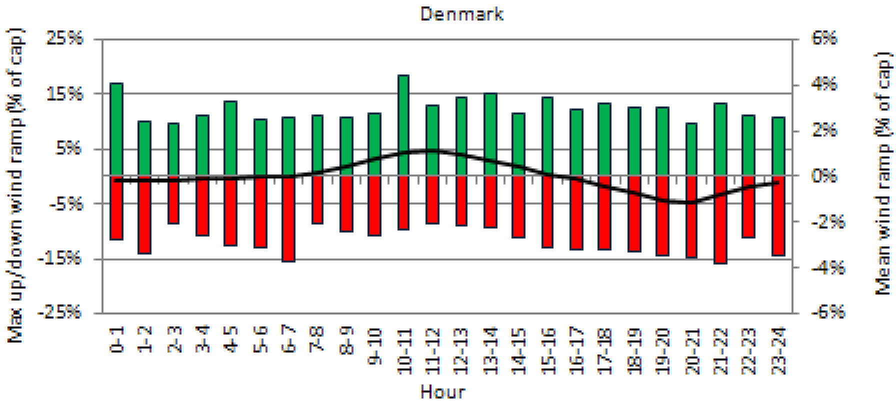

Figure 84. Maximum, minimum and average wind ramps in Denmark.

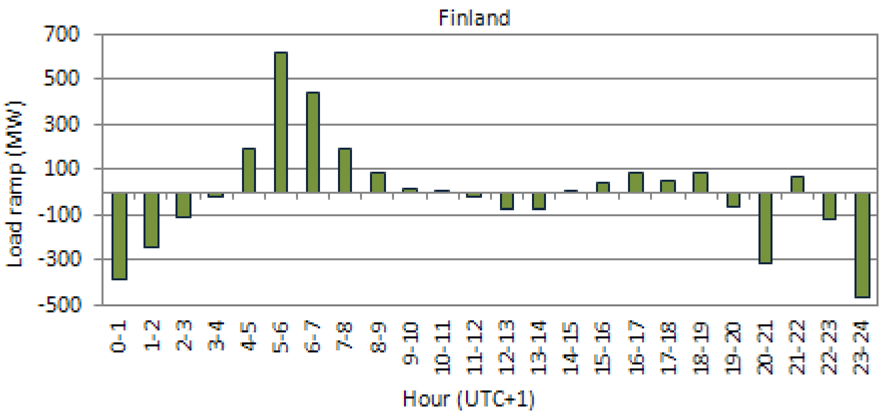

Figure 85. Average load ramps in Finland, years 2009–2011.

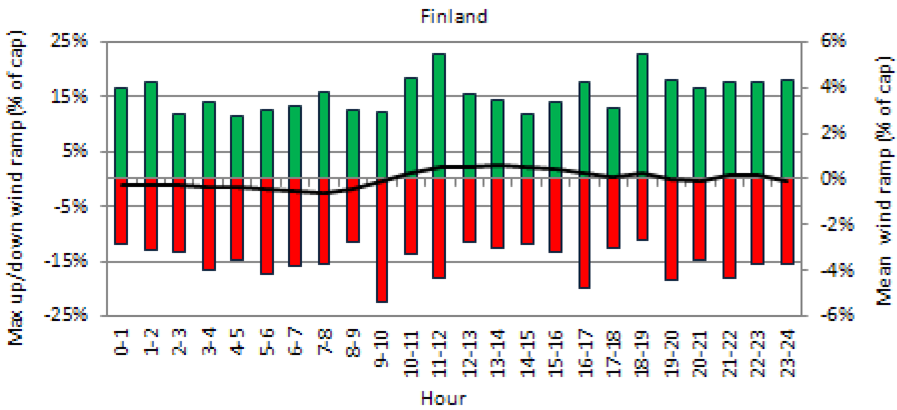

Figure 86. Maximum, minimum and average wind ramps in Finland, years 2009–2011.

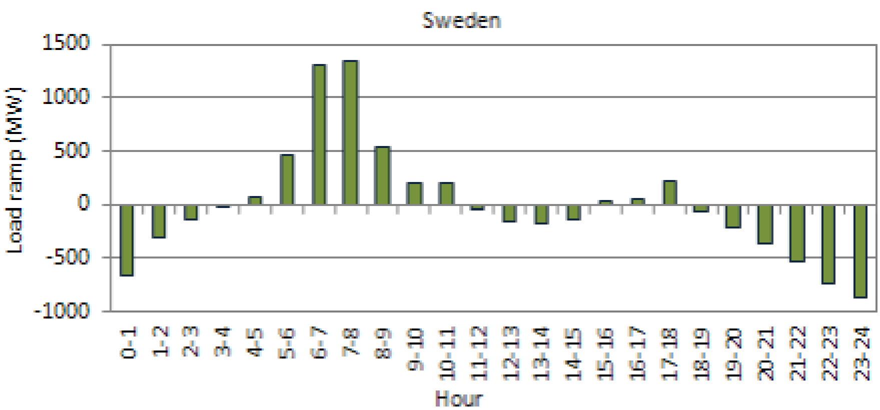

Figure 87. Average load ramps in Sweden, years 2009–2011.

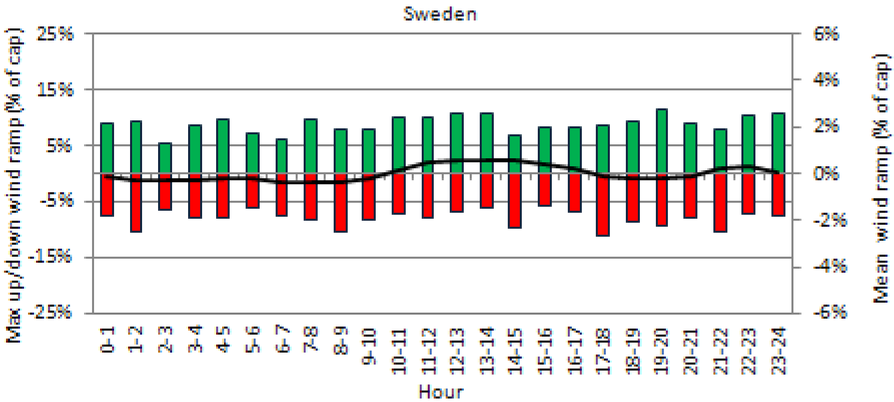

Figure 88. Maximum, minimum and average wind ramps in Sweden, years 2009–2011.

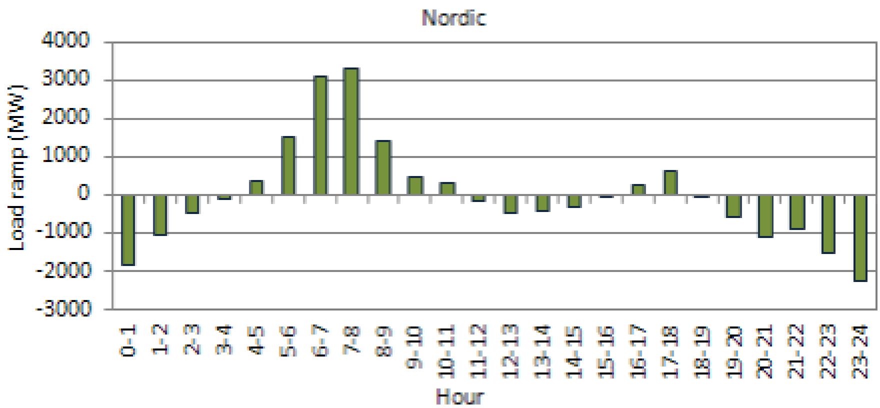

Figure 89. Average load ramps in Nordic countries, years 2009–2011.

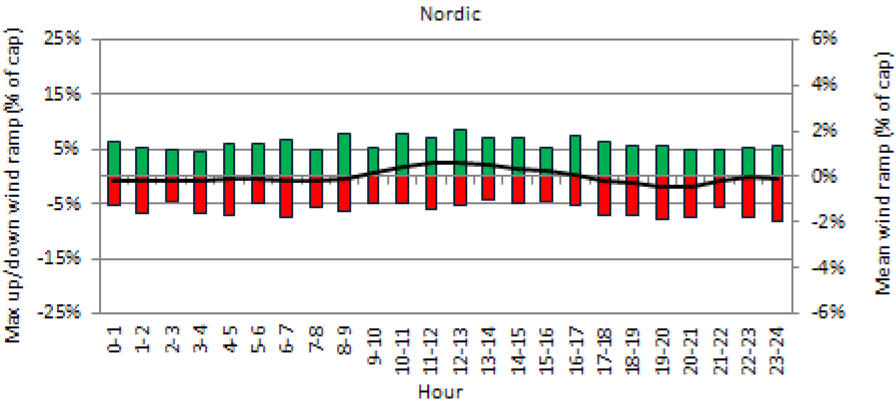

Figure 90. Maximum, minimum and average wind ramp in Nordic countries.

It is important to notice that the regular pattern of load following will change dramatically when the share of wind power becomes large. The magnitudes of existing ramps will increase and new ramps will appear also outside morning and evening hours. Again, this impact is not as strong in the Nordic level as for one country. Figures Figure 91–Figure 94 show the maximum up-ramps that the system sees, without wind (from load only) and with increasing penetration levels of wind power. The maximum ramp for each hour of the day and month of the year is shown in these “magic carpet” plots (Holttinen et al. 2011).

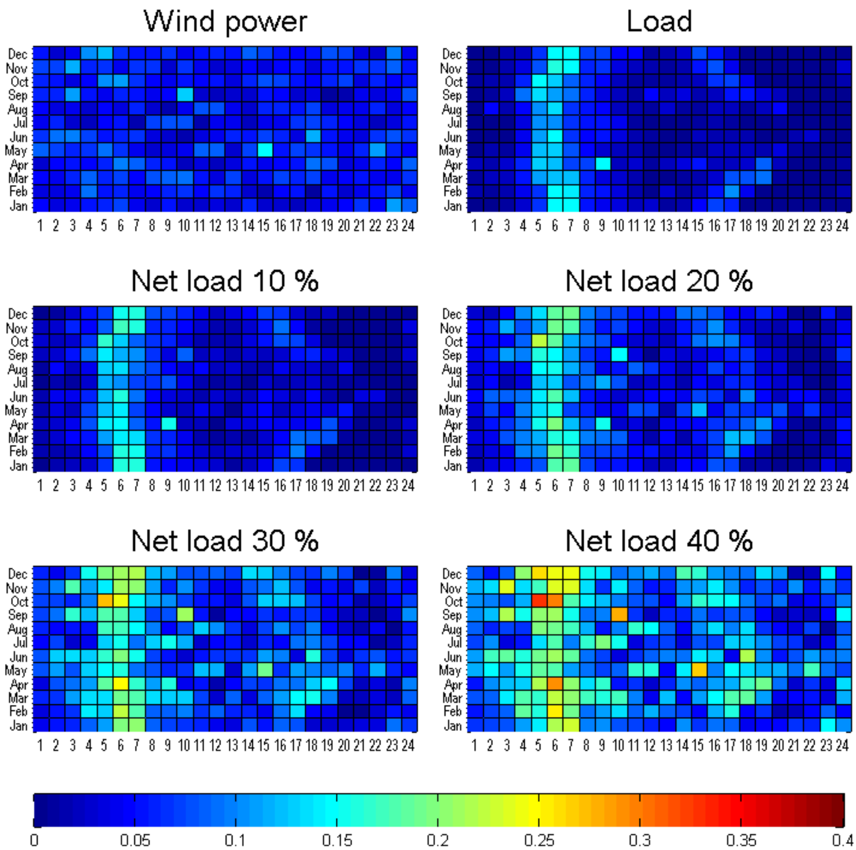

Figure 91. Timing of largest up-ramps in Finland, year 2011. Magnitudes of the ramps, relative to the average load, are depicted in colours (highest ramps in red). 24 hours of the day are on the x-axis and 12 months of the year on the y-axis in each of the 6 plots. Upper plots: Wind power production (left), Load (right). Middle plots: Net load with 10% wind penetration (left), Net load with 20% wind penetration (right). Bottom plots: Net load with 30% wind penetration (left), Net load with 40% wind penetration (right).

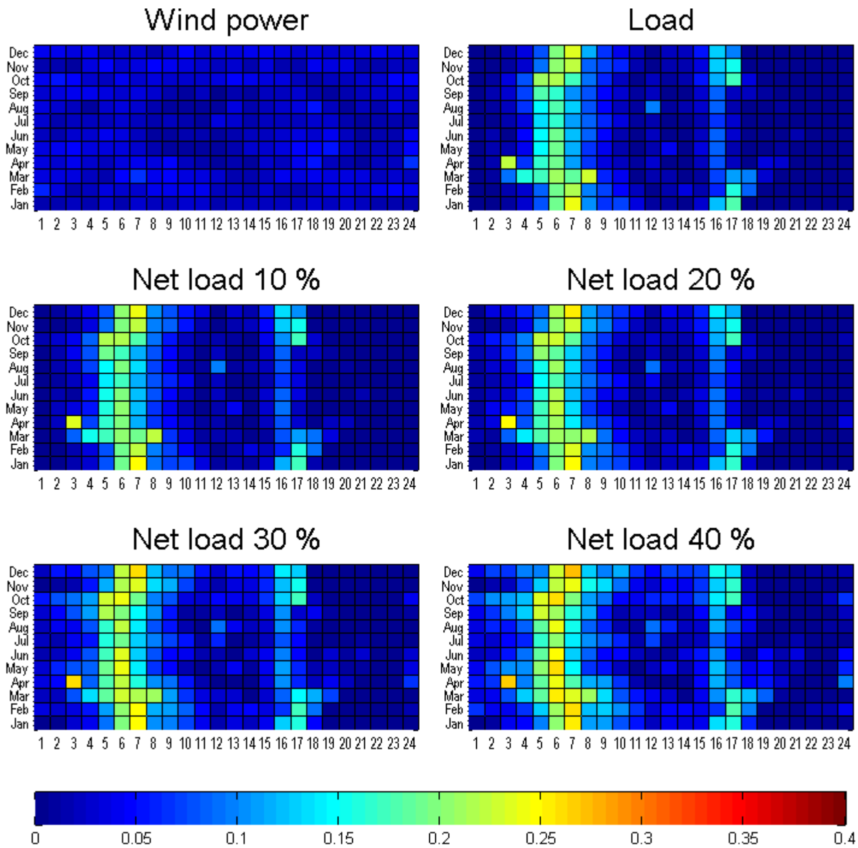

Figure 92. Timing of largest up-ramps in Sweden, year 2011. Scale is as % of average load. 24 hours of the day are on the x-axis and 12 months of the year on the y-axis in each of the 6 plots.

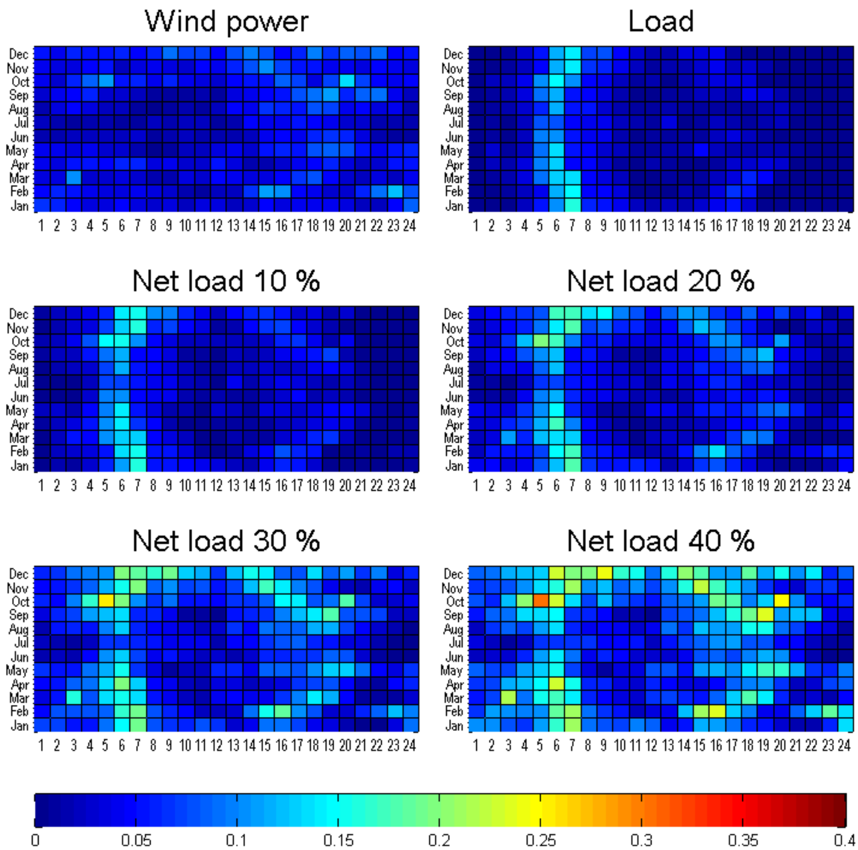

Figure 93. Timing of largest up-ramps in Denmark, year 2011. Scale is as % of average load. 24 hours of the day are on the x-axis and 12 months of the year on the y-axis in each of the 6 plots.

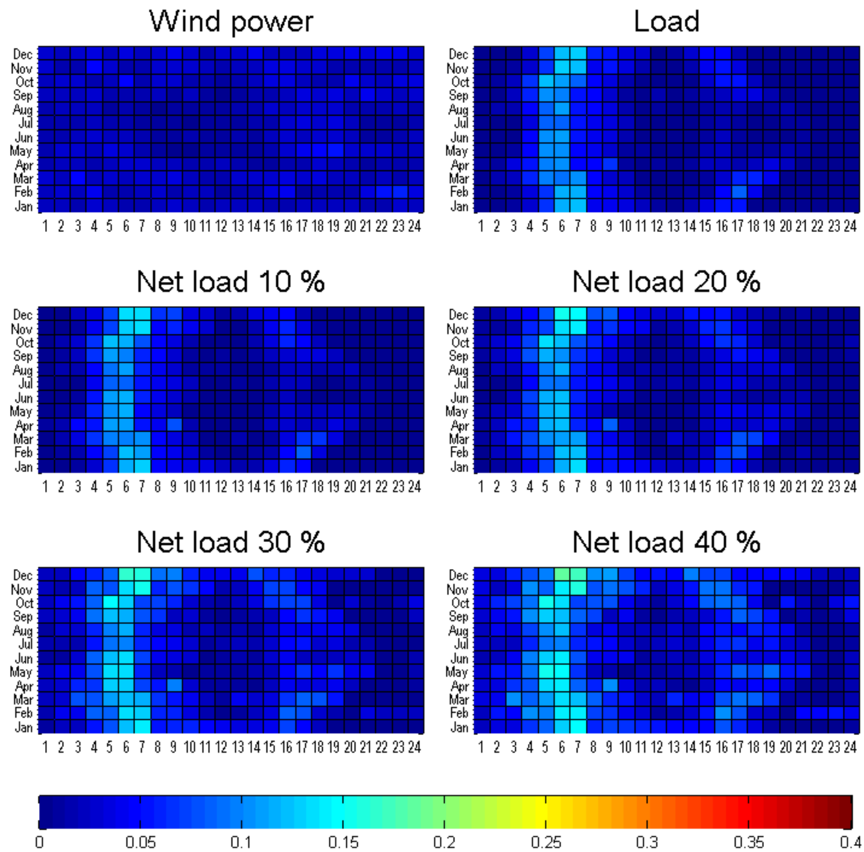

Figure 94. Timing of largest up-ramps in Nordic countries, year 2011. Scale is as % of average load. 24 hours of the day are on the x-axis and 12 months of the year on the y-axis in each of the 6 plots.

5.5 Occurrences of high and low wind penetration

The combined hourly load and wind production with different penetration levels were also studied for two kinds of challenging events. First, high instant penetration levels of wind power are most difficult for wind integration, as has been reported by countries with experience in the area (Holttinen et al. 2009; Söder et al. 2007). Second, low wind power production during peak load situations has implications on capacity adequacy in power systems and will become more important in the future when increasing amounts of wind power and aging of conventional power plants will reduce the conventional capacity in power systems.

5.5.1 High wind power penetration

For this analysis, a time series of hourly wind penetration (wind power production divided by load) using different penetration levels was produced for each country. Table 22 – Table 25 and Figure 95 show the maximum shares that wind power cover from the total load during one hour, for different years and (yearly) penetration levels.

When wind power covers 10% of the yearly electricity consumption, the share of wind power can reach 36–46% during one hour – depending on how high winds occur during low load situations. Already with a 20% yearly penetration level the maximum instant penetration can be 100% in a small country like Denmark, up to 90% in larger countries Finland and Sweden and close to 80% in the whole of Nordic countries. Differences between Denmark and the other Nordic countries may partly be due to lower low load situations in Denmark as there is not as much industrial base load consumption. In the Nordic region the maximum instant penetration is generally lower than for the single countries, but still exceeds 100% when the wind share is 30%. There is not so much difference in the three years of analysis for Nordic data as for single countries.

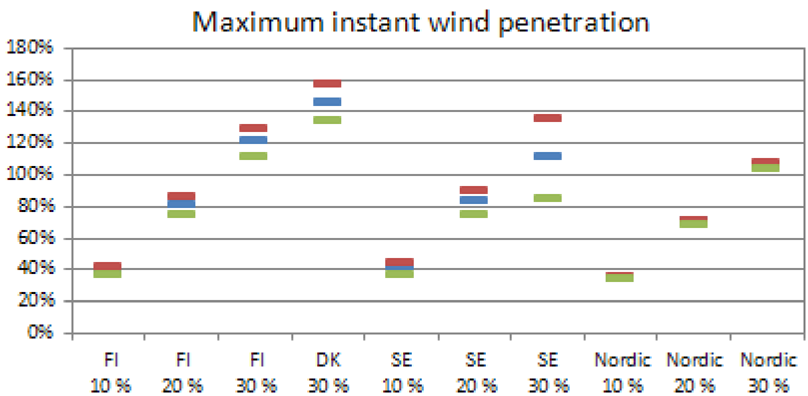

Figure 95. Maximum instant wind penetration (wind share of load during one hour) reached during 2009–2011 with different yearly wind shares.

Table 22. Maximum instant wind penetration in Denmark during one hour with different penetration levels.

	20–23%	30%	40%	50%
2009	95.6%	146.4%	195.2%	244.0%
2010	99.1%	135.1%	180.2%	225.2%
2011	119.6%	158.4%	211.2%	264.0%

Table 23. Maximum instant wind penetration in Finland during one hour.

	0.3%	**10%**	**20%**	**30%**
2009	1.4%	42.1%	84.1%	126.2%
2010	1.5%	43.5%	86.9%	130.4%
2011	2.1%	36.2%	72.4%	108.6%

Table 24. Maximum instant wind penetration in Sweden during one hour.

	2.4–4.4%	**10%**	**20%**	**30%**
2009	8.4%	45.7%	91.4%	137.1%
2010	10.3%	43.2%	86.4%	129.3%
2011	17.0%	38.2%	76.4%	114.6%

Table 25. Maximum instant wind penetration in Nordic countries during one hour. Finland and Norway are up-scaled to 50% of Denmark and Sweden to 100% of Denmark wind power production.

	10%	**20%**	**30%**
2009	35.0%	70.1%	105.1%
2010	36.3%	72.6%	109.0%
2011	36.0%	72.0%	108.0%

As the yearly wind penetration level of wind power is increased to 20% or above, there are already frequent situations when wind power produces more than 50% of the load. The durations of high wind penetration situations are presented in Table 26 – Table 29 using wind and load data from 2010.

Table 26. Durations of high wind penetration situations in Denmark with different penetration levels, year 2010.

	> 50%	**> 60%**	**> 70%**	**> 80%**	**> 90%**	**> 100%**
22%	791 h	435 h	156 h	54 h	16 h	0 h
30%	1772 h	1165 h	728 h	472 h	230 h	112 h
40%	2868 h	2156 h	1598 h	1165 h	820 h	583 h
50%	3652 h	3004 h	2448 h	1906 h	1492 h	1165 h

Table 27. Durations of high wind penetration situations in Finland with different penetration levels, year 2010.

	> 50%	**> 60%**	**> 70%**	**> 80%**	**> 90%**	**> 100%**
0.3%	0 h	0 h	0 h	0 h	0 h	0 h
10%	0 h	0 h	0 h	0 h	0 h	0 h
20%	632 h	297 h	97 h	14 h	0 h	0 h
30%	1775 h	1224 h	796 h	502 h	297 h	152 h
40%	2784 h	2097 h	1627 h	1224 h	873 h	632 h
50%	3585 h	2912 h	2348 h	1895 h	1531 h	1224 h

Table 28. Durations of high wind penetration situations in Sweden with different penetration levels, year 2010.

	> 50%	**> 60%**	**> 70%**	**> 80%**	**> 90%**	**> 100%**
2.4%	0 h	0 h	0 h	0 h	0 h	0 h
10%	0 h	0 h	0 h	0 h	0 h	0 h
20%	430 h	218 h	79 h	9 h	0 h	0 h
30%	1463 h	909 h	565 h	338 h	218 h	109 h
40%	2571 h	1835 h	1297 h	909 h	635 h	430 h
50%	3619 h	2761 h	2108 h	1619 h	1202 h	909 h

Table 29. Durations of high wind penetration situations in Nordic countries with different penetration levels, year 2010.

	> 50%	**> 60%**	**> 70%**	**> 80%**	**> 90%**	**> 100%**
2.40%	0 h	0 h	0 h	0 h	0 h	0 h
10%	0 h	0 h	0 h	0 h	0 h	0 h
20%	211 h	60 h	7 h	0 h	0 h	0 h
30%	1076 h	570 h	312 h	147 h	60 h	17 h
40%	2380 h	1540 h	916 h	570 h	364 h	211 h
50%	3703 h	2616 h	1839 h	1248 h	847 h	570 h

5.5.2 Wind power production during peak loads

In the Nordic countries peak loads occur during the wintertime. In Finland, Sweden and Norway peak loads are directly dependent on the outside temperature (due to a large share of electric heating). Three years of data was used to resolve the level of wind power production during peak load situations (Table 30 and Figure 96). This three year period already shows how the figures may differ substantially on yearly basis. One of the years (but different one for each country) shows a very low wind power production level during peak load of only 2–3% in Denmark and Finland and 7% in Sweden. Two of the years in each country had one low production value during 10 highest peaks. The maximum wind production during the highest yearly peak load was close to 60% in Finland and Denmark and 14% in Sweden. Similar data has been collected in Finland since 1999 and is published in the yearly statistics of wind power (Nord Pool Spot 16.5.2012; Turkia & Holttinen 2013).

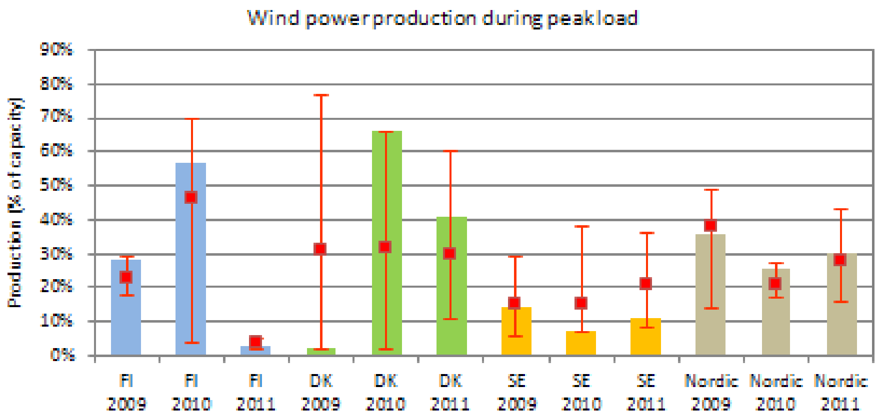

Figure 96. Wind power production during peak load. Each bar shows the production, as % of installed capacity, during the single highest peak load hour. Minimum, maximum and average production during 10 highest peaks are shown with red error bars.

Table 30. Wind power production during peak load situations in the Nordic countries. Each entry in the table shows the production, as % of installed capacity, during the single highest peak load hour followed by the average production during the 10 highest peaks (minimum-maximum). For Nordic time series Finland and Norway are up-scaled to 50% Denmark wind power production and Sweden to 100% of Denmark.

	Finland	**Denmark**	**Sweden**	**Nordic**
2009	28%, 23% (18–29%)	2%, 31% (2–77%)	14%, 15% (6–29%)	36%, 38% (14–49%)
2010	57%, 46% (4–70%)	66%, 32% (2–66%)	7%, 15% (7–38%)	26%, 21% (17–27%)
2011	3%, 4% (2–5%)	41%, 30% (11–60%)	11%, 21% (8–36%)	30%, 28% (16–43%)

5.6 Length of low- and high-wind periods

The amount of low wind periods, during which wind power production was less than 5% of the installed capacity, can be seen in Table 31. During 2009–2011 Sweden had 7 occurrences of low wind periods that lasted for 24 to 47 hours, Finland had 17 and Denmark 36. All countries had 1–3 occurrences that lasted for 72 to 95 hours. The maximum length of low wind periods from each year range from 24 to 82 in Sweden, 63 to 80 in Denmark and 72 to 98 in Finland.

Correspondingly, the amount of high wind occurrences with production over 70% of installed capacity is shown in Table 32. Sweden had none of these occurrences during 2009–2011, Denmark had 5 and Finland 3. Maximum durations of high wind periods were smaller each year in Sweden compared to the other two countries.

The length and number of low- and high-wind periods show also considerable smoothing effect from single countries to Nordic wide data. For example, there were no occurrences of 70% production lasting over 24 hours Nordic-wide. During year 2009 there was one more than 20-hour long period of high wind penetration in the Nordic wide data. During 2009–2011 Nordic data there was one low wind period lasting for 70 hours, and 4 occurrences that lasted for 24 to 47 hours.

Table 31. Amount of periods when wind power production was less than 5% of installed capacity, years 2009–2011.

Length	Finland	Denmark	Sweden	Nordic original	Nordic scaled
24–47 h	17	36	7	16	4
48–71 h	3	9	2	4	1
72–95 h	3	2	1	0	0
96–120 h	1	0	0	0	0
Max length 2009	98 h	64 h	82 h	92 h	70 h
Max length 2010	72 h	63 h	24 h	20 h	15 h
Max length 2011	79 h	80 h	34 h	43 h	41 h

Table 32. Length of periods when wind power production was over 70% of installed capacity, years 2009–2011.

	Finland	Denmark	Sweden	Nordic
No of periods > 24 h	3	5	1	0
Max length 2009	16 h	33 h	18 h	21 h
Max length 2010	25 h	28 h	6 h	0 h
Max length 2011	28 h	32 h	30 h	10 h

The low-wind periods occur primarily in the summertime. The longest low wind power production event in the Nordic countries was in August (70 hours of production below 5% of installed capacity, Figure 97). Also other low wind periods over 30 hours occurred during summer (41 hours in July, 33 hours in August). In wintertime there were two periods of more than 20 hours having less than 5% of installed capacity during the three years analysed: 30 hours (27.1.2009) and 21 hours (16.2.2009).

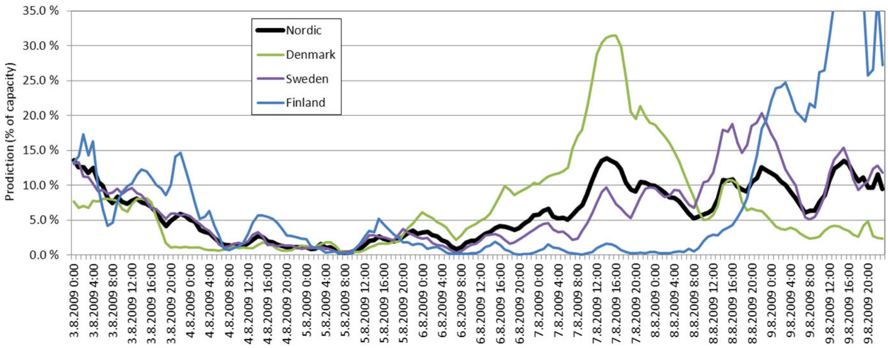

Figure 97. Longest low wind period in 3 years of data (70 hours < 5% of capacity) occurred in August, 2009.

Figure 98 – Figure 100 show the amount of low wind periods during each month. Most of the periods occurred during the summertime, although data from 2009 shows also many occurrences during winter months.

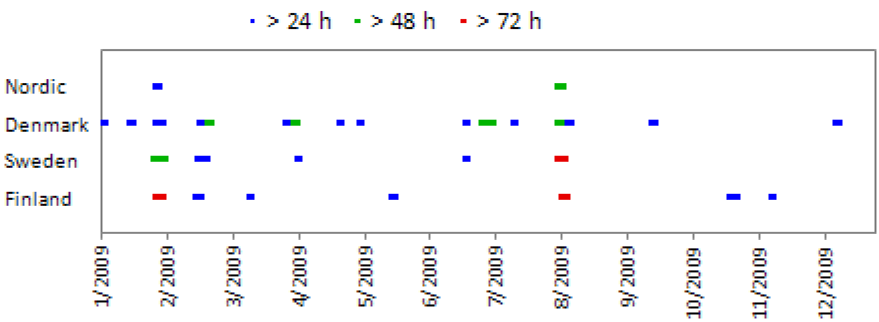

Figure 98. Low wind periods in 2009 (wind production < 5% of capacity).

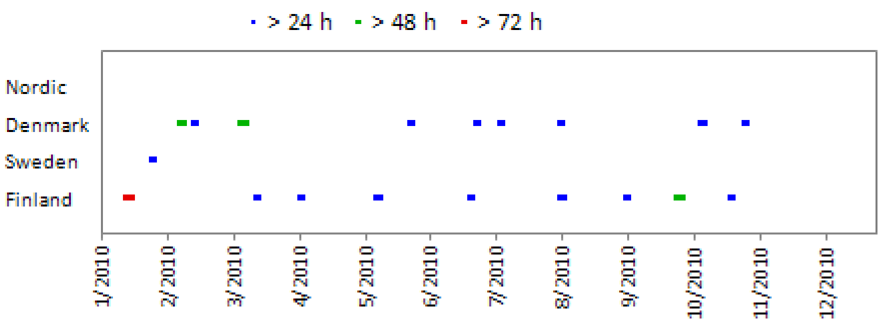

Figure 99. Low wind periods in 2010 (wind production < 5% of capacity).

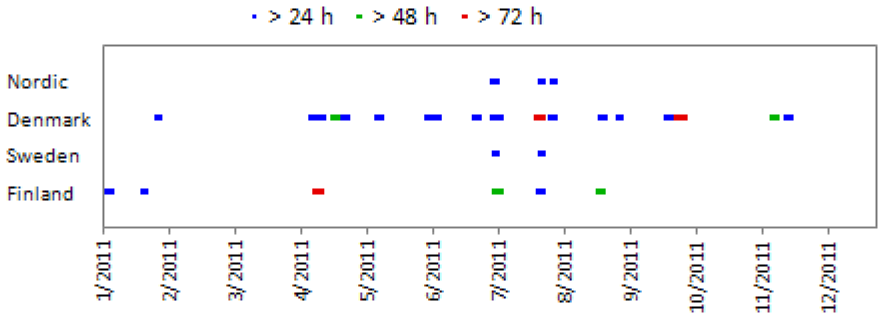

Figure 100. Low wind periods in 2011 (wind production < 5% of capacity).

The number of occurrences when wind production is over 50% of load was analysed with different wind penetration levels. The number of periods increase rapidly when wind penetration exceeds 20% (Table 33). For example, with a 20% penetration level Finland had 8 periods that lasted over 24 hours, Denmark 18 and Sweden 11. With a 30% penetration the corresponding figures were 70 in Finland, 63 in Denmark and 53 in Sweden (Figure 101 – Figure 103). The smoothing effect can again be seen in that the Nordic figures are clearly smaller compared to all individual countries and with all penetration levels. However, at larger penetration levels > 30% there will be longer periods with high penetration levels also Nordic wide (Figure 104 – Figure 106). In the Nordic region, increasing the wind penetration level to 40% results in high production periods that last 3–5 days to occur during almost every month in 2009 (Figure 107 – Figure 109). Furthermore, several periods that last longer than one week appear. With a 20% penetration level situations when wind power production exceeded 50% of load in 2009 and 2010 mostly occurred during summer and autumn months (Figure 101 – Figure 102). Days with exceptionally high wind speeds in the end of December 2011 are clearly visible from Figure 103.

Table 33. Number of periods with wind power production over 50% of load, years 2009–2011.

20% penetration level

length of period	Finland	Denmark	Sweden	Nordic
> 1 day	8	18	11	5
> 2 days	2	2	1	1
> 3 days	1	0	1	0
> 4 days	1	0	0	0
> 5 days	0	0	0	0
> 6 days	0	0	0	0
> 7 days	0	0	0	0

30% penetration level

length of period	**Finland**	**Denmark**	**Sweden**	**Nordic**
> 1 day	70	63	53	43
> 2 days	21	19	23	18
> 3 days	6	2	7	4
> 4 days	2	0	1	1
> 5 days	0	0	0	0
> 6 days	0	0	0	0
> 7 days	0	0	0	0

40% penetration level

length of period	**Finland**	**Denmark**	**Sweden**	**Nordic**
> 1 day	122	122	95	96
> 2 days	44	42	41	40
> 3 days	19	8	16	15
> 4 days	6	3	7	6
> 5 days	1	1	5	5
> 6 days	0	0	2	2
> 7 days	0	0	2	2

50% penetration level

length of period	**Finland**	**Denmark**	**Sweden**	**Nordic**
> 1 day	156	148	134	148
> 2 days	65	62	62	67
> 3 days	28	23	31	30
> 4 days	13	11	13	15
> 5 days	5	3	9	9
> 6 days	0	1	5	5
> 7 days	0	1	4	4

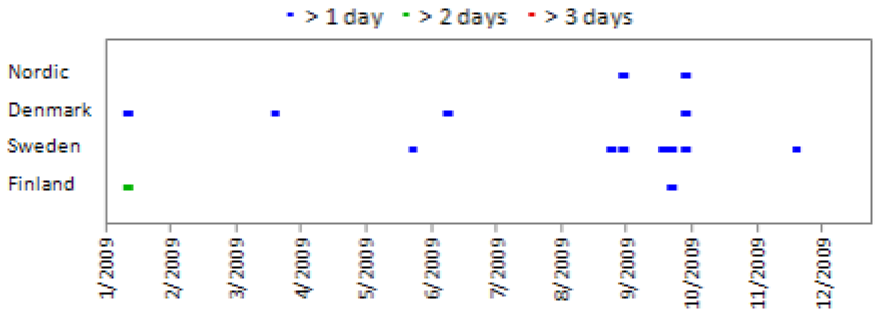

Figure 101. At 20% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2009.

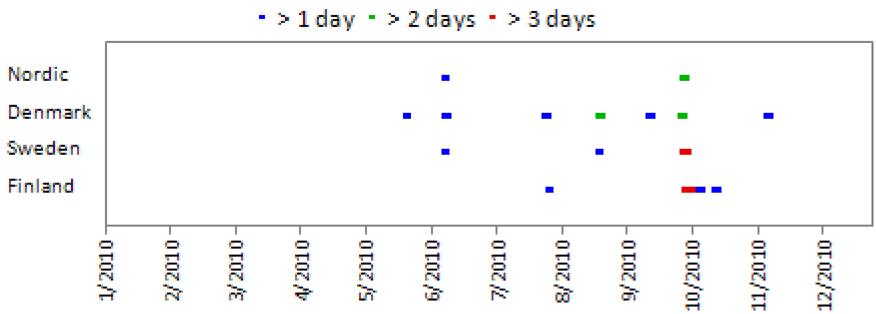

Figure 102. At 20% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2010.

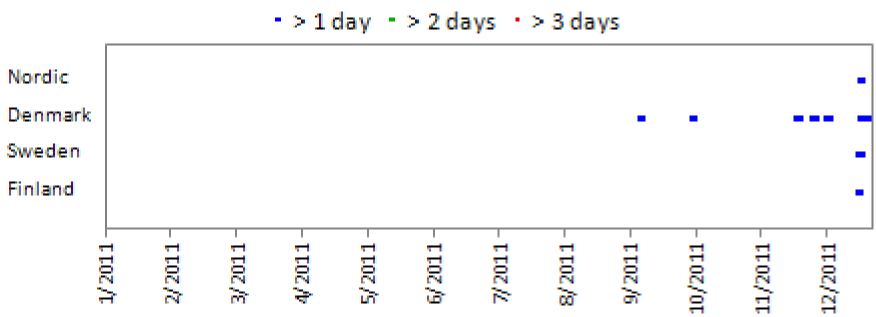

Figure 103. At 20% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2011.

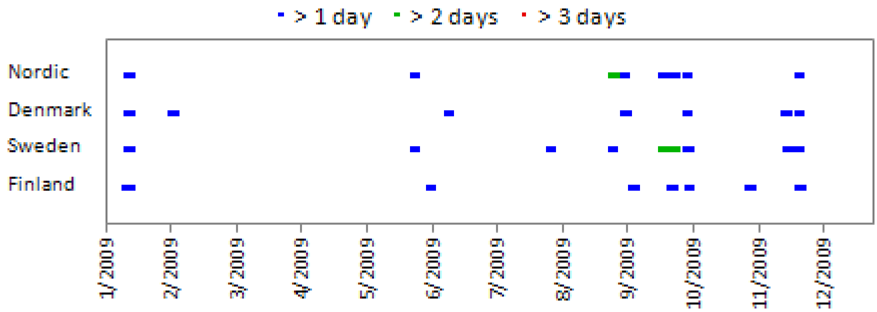

Figure 104. At 30% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2009.

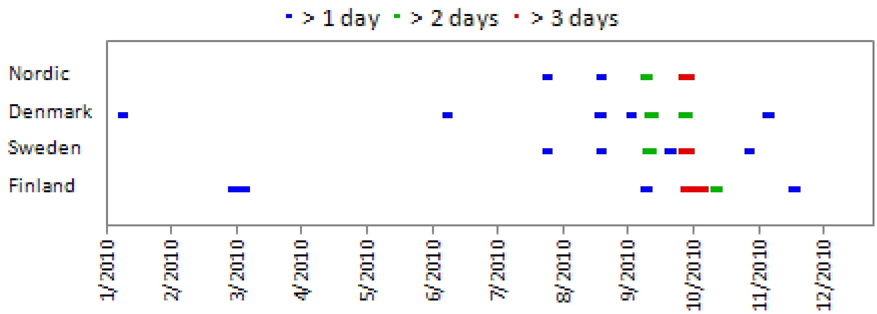

Figure 105. At 30% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2010.

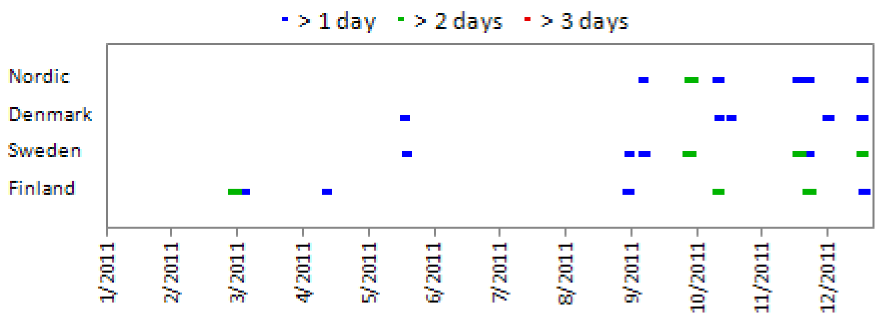

Figure 106. At 30% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2011.

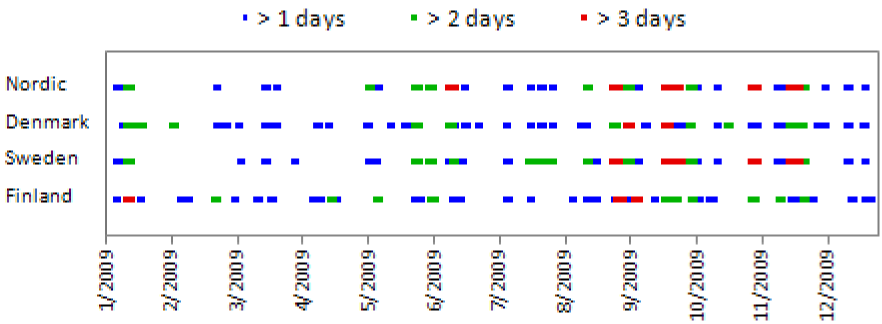

Figure 107. At 40% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2009.

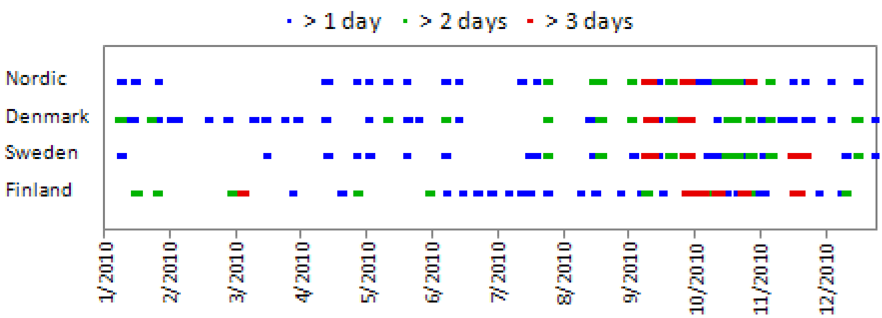

Figure 108. At 40% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2010.

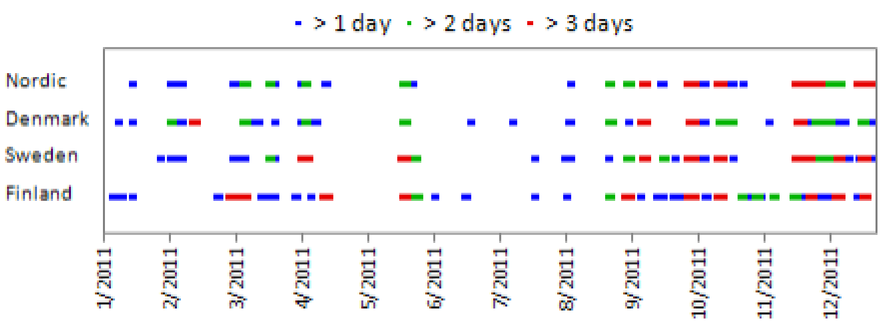

Figure 109. At 40% yearly wind penetration level, longer periods when wind power production is over 50% of load, year 2011.

6. Conclusions and future work

This publication analysed the variability of wind production and load in Denmark, Finland, Sweden, and the Nordic region as a whole. The Nordic-wide wind power time series was scaled up such that Sweden had same amount of wind power production than Denmark, and Finland and Norway only 50% of the wind power production in Denmark.

The smoothing effect of wind power production can be clearly seen in the hourly data. Wind power production in Denmark and Sweden is somewhat correlated (coefficient 0.7) but less correlation is found between the other countries. The variations from one hour to the next are only weakly correlated between all countries, even between Denmark and Sweden. In all countries the variability of wind power production depends on the current production level. Largest variations occur when the production is approximately 30–70% of installed capacity and variability is low at small winds. For some sites more detailed data on sub-hourly changes of production and load were available. This data showed that the variability in shorter time scales was less than the hourly variations. During the three years analysed in this publication there were few storm incidents and they did not produce dramatic wind power ramps in the Nordic region.

The load has a pronounced pattern, and its variability is dependent on the time of day. The load is clearly correlated between the Nordic countries, and is not smoothed out from one country to the whole Nordic wide area.

The impact of wind power on the variability that the system sees was depicted by analysing the net load time series with different wind power penetration levels. The amount that the highest variations increase when using larger wind shares was presented with different exceedance levels. The Nordic wide wind power production increases the highest hourly ramps by 2.4% (up) and -3.6% (down) of installed wind power capacity when there is 20% wind power penetration and by 2.7% (up) and -4.7% (down) for 30% wind penetration. These results assess the impacts of variability only. The next step will be assessing the uncertainty from forecast errors.

The maximum penetration level, during one hour, can reach high levels already with a 20% (yearly) penetration level. The largest wind share in the Nordic countries reached only 36% during one hour when wind power covers 10% of the yearly electricity consumption. With a 20% yearly penetration level the maximum instant penetration is more than 100% in a small country like Denmark, up to 90% in larger countries Finland and Sweden and 73% in the whole of Nordic countries. At 30% penetration on yearly level the maximum hourly wind share was 160% in Denmark, 130–140% in Finland and Sweden and 110% in Nordic region.

Low penetration levels (2.5% of installed wind power during highest loads) can occur in a single country. For Nordic wide wind power the production during high loads was above 14% of installed capacity during the 10 highest peaks in the three years analysed. The low wind periods occur mostly in summertime. The longest wind power production event in the Nordic countries was in August (70 hours of production below 5% of installed capacity). In wintertime there were 2 periods of more than 20 hours below 5% of installed capacity in the three years of data (longest 30 hours).

Wind and load variations are not correlated, which is important when integrating wind power to the system. This means that it is not probable that wind power production and load would both be simultaneously affected by large variations. Timing of the largest ramps will change dramatically with larger wind shares. This could be seen in one country at 20% wind penetration and in the whole Nordic area at 30% penetration.

Analyses of the variability of wind power production and load can be used to assess the impacts of increasing shares of wind power to the power system. This is valuable information, for example, when allocating sufficient operating reserves and estimating the uncertainty of the production during different conditions. The future work will focus more on the uncertainty of wind power production in the Nordic countries analysing the forecast error data available. Regarding the variability of wind power in the Nordic countries, the analyses presented in this publication are worth updating when more data is available. The time series of Finland and Norway is still based on too few sites to represent properly smoothing effect of larger scale wind power production. In Denmark the deployment of more concentrated offshore wind may increase the variability of the total wind power, especially during storms that for the three years analysed here were not seen in the data. Any changes in the installed wind power siting more generation outside Denmark and Southern Sweden would increase the smoothing effect in Nordic countries.

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Appendix A: Wind power production and load time series from years 2009 and 2011

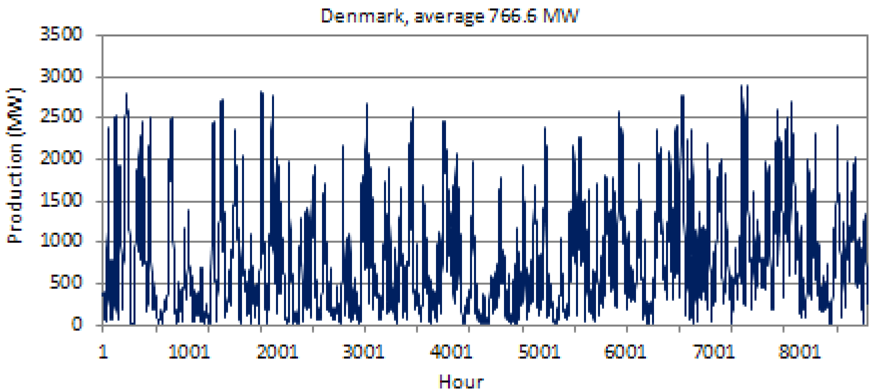

Figure A1. Wind power production in Denmark, year 2009.

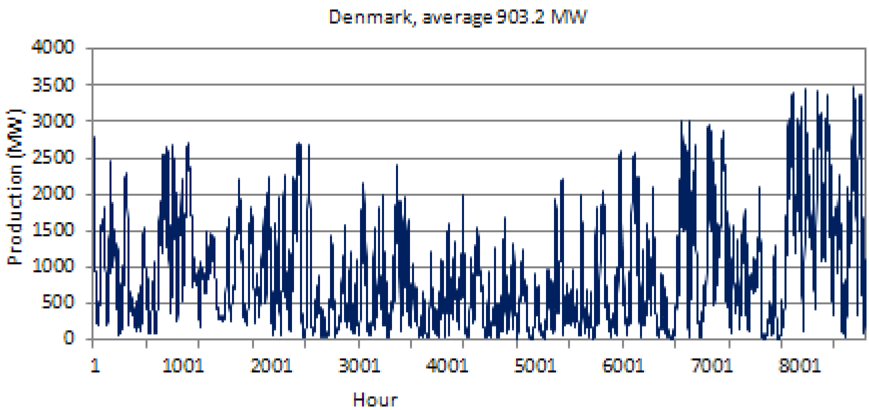

Figure A2. Wind power production in Denmark, year 2011.

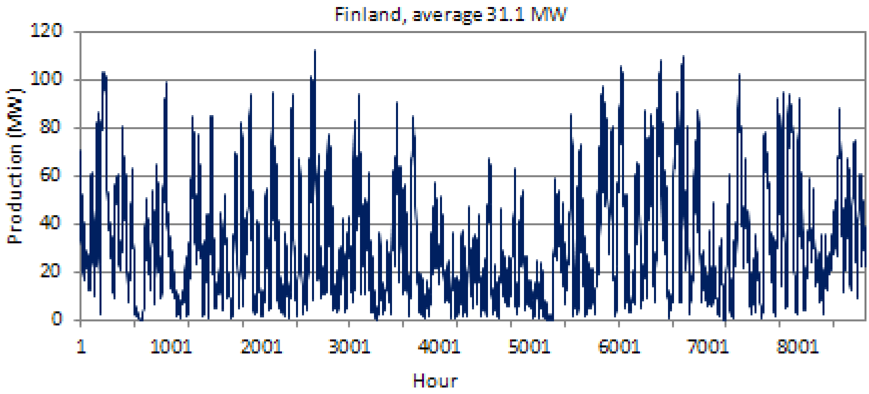

Figure A3. Wind power production in Finland, year 2009.

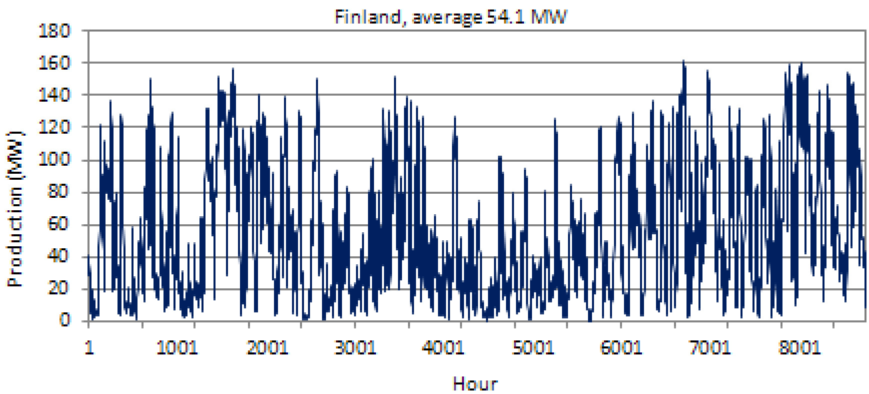

Figure A4. Wind power production in Finland, year 2011.

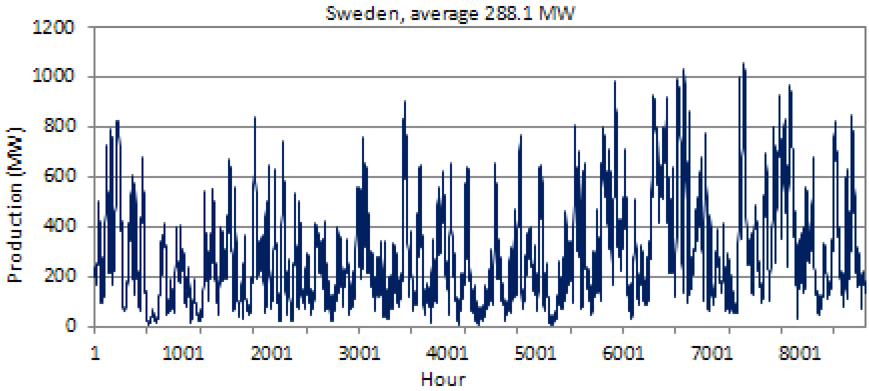

Figure A5. Wind power production in Sweden, year 2009.

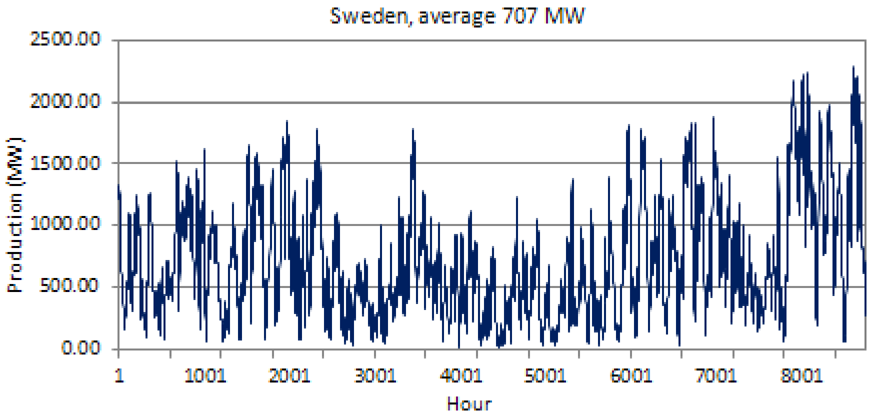

Figure A6. Wind power production in Sweden, year 2011.

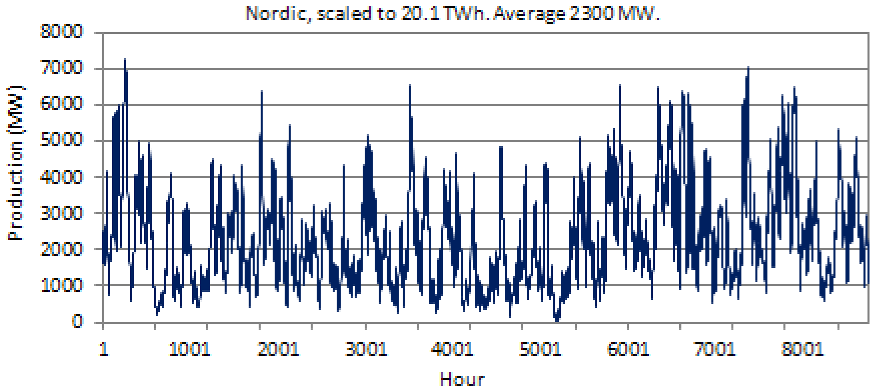

Figure A7. Wind power production in Nordic countries, year 2009.

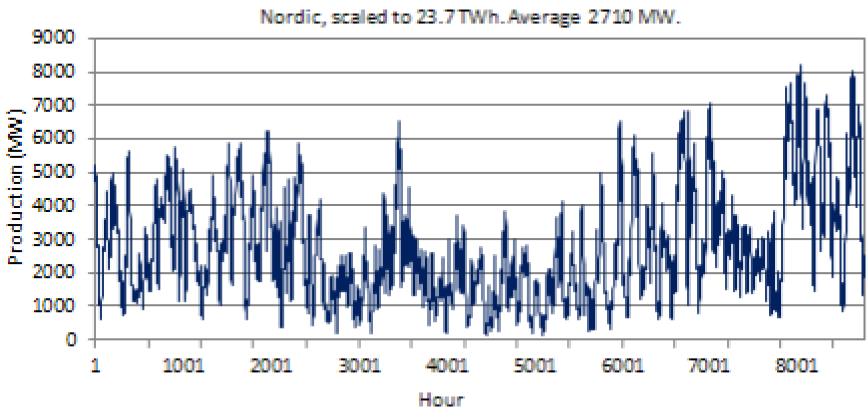

Figure A8. Wind power production Nordic countries, year 2011.

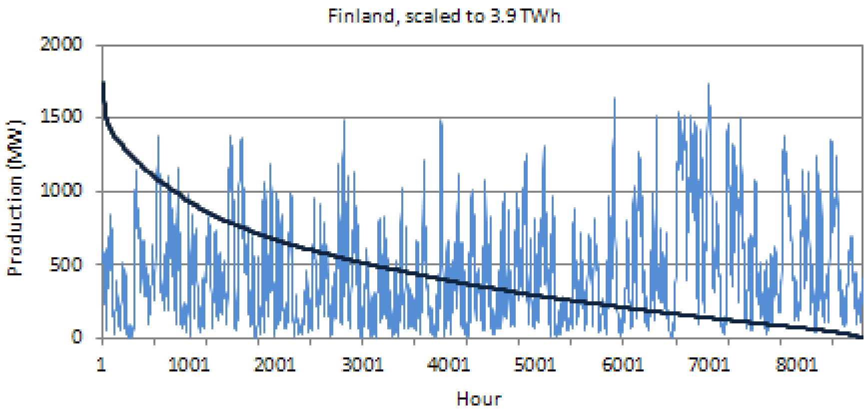

Figure A9. Finland scaled to 3.9 TWh, year 2010.

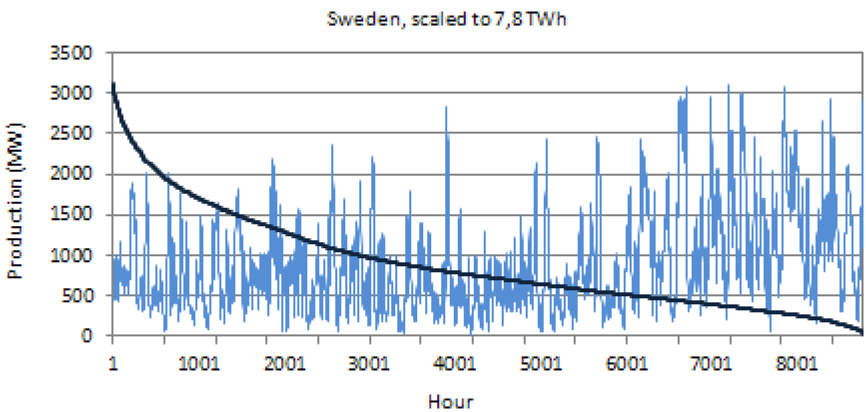

Figure A10. Sweden scaled to 7.8 TWh, year 2010.

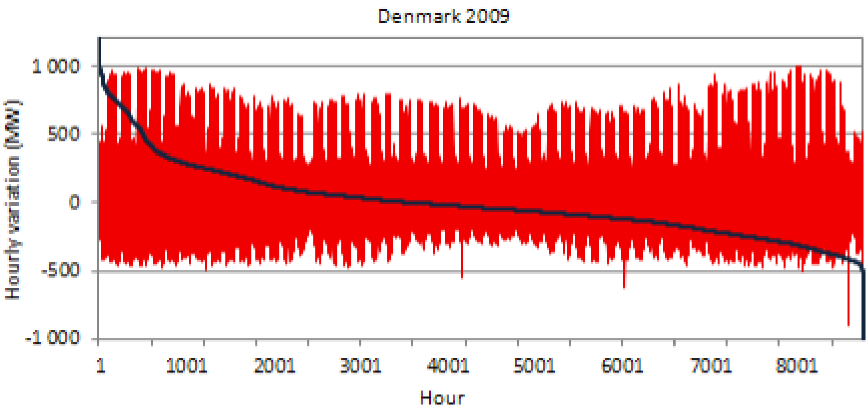

Figure A11. Consumption hourly variation in Denmark, year 2009.

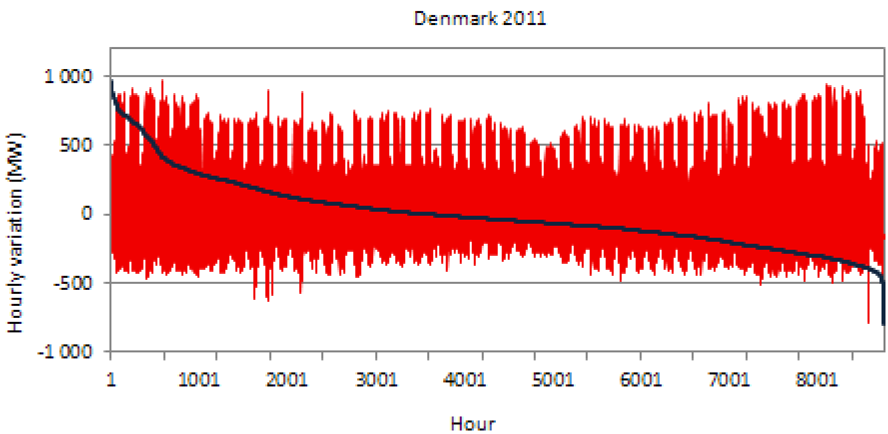

Figure A12. Consumption hourly variation Denmark 2011.

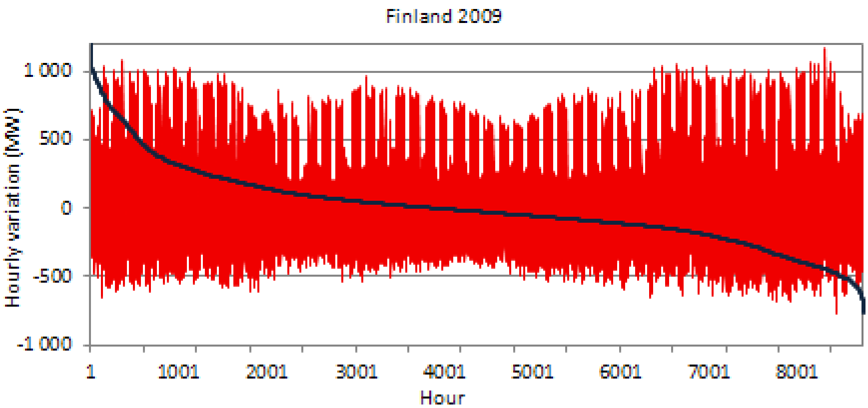

Figure A13. Consumption hourly variation in Finland, year 2009.

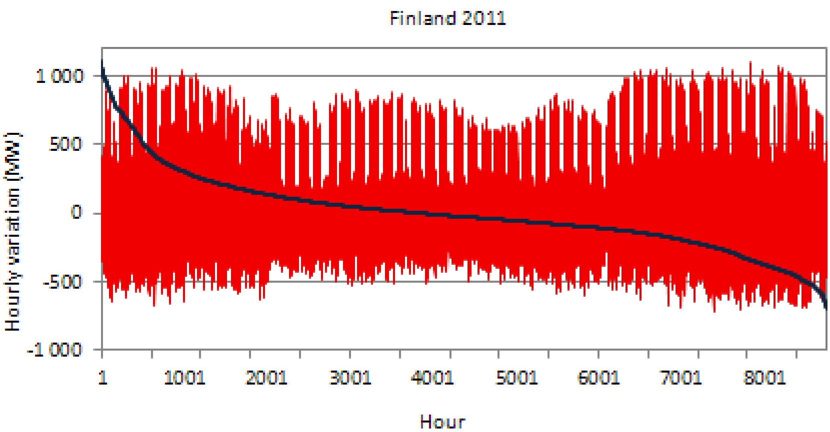

Figure A14. Consumption hourly variation Finland 2011.

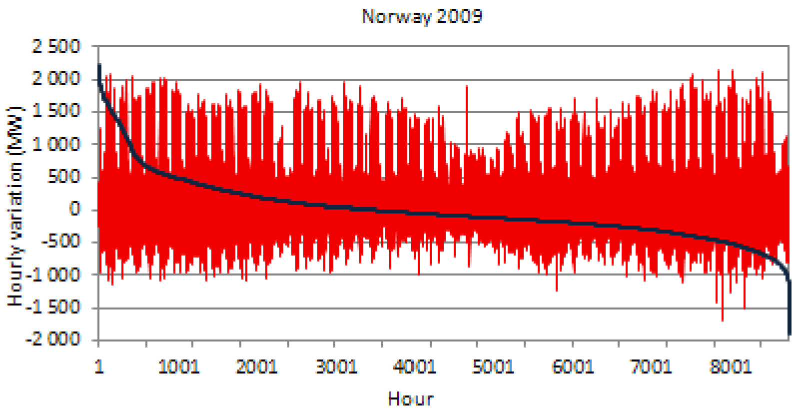

Figure A15. Consumption hourly variation Norway 2009.

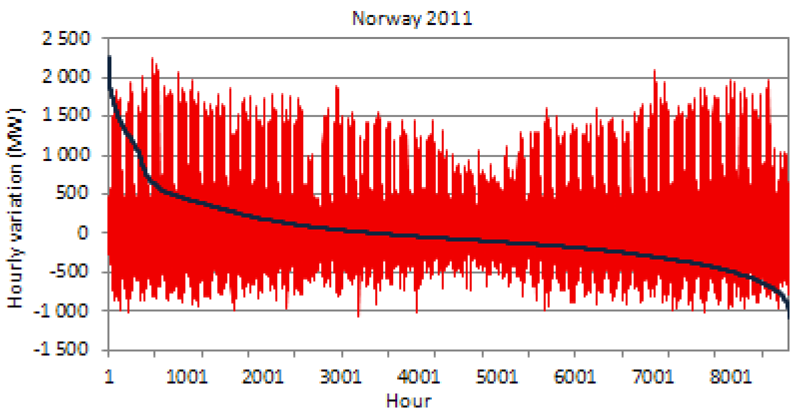

Figure A16. Consumption hourly variation Norway 2011.

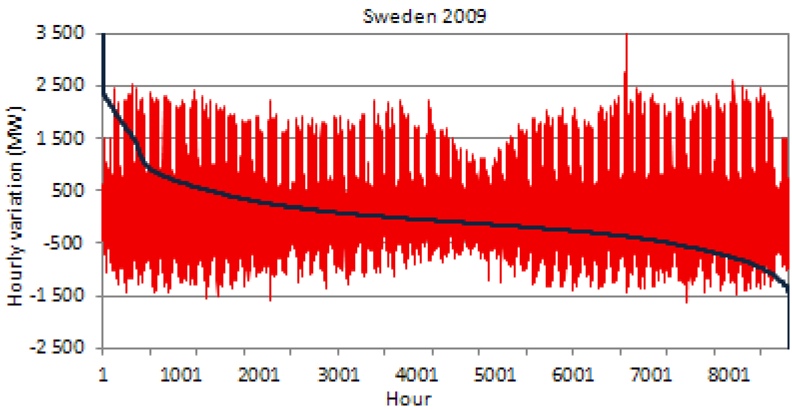

Figure A17. Consumption hourly variation Sweden 2009.

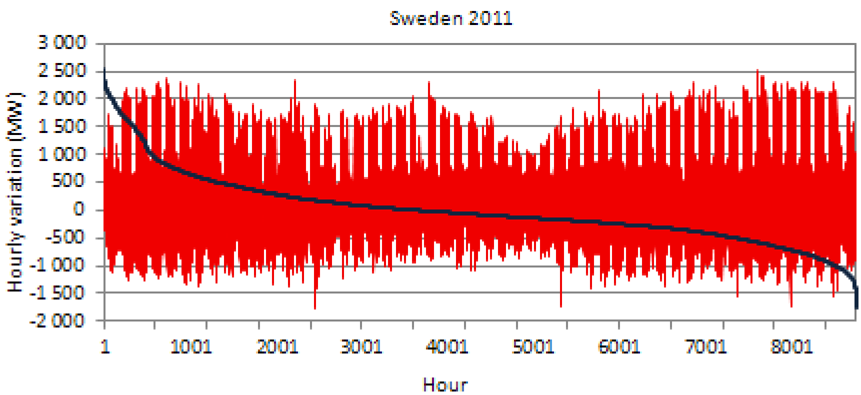

Figure A18. Consumption hourly variation Sweden 2011.

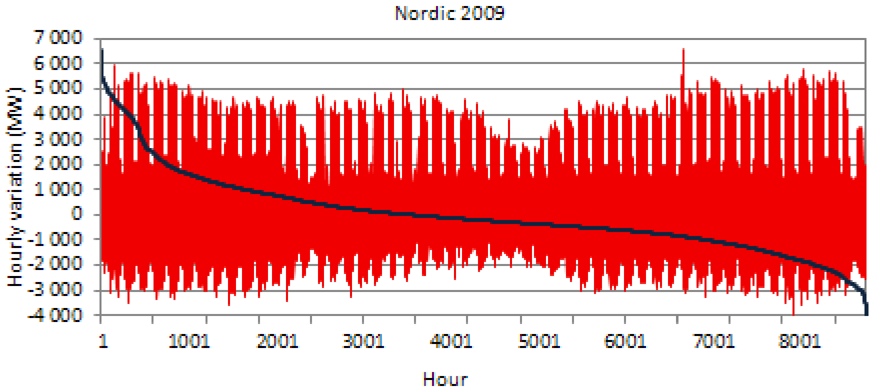

Figure A19. Consumption hourly variation Nordic countries 2009.

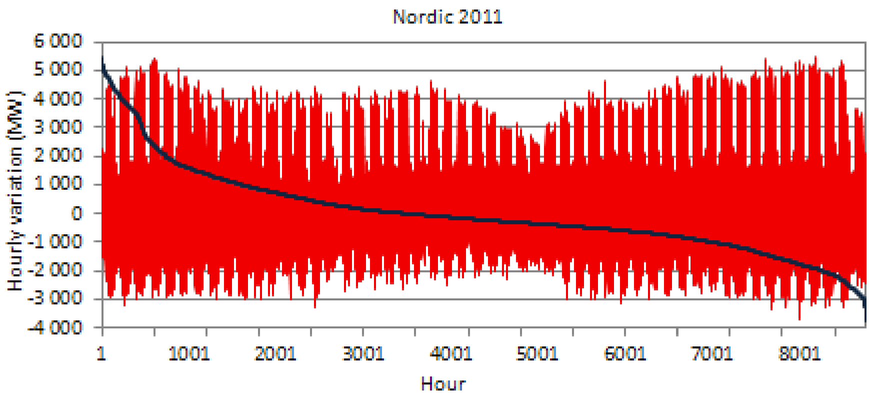

Figure A20. Consumption hourly variation Nordic countries 2011.

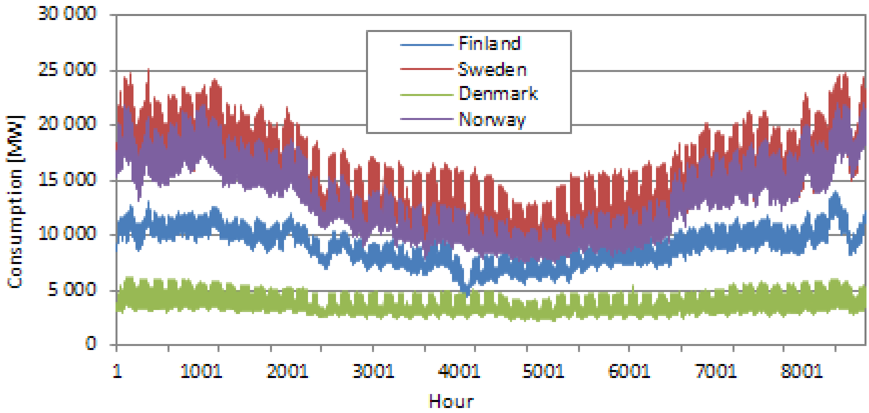

Figure A21. Consumption in Finland, Sweden, Denmark and Norway 2009.

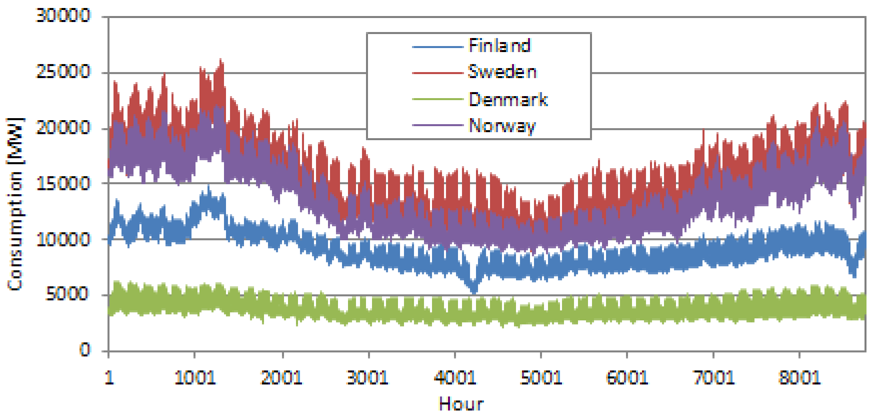

Figure A22. Consumption in Finland, Sweden, Denmark and Norway 2011.

Appendix B: Wind power production variation time series from years 2009 and 2011

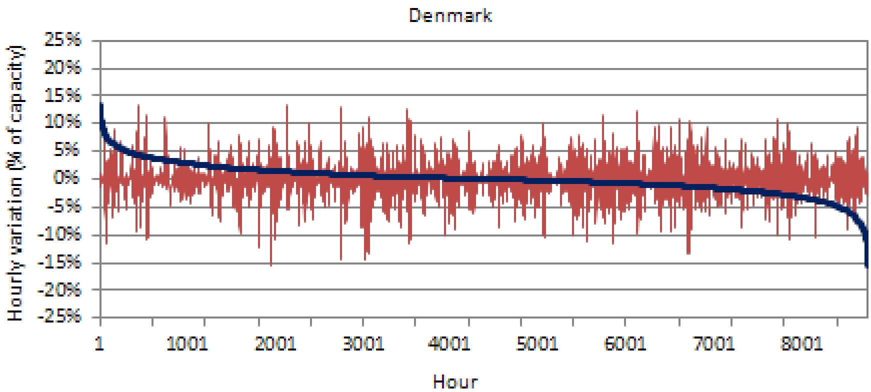

Figure B1. Hourly variation of wind power production in Denmark 2009.

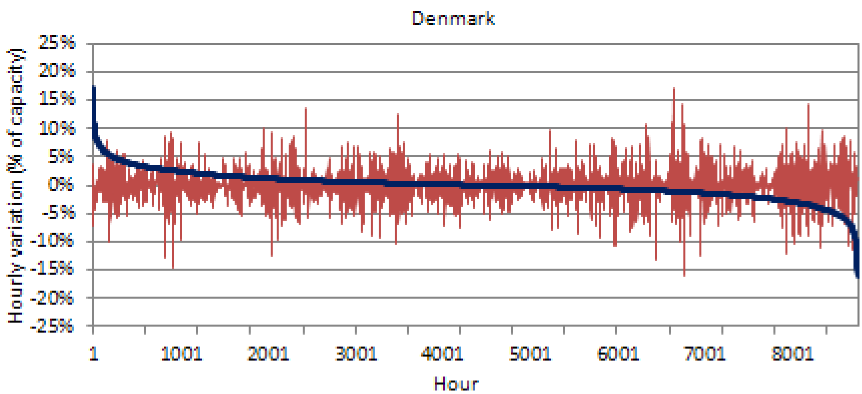

Figure B2. Hourly variation of wind power production in Denmark 2011.

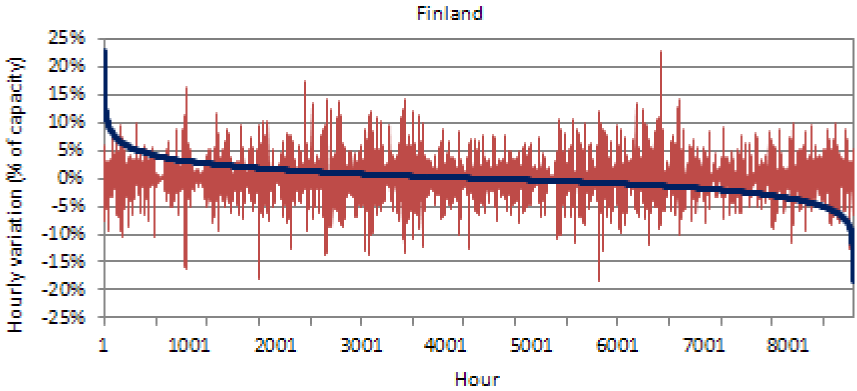

Figure B3. Hourly variation of wind power production in Finland 2009.

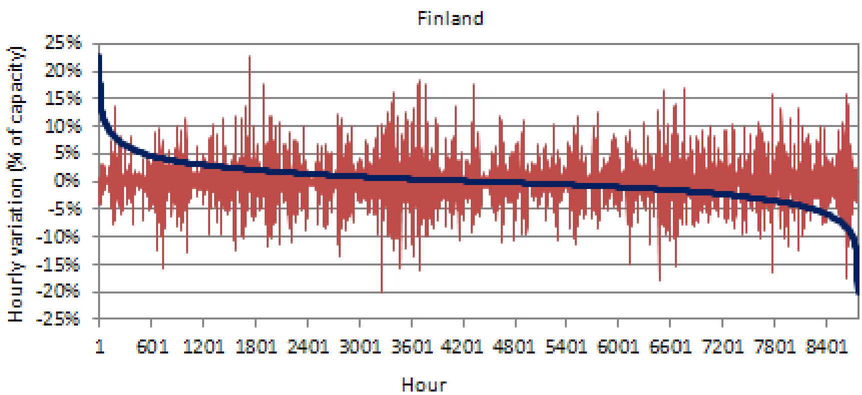

Figure B4. Hourly variation of wind power production in Finland 2011.

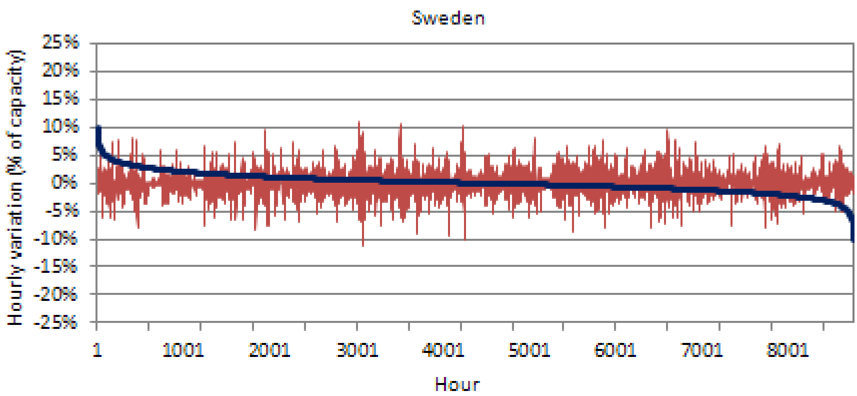

Figure B5. Hourly variation of wind power production in Sweden 2009.

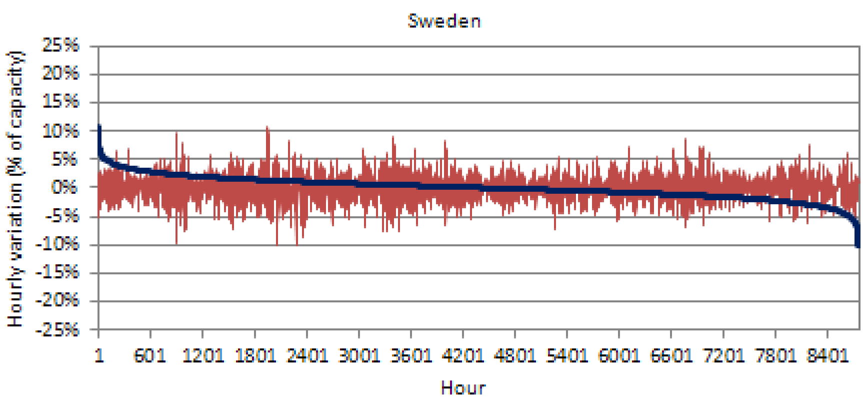

Figure B6. Hourly variation of wind power production in Sweden 2011.

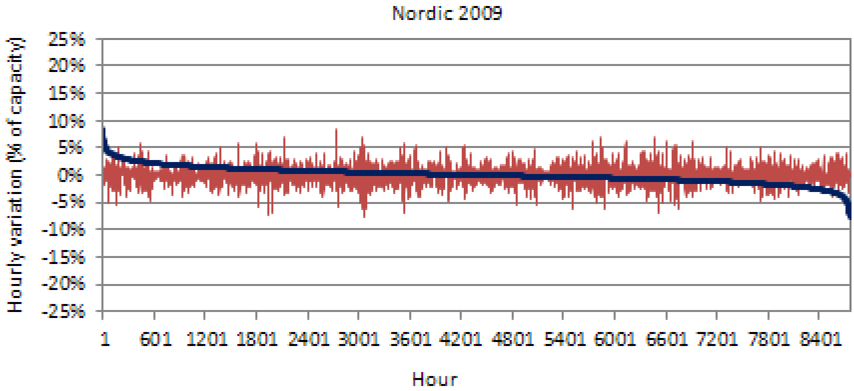

Figure B7. Hourly variation of wind power production in Nordic countries 2009. Production is scaled to 20.1 TWh.

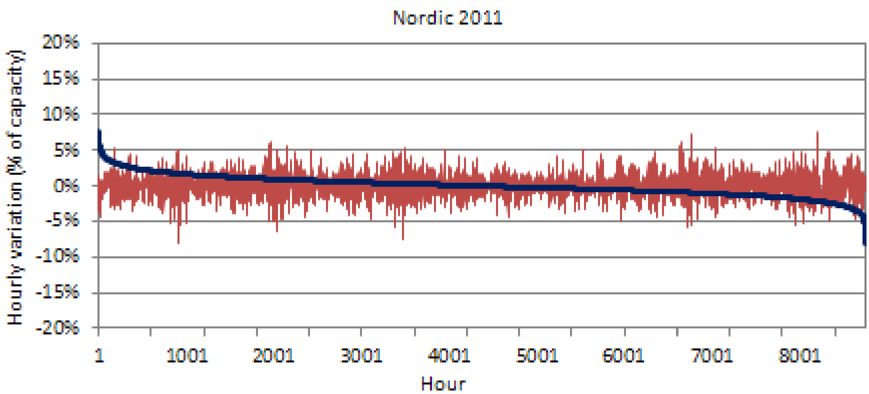

Figure B8. Hourly variation of wind power production in Nordic countries 2011.

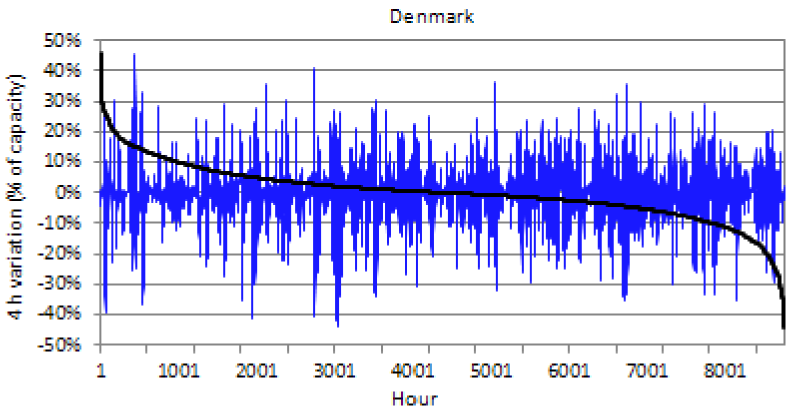

Figure B9. 4 hour variation in Denmark 2009.

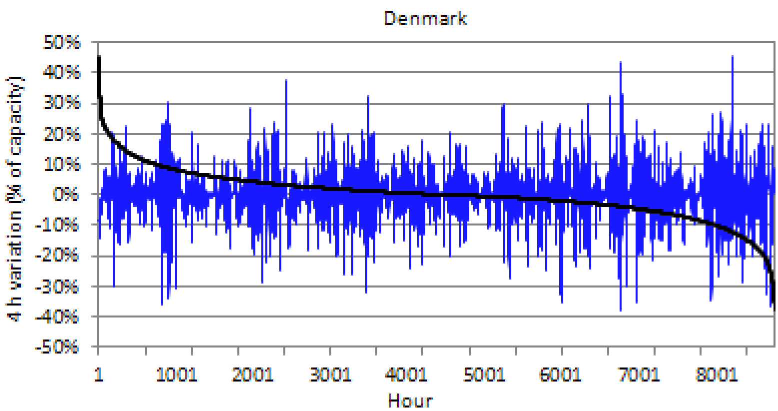

Figure B10. 4 hour variation in Denmark 2011.

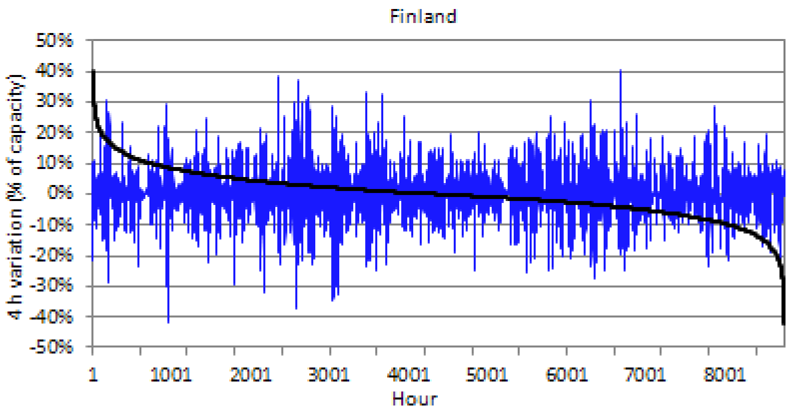

Figure B11. 4 hour variation in Finland 2009.

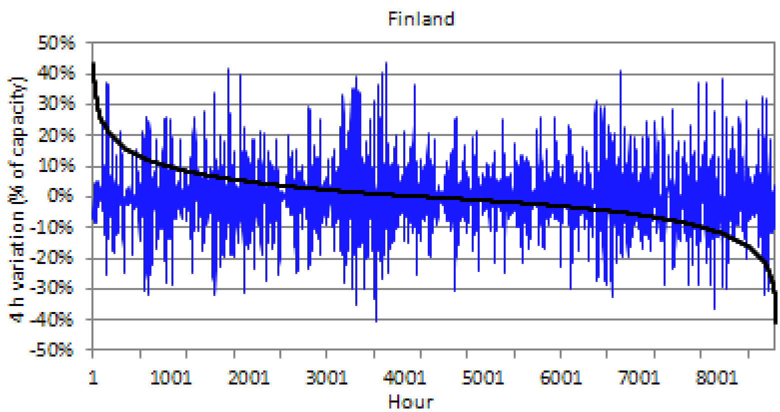

Figure B12. 4 hour variation in Finland 2011.

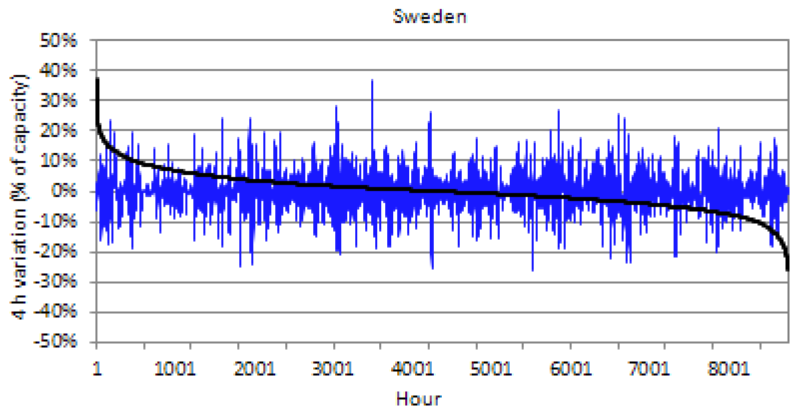

Figure B13. 4 hour variation in Sweden 2009.

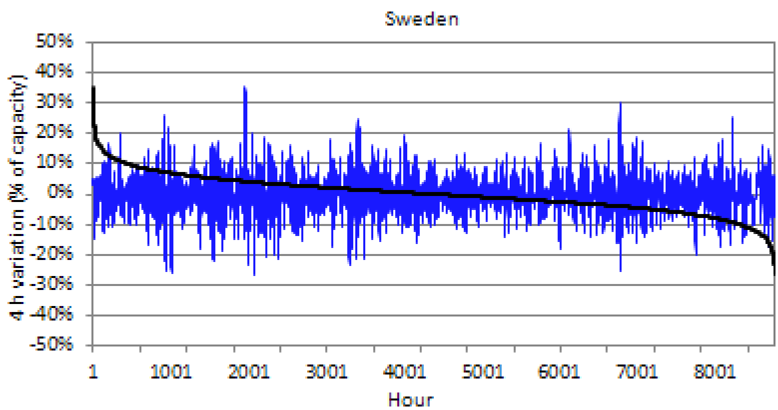

Figure B14. 4 hour variation in Sweden 2011.

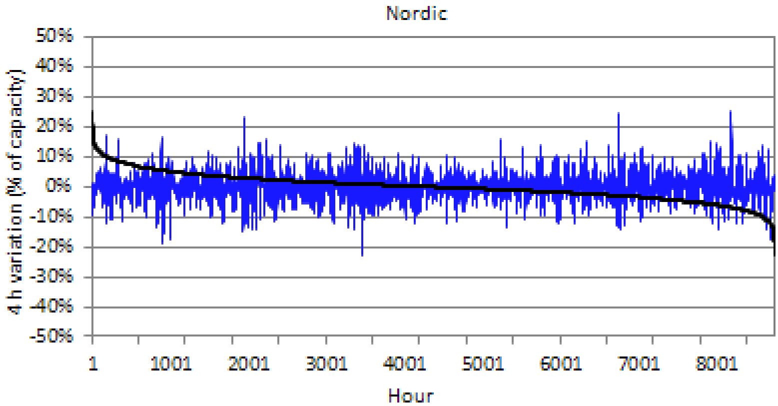

Figure B15. 4 hour variation in Nordic countries 2009.

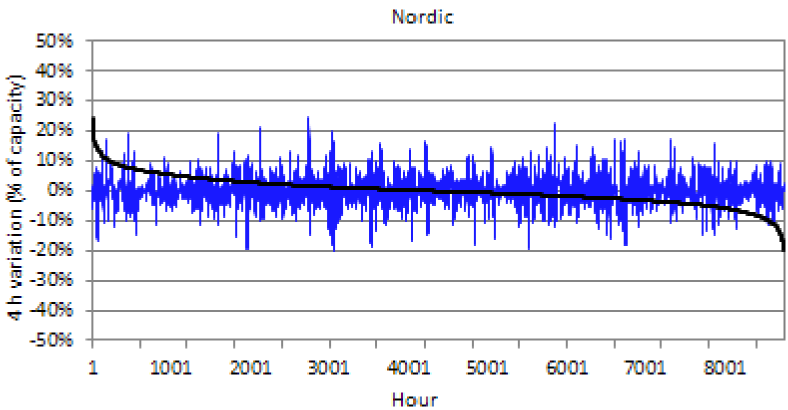

Figure B16. 4 hour variation in Nordic countries 2011.

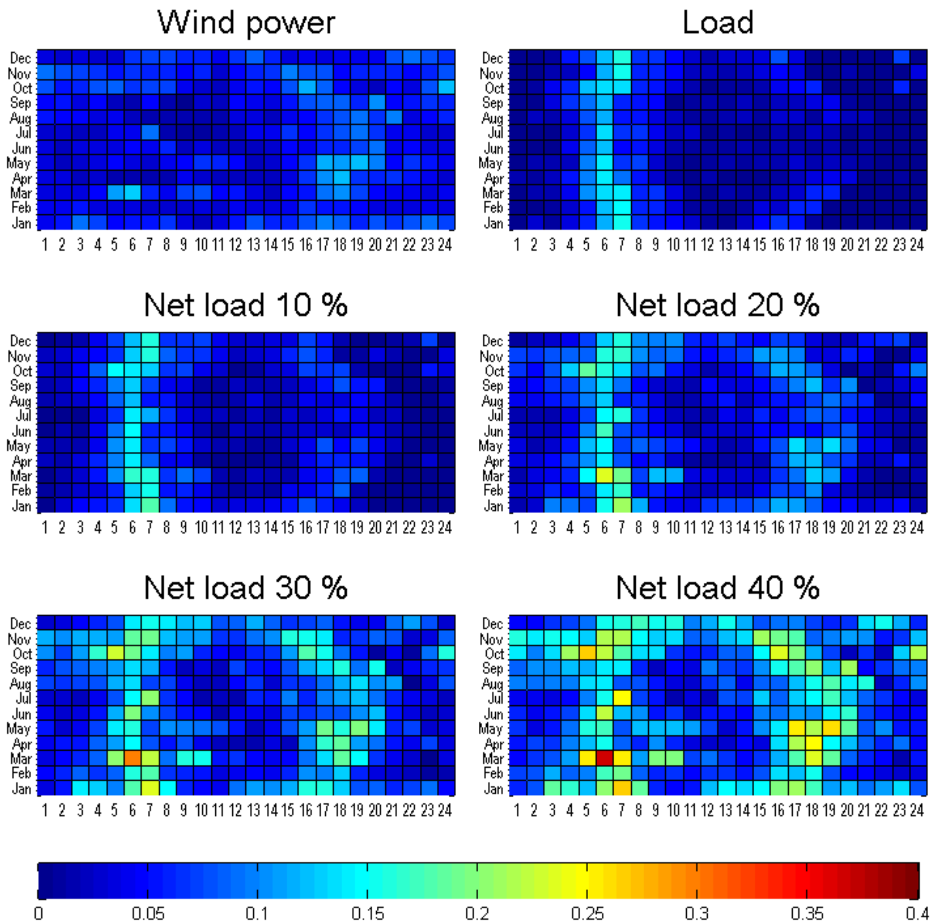

Figure B17. Timing of largest up-ramps in Denmark 2009. Scale of the ramps is depicted in colours, as relative to average load (highest ramps are in red). 24 hours of the day are in the x-axis and 12 months of the year in the y-axis of each of the 6 plots. Upper plots: left Wind right Load. Middle plots: left net load with 10% wind penetration, right net load with 20% wind penetration. Down: left net load with 30% wind penetration, right net load with 40% wind penetration.

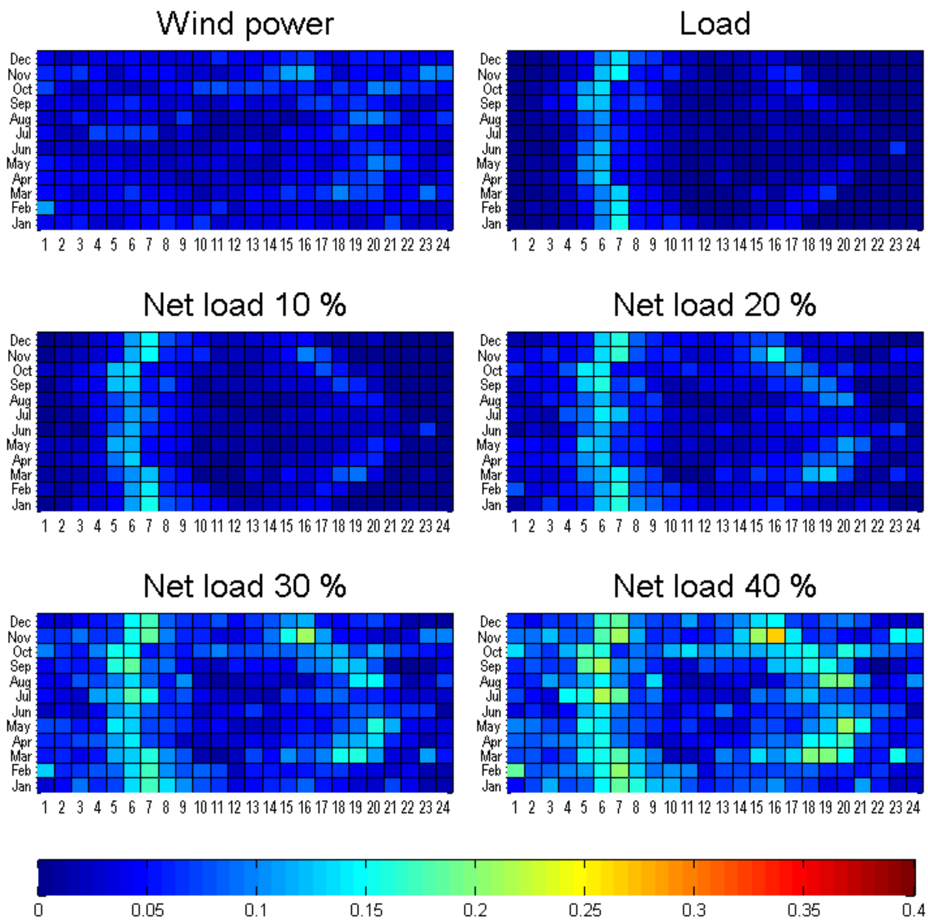

Figure B18. Timing of largest up-ramps in Denmark 2010.

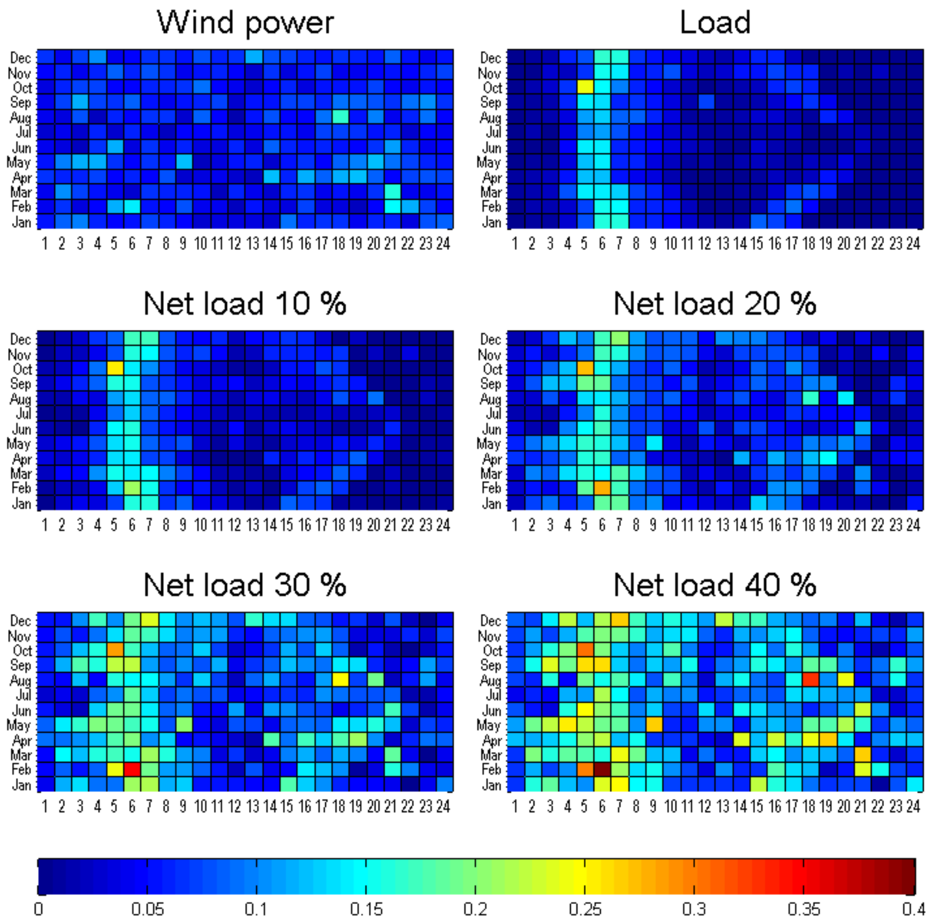

Figure B19. Timing of largest up-ramps in Finland with year 2009 data.

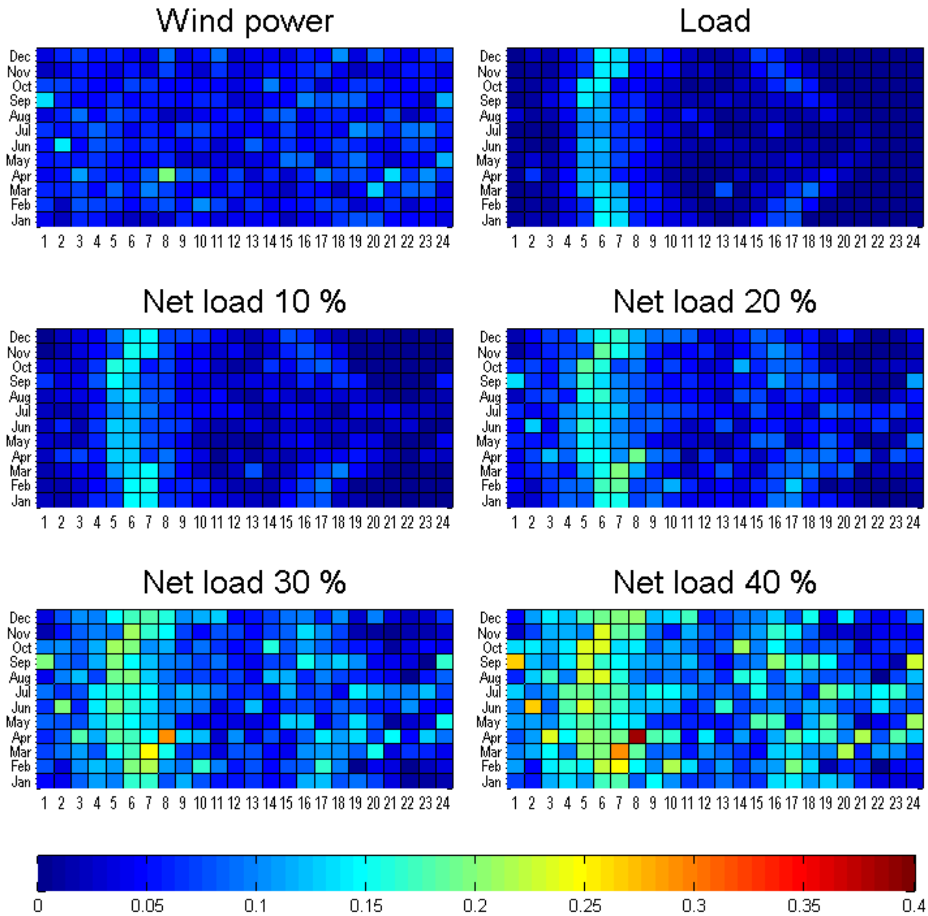

Figure B20. Timing of largest up-ramps in Finland 2010.

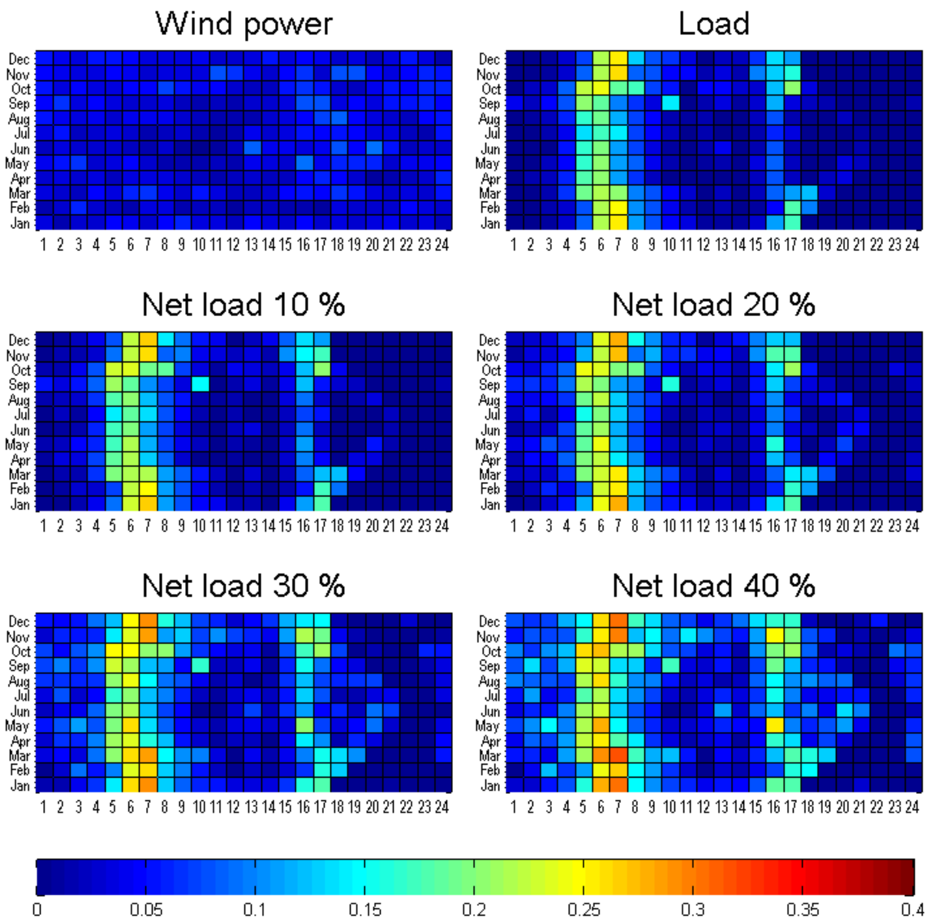

Figure B21. Timing of largest up-ramps in Sweden 2009.

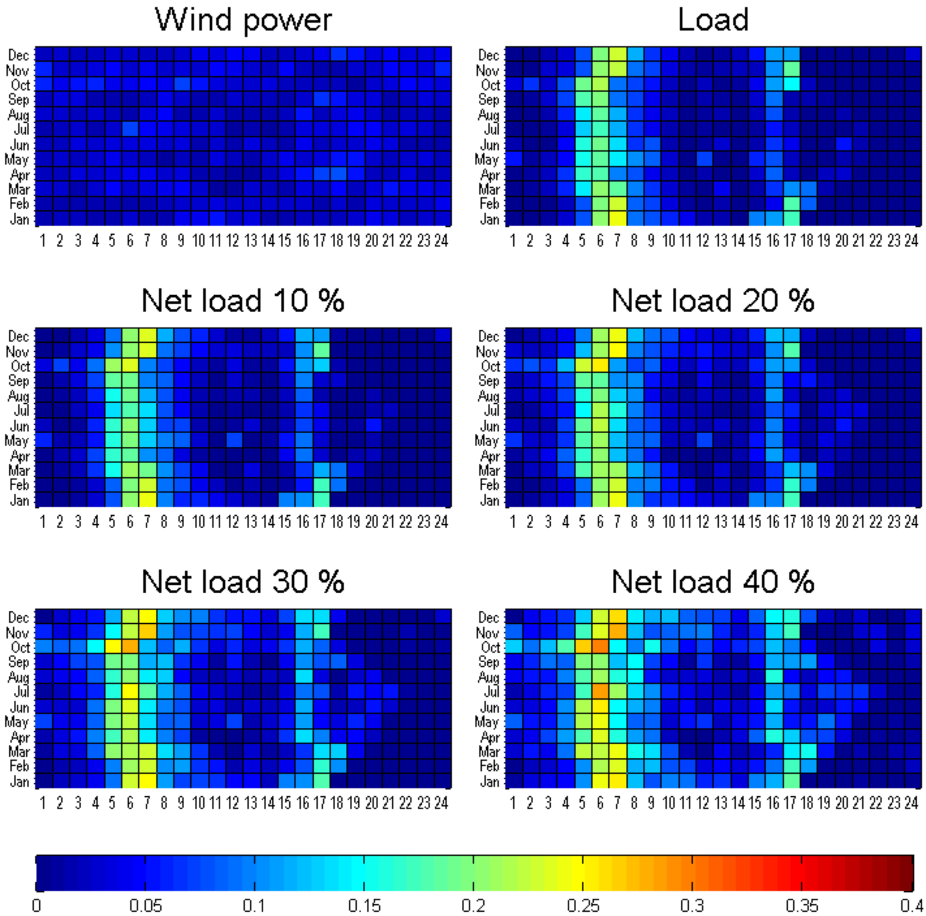

Figure B22. Timing of largest up-ramps in Sweden 2010.

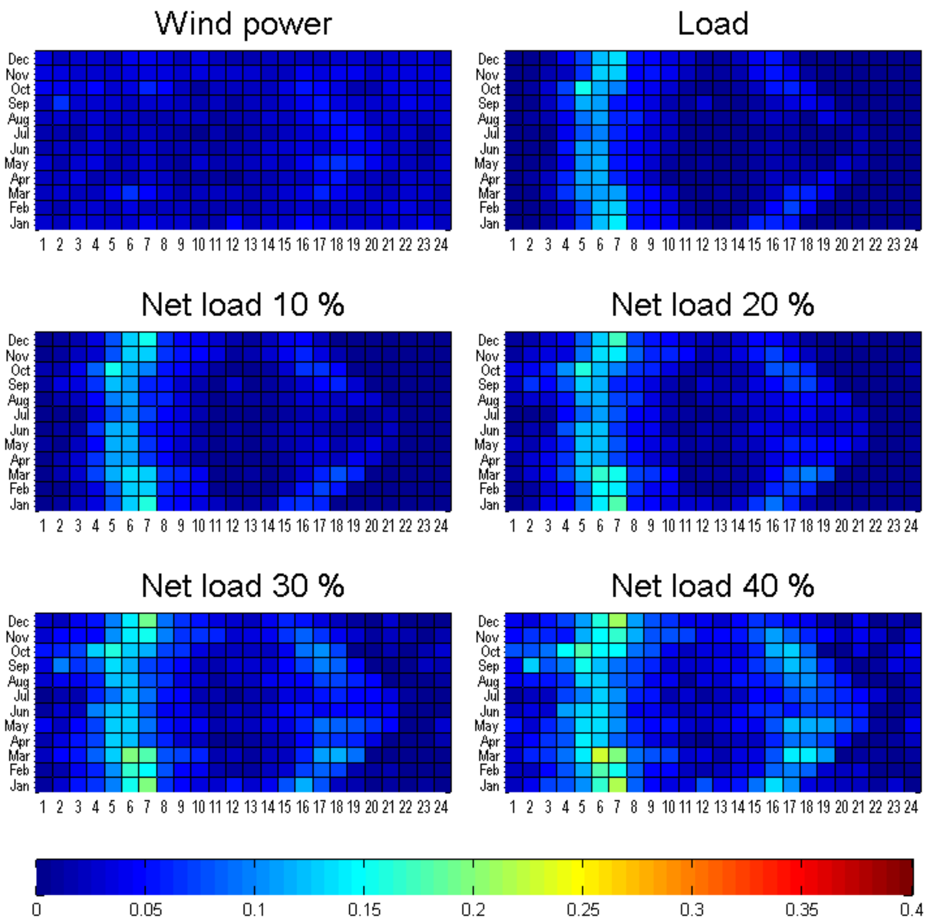

Figure B23. Timing of largest up-ramps in Nordic countries 2009.

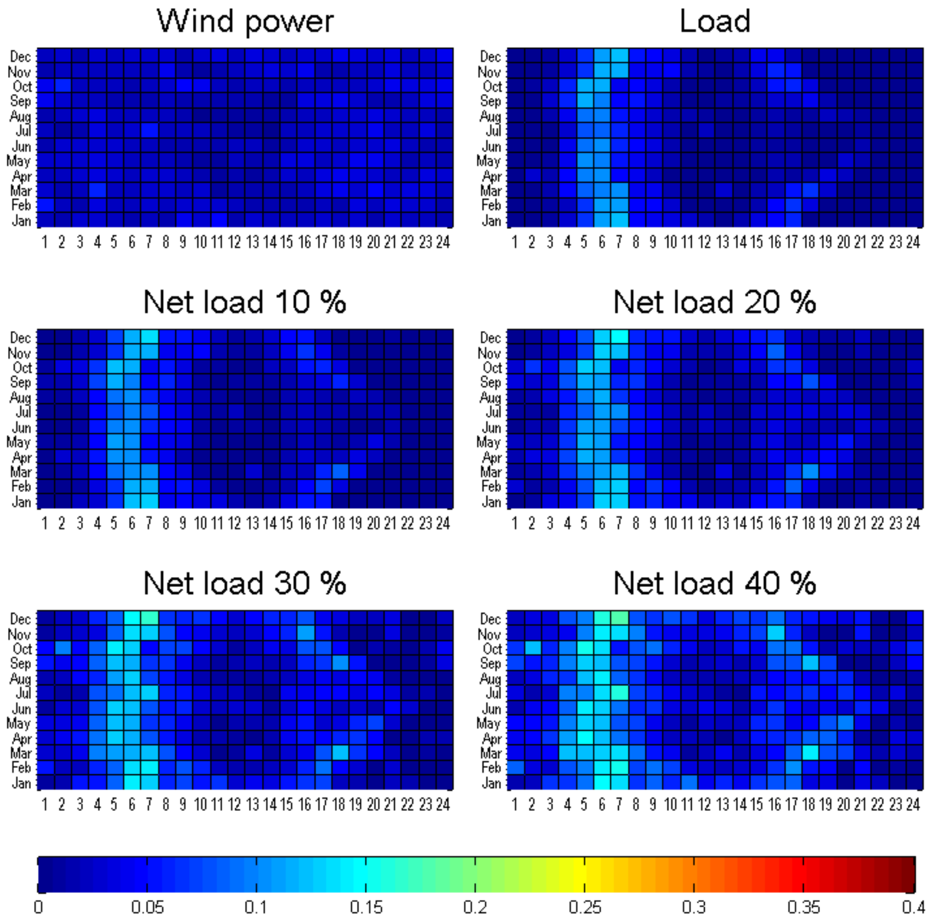

Figure B24. Timing of largest up-ramps in Nordic countries 2010.

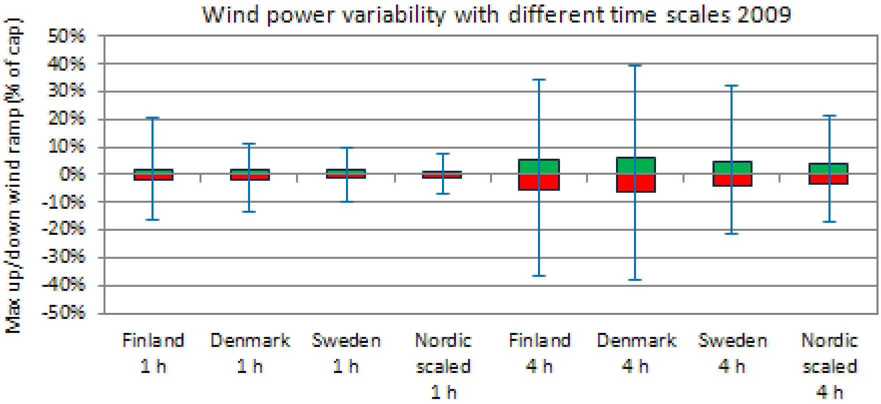

Figure B25. Average 1 hour and 4 hour wind power up-ramps (green bars) and down-ramps (red) during 2009. Range of variations is shown with blue error bars.

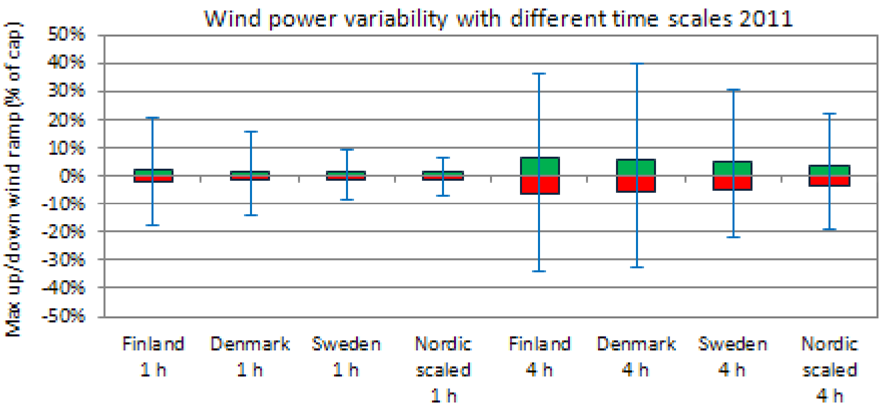

Figure B26. Average 1 hour and 4 hour wind power up-ramps (green bars) and down-ramps (red) during 2011. Range of variations is shown with blue error bars.

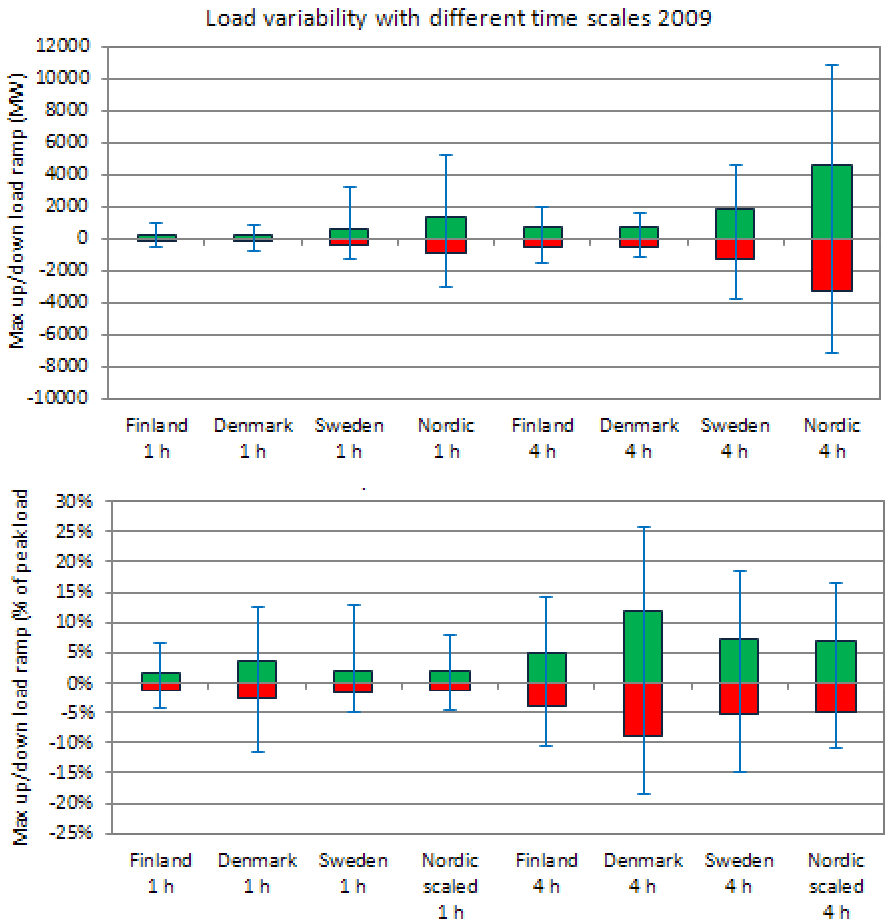

Figure B27. Average 1 hour and 4 hour load up-ramps (green bars) and down-ramps (red) during 2009. Range of variations is shown with blue error bars. Upper graph shows absolute MW values and lower graph relative to peak load.

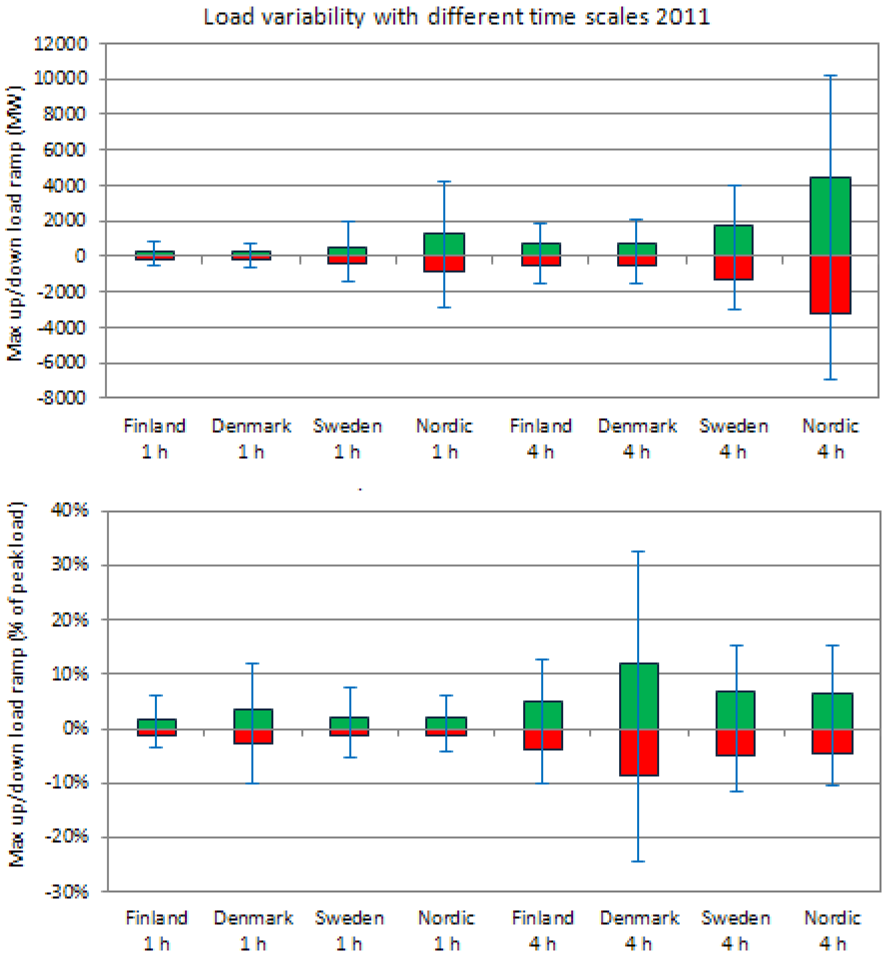

Figure B28. Average 1 hour and 4 hour load up-ramps (green bars) and down-ramps (red) during 2011. Range of variations is shown with blue error bars. Upper graph shows absolute MW values and lower graph relative to peak load.

Appendix C: Consumption data correction

Denmark
16.9.2009 14–15 DK1 production changed from 442 to 2462 MW
8.10.2009 23:00 – 9.10.2009 23:00 time series copied from 15.10.2009 23:00 – 16.10.2009 23:00
25.10.2009 02:00–03:00 hour interpolated due to wintertime
25.5.2010 8:00–10:00 5910 and 5609 MW changed to 4669 and 4659 MW
6.7.2010 10:00–11:00 5645 MW changed to 4681.5 MW
21.8.2010 1:00–2:00 1044 MW changed to 2571 MW
31.10.2010 03:00–04:00 hour interpolated due to wintertime
21.1.2011 23:00–24:00 3180 MW changed to 3846 MW
10.3.2011 03:00–04:00 2640 MW changed to 3228 MW (peak removed from 1 h variation)
11.3.2011 0:00–1:00 3301 MW changed to 3477 MW (peak removed from 1 h variation)
18.3.2011 0:00–1:00 2895 MW changed to 3565 MW
29.3.2011 22:00–23:00 3340 MW changed to 3708 MW (peak removed from 1 h variation)
1.5.2011 23:00 – 16.5.2011 9:00 time series copied from 16.5. 23:00 – 31.5. 9:00
18.6.2011 23:00–24:00 1708 MW changed to 2677 MW
21.6.2011 23:00 – 22.6.2011 01:00 2 hours interpolated (peak removed from 1 h variation)
26.9.2011 15:00–19:00 data copied from 27.9.2011 15:00–19:00 (peak removed from 1 h variation)
30.10.2011 2:00–3:00 hour interpolated due to wintertime

Finland
25.10.2009 03:00–04:00 hour interpolated due to wintertime
28.10.2009 15:00–16:00 8668 MW changed to 10456 MW
31.10.2010 03:00–04:00 hour interpolated due to wintertime
15.9.2011 11:00–12:00 5234 MW changed to 9080.5 MW
30.10.2011 2:00–3:00 hour interpolated due to wintertime

Norway
20.7.2009 06:00–07:00 10603 MW changed to 9051 MW (peak removed from 1 h variation)
25.10.2009 01:00–02:00 11890 MW changed to 12903 MW (peak removed from 1 h variation)
25.10.2009 02:00–03:00 hour interpolated due to wintertime
31.10.2010 03:00–04:00 hour interpolated due to wintertime
30.10.2011 02:00–03:00 hour interpolated due to wintertime

Sweden
21.4.2009 02–03 missing value interpolated
29.6.2009 10–11 missing value interpolated
7.8.2009 11:00–13:00 14986 MW and 12903 MW changed to 14 018 MW and 13 425 MW
14.7.2009 10–11 missing value interpolated (12766 MW)
29.7.2009 03–04 missing value interpolated (9411 MW)
31.8.2009 12–13 missing value interpolated (15825 MW)
7.10.2009 23:00–24:00 10648 MW changed to 13080 MW
25.10.2009 03:00–04:00 hour interpolated due to wintertime
12.11.2009 11–12 missing value interpolated (20211 MW)
22.12.2009 0:00–01:00 15500 MW changed to 19673 MW
23.2.2010 21:00–22:00 14379 MW changed to 22757 MW
25.5.2010 6:00–7:00 missing value interpolated (15194.5 MW)
31.10.2010 14:00–16:00 2 missing hours interpolated
31.10.2010 03:00–04:00 hour interpolated due to wintertime
3.5.2011 6:00–7:00 missing value interpolated (17019.5 MW)
5.5.2011 5:00–6:00 missing value interpolated (15817.5 MW)
9.5.2011 23:00–24:00 missing value interpolated (12360.5 MW)
6.8.2011 8:00–9:00 missing value interpolated (11511.5 MW)
30.10.2011 2:00–3:00 hour interpolated due to wintertime

Denmark 5 min data

wind
11.1.2010 19:15 – 12.1.2010 9:30 DK2 production copied from 6.2. 19:10 – 7.2. 9:25
3.2.2010 22:40 – 4.2.2010 10:50 DK 2 production copied from 4.3. 21:55 – 5.3. 10:05
24.2.2010 19:20 DK 1 production interpolated
18.2.2010 10:00 – 19.2. 1:25 DK 2 production copied from 3.3. 1:50–17:15
28.3.2010 2:00–2:55 missing. DK 1 + DK 2 copied from 1:00–1:55. Load copied from 29.3.2010 2:00–2:55.
23.5.2010 2:40–9:00 DK 2 production copied from 28.5. 13:25–20:45
23.5.2010 9:15–9:35 DK 1 production interpolated
29.7.2010 12:40 – 2.8.2010 8:55 DK2 production copied from 24.7. 11:00 – 28.7. 7:15
23.8.2010 12:00–21:45 DK2 production copied from 11.6.2010 13:30–23:15
14.9.2010 16:15–16:25 DK2 production interpolated from 0 MW to 202 and 208 MW
5.10.2010 0:00–0:10 DK 1 and DK 2 production interpolated
5.10.2010 2:45 missing. Values interpolated.
9.10.2010 23:55 missing. Values interpolated.
19.10.2010 23:55 missing. Values interpolated.

31.10.2010 0:00–23:55 missing. DK 1 production copied from 7.2.2010 1:30–8.2.2010 1:25. DK 2 production copied from 10.10.2010 0:45 – 11.10.2010 0:40. Load copied from 17.10.2010.
9.12.2010 10:15 missing. Values interpolated.

load
1.4.2010 10:05–10:45 DK2 copied from 2.4.2010
1.4.2010 11:30 DK 2 value interpolated.
1.4.2010 11:40 DK 2 value interpolated.
9.4.2010 21:40 DK 1 value interpolated.
21.4.2010 22:55–0:10 DK 2 copied from 22.4.2010

22.4.2010 0:35 DK 2 value interpolated
28.4.2010 17:10–17:20 DK2 values interpolated.
10.5.2010 9:50–10:00 DK2 values interpolated.
10.6.2010 11:15–11:35 Values copied from 9.6.2010
11.6.2010 22:05–22:15 DK1 interpolated
15.6.2010 15:10–15:25 DK 1 values interpolated
27.6.2010 5:35 DK 2 value interpolated
30.6.2010 17:35–18:35 DK 2 values copied from 1.7.2010
2.8.2010 6:45 DK 2 interpolated
2.8.2010 8:55–9:00 DK 2 interpolated
23.8.2010 16:30–21:45 DK2 values copied from 20.8.2010
8.9.2010 14:30–15:05 DK 2 values copied from 13:55–14:30.
14.9.2010 16:15–16:25 DK 2 values interpolated
30.9.2010 20:00 DK 2 value interpolated
5.10.2010 2:45 values interpolated
5.10.2010 copied from 11.10.2010
13.10.2010 17:00 and 17:10 DK 1 values interpolated
14.10.2010 12:55–13:10 DK 1 values interpolated
11.11.2010 15:10 DK 1 value interpolated
25.11.2010 13:35 DK 1 value interpolated
25.11.2010 19:05–19:20 DK 2 values interpolated
25.11.2010 14:50–15:20 DK 1 values interpolated
9.12.2010 8:50 DK 1 value interpolated.
9.12.2010 10:15 values interpolated.

Series title and number
VTT Technology 96

Title	**Wind and load variability in the Nordic countries**
Author(s)	Hannele Holttinen, Simo Rissanen, Xiaoli Larsen & Anne Line Løvholm
Abstract	This publication analysed the variability of wind production and load in Denmark, Finland, Sweden, and the Nordic region as a whole, based on real data measured from large-scale wind power during 2009–2011. The Nordic-wide wind power time series was scaled up such that Sweden had same amount of wind power production than Denmark, and Finland and Norway only 50% of the wind power production in Denmark. Wind power production in Denmark and Sweden is somewhat correlated (coefficient 0.7) but less correlation is found between the other countries. The variations from one hour to the next are only weakly correlated between all countries, even between Denmark and Sweden. Largest variations occur when the production is approximately 30–70% of installed capacity and variability is low during periods of light winds. The variability in shorter time scales was less than the hourly variations. During the three years analysed in this publication there were few storm incidents and they did not produce dramatic wind power ramps in the Nordic region. Wind and load variations are not correlated between the countries, which is beneficial from the viewpoint of wind integration. The smoothing effect is shown as reduction of variability from a single country to Nordic-wide wind power. The impact of wind power on the variability that the system experiences is evaluated by analysing the variability of net load with different wind power penetration levels. The Nordic-wide wind power production increases the highest hourly ramps by 2.4% (up) and -3.6% (down) of installed wind power capacity when there is 20% wind power penetration and by 2.7% (up) and -4.7% (down) for 30% wind penetration. These results assess the impacts of variability only. The next step will be assessing the uncertainty from forecast errors. The timing of ramp events, and occurrence of high-wind and low-load are studied. With current wind penetration, low production levels (2–5% of installed wind power) can occur in a single country during peak loads, but in the Nordic region the production during peak loads does not fall to such low levels (minimum 14% during 10 highest peaks). The low wind periods occur primarily in the summertime. The longest period with wind generation below 5% of installed capacity in the wintertime for three years of data was 30 hours. The maximum penetration level, during one hour, can reach high levels already with a 20% (yearly) penetration level. At 30% penetration on yearly level the maximum hourly wind share was 160% in Denmark, 130–140% in Finland and Sweden and 110% in Nordic region.
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Julkaisun sarja ja numero
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Nimeke	**Tuulivoiman ja sähkönkulutuksen vaihtelut Pohjoismaissa**
Tekijä(t)	Hannele Holttinen, Simo Rissanen, Xiaoli Larsen & Anne Line Løvholm
Tiivistelmä	Tässä julkaisussa tarkastellaan tuulivoimatuotannon ja sähkönkulutuksen vaihteluita Suomessa, Tanskassa, Ruotsissa ja koko Pohjoismaiden alueella. Analyysit perustuvat pääosin mitattuihin tuulivoiman ja sähkönkulutuksen tuntiaikasarjoihin. Pohjoismainen tuulivoiman tuotantoaikasarja skaalattiin eri tuulivoimaosuuksille siten, että Ruotsissa ja Tanskassa oli sama määrä tuulivoimatuotantoa ja Suomessa ja Norjassa vain puolet tästä. Tuulivoimatuotanto Tanskassa ja Ruotsissa korreloi jonkin verran (korrelaatiokerroin 0,7), mutta muiden maiden tuulivoimatuotanto korreloi vähemmän. Tuulivoiman tuntivaihtelut korreloivat vain heikosti eri maiden välillä. Suurimmat vaihtelut syntyvät, kun tuotanto on noin 30–70 % asennetusta kapasiteetista. 15 minuutin vaihtelut ovat pienempiä kuin tuntivaihtelut. Analysoidussa kolmen vuoden datassa oli vain muutama myrsky, eikä niistä aiheutunut Pohjoismaiden tasolla suuria ramppeja tuotantoon. Tuulivoiman ja sähkönkulutuksen vaihtelut eivät korreloi, mikä helpottaa tuulivoiman integrointia järjestelmään. Tuulivoimavaihteluissa näkyy selvä tasaantuminen, kun tarkastellaan alueellista, yhden maan laajuista ja Pohjoismaiden laajuista tuulivoimatuotantoa. Tuulivoimavaihteluiden vaikutuksia sähköjärjestelmään on arvioitu tarkastelemalla nettokuormaa – sähkönkulutus miinus tuulivoimatuotanto – eri tuulivoimaosuuksilla. Pohjoismaiden tasolla suurimmat tuntivaihtelut lisääntyvät 2,4 % (ylös) ja –3,6 % (alas) suhteessa installoituun tuulivoimakapasiteettiin, kun tuulivoimaa on 20 % sähkönkulutuksesta. Tuulivoimaosuudella 30 % vaihtelut lisääntyvät 2,7 % (ylös) ja –4,7 % (alas). Kun tarkastellaan vaihteluiden lisääntymistä pelkästään Suomen alueella, tuulivoiman vaikutus on huomattavasti suurempi, 4,6 % (ylös) ja –7,6 % (alas). Tämä tarkastelu ottaa huomioon vain tuntivaihtelut, ja jatkotyön aiheena on selvittää tuulivoiman ennusvirheiden vaikutukset säätöön. Tuulivoiman saatavuus huippukuorman aikaan voi joinakin vuosina olla pientä, 2–5 % yhden maan alueella. Pohjoismaiden alueella pienin tuulivoimateho kymmenen suurimman kuorman aikana oli 14 % asennetusta kapasiteetista, kolmen vuoden datasta. Pisimmät pienen tuotannon ajanjaksot osuivat kesälle (pisin 70 tuntia alle 5 % kapasiteetista), talviaikaan pisin oli 30 tuntia. Tuulivoimaosuus yhden tunnin aikana voi ylittää 100 % siinä vaiheessa, kun tuulivoimalla tuotetaan 20 % vuotuisesta sähköntarpeesta. Kun tuulivoimaosuus on 30 % vuotuisesta tarpeesta, suurin tunnittainen tuulivoimaosuus oli 160 % Tanskassa, 130–140 % Suomessa ja Ruotsissa ja 110 % koko Pohjoismaiden alueella. Aikasarjoista on myös analysoitu suurimpien vaihteluiden ajoittumista.
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Toimeksiantajat	
Avainsanat	Wind variability, wind integration, smoothing effect, ramping
Julkaisija	VTT PL 1000, 02044 VTT, Puh. 020 722 111

Wind and load variability in the Nordic countries

This publication analysed the variability of wind production and load in Denmark, Finland, Sweden, and the Nordic region as a whole, based on real data measured from large-scale wind power. The increased variability of net load (the load minus wind power) is presented for different wind penetration levels, and analyses on timing of ramps as well as wind power during high and low load situations are presented.

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