Variability and Smoothing Effect of Wind Power Production Compared to Load Variability in the Nordic Countries

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Abstract—**This paper analyses the variability of load, wind power production and their combination in the Nordic countries during 2009-11, based on real data measured from large-scale wind power. The results show that 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 sees is depicted by analysing the variability of net load with different wind power penetration levels. The timing of ramps, 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 so low levels (minimum 14 % during 10 highest peaks).**

Index Terms – Wind integration, reserve allocation, power system operations, wind power

I. Introduction

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, when allocating sufficient operating reserves and estimating the uncertainty of the production during different conditions. This report summarises the results of a study on the variability of large scale wind power production and load in Denmark, Finland, Sweden, and the Nordic region as a whole during 2009-11 [1].

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 to the power system. For this reason the focus is on system implications within a single country and the Nordic region with different wind penetration levels.

II. Data

The analysis is based on hourly production data from a real, system wide distributed fleet of wind farms in Denmark, Sweden and Finland. It covers hundreds of sites in Sweden (Svenska Kraftnät website) and Denmark (Energinet.dk website), and 30 sites in Finland (provided by Finnish Energy Industries). 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). The modelled wind power production was validated with production measurement from 2 existing wind farms.

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

Hourly load data for each country was obtained from Nord Pool Spot. The data covers also West Denmark, which belongs to a different synchronous power system (Central Europe) than the other Nordic countries and East Denmark (Nordic system), but has access on the balancing market (TSO market for bids activated in 10 minutes, called Regulating Power Market) of the Nordic countries over the HVDC links.

Since the Nordic wind power production is currently heavily dominated by Denmark (Table 1) the Swedish production has been up-scaled to the same level, and the production of Finland and Norway to half of Denmark. Currently, approximately 28 % of the electricity consumption was 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 % (6 % from scaled data).

TABLE I. WIND POWER PRODUCTION AND CONSUMPTION TIME SERIES AS INPUT TO THE STUDY (YEAR 2011). THE NORDIC FIGURES FOR WIND ARE SCALED, ASSUMING SAME AMOUNT OF WIND IN SWEDEN AS IN DENMARK, AND HALF OF THAT IN BOTH NORWAY AND FINLAND.

	DK	FI	SE	Nordic
Wind:				
Capacity, MW	3871	193	2769	10737
Production, TWh	7.9	0.5	6.2	23.7
Average, % of rated	23.7 %	28.1 %	29.5 %	26.8 %
Standard deviation, %	20.1 %	21.4 %	18.7 %	15.7 %
Consumption:				
Total, TWh	34.9	81.9	139.2	379
Peak load, MW	6270	14803	26174	67335

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.

Diurnal effect of wind power is especially clear in Denmark where the production is at the highest level in the afternoons from 1 to 5 pm. During summer and spring the diurnal variation affects Finland and Sweden as well. However, in the wintertime it is almost non-existent in all Nordic countries.

According to wind production index information, years 2009-10 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 loads in Sweden, Norway and Finland are higher during winter months than in summer, and depend on the outside temperature due to electrical heating (Figure 1).
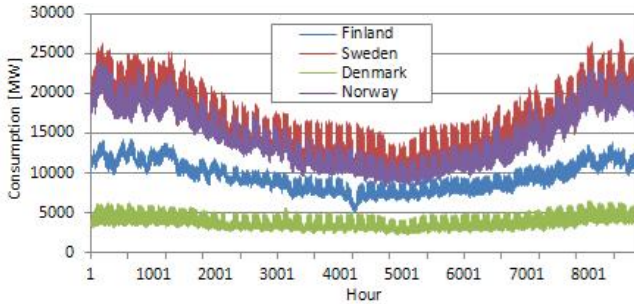

Figure 1.   Hourly time series of electricity consumption in the Nordic countries in 2010.

Load has a clear diurnal and weekly pattern – low at nights and high at daytime, and lower during Saturdays and Sundays. 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. 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 of the day. This makes the daily variations in Denmark almost as high as in the other countries despite that the total consumption is lower.

III.   SMOOTHING EFFECT OF WIND POWER PRODUCTION TIME SERIES

The smoothing effect from distributing wind power production to a larger area is apparent from the duration curves of hourly production levels (Figure 2): within a large area the maximum production will never reach 100 % of installed capacity and occurrences of 0 % production will be rarer.
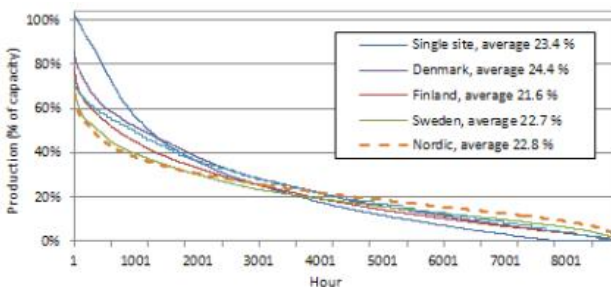

Figure 2.   Smoothing effect when increasing the area size from a single site to a whole country and further to Nordic wide wind power, year 2010.

Maximum production is approximately 75 % for the Nordic region. However, 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 %, Figure 2).

The same effect is seen when comparing the standard deviation of hourly production, which is 21 % for Denmark, 19 % in Sweden and 16 % the Nordic region (Table 1).

A.   *Correlation between the Nordic countries*

The correlation coefficients of hourly wind power production between the countries show that the production in Denmark and Sweden are correlated (Table 2). This is explained by noting that a large share of the Swedish capacity is located along the south coast, close to Denmark. Finland, Sweden and Norway show a weaker correlation between each other, and the correlation between Finland and Denmark, and Norway and Denmark is almost non-existent. However, the correlations calculated for Finland and Norway vary significantly on yearly basis, especially for 2011 that was more windy than average.

TABLE II.   CORRELATION COEFFICIENTS OF HOURLY PRODUCTION

	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

IV.   SMOOTHING EFFECT IN WIND POWER VARIABILITY TIME SERIES

The production during consecutive hours was analysed in order to find out to what extent the production varies hourly. Due to wider distribution of sites, the variations in both up or down directions are smaller in Sweden than in Finland or Denmark (Figure 3). 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.
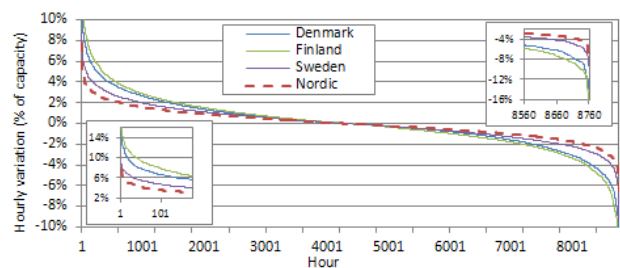

Figure 3.   Duration curves of hourly variation of production in 2010. Finland has been scaled to 50 % and Sweden to 100 % of Denmark.

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. In this light, it is rare that variations in the same direction will occur during the same hour in different countries.

A. Variability with different 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 a 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 (Figure 4).
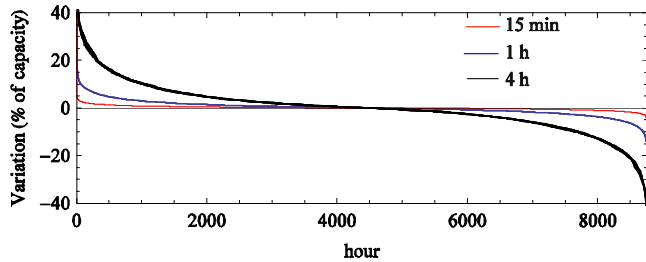

Figure 4.   Duration curves of 15 minute, 1 hour and 4 hour variation in Western Denmark during 2009.

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 5).
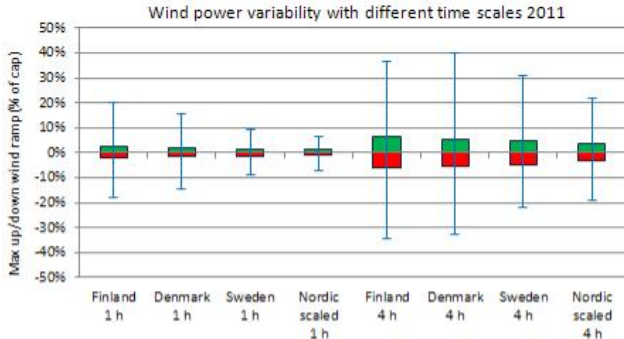

Figure 5.   Average 1 hour and 4 hour wind power up-ramps (green bars) and down-ramps (red) during 2010. Range of variations is shown with blue error bars.

V. VARIABILITY OF LOAD TIME SERIES

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.

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

TABLE III.   CORRELATION OF HOURLY 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

The load can vary 2-3 times as much in 4 hours than in 1 hour (Figure 6). However, load changes can be predicted more accurately than wind power production.
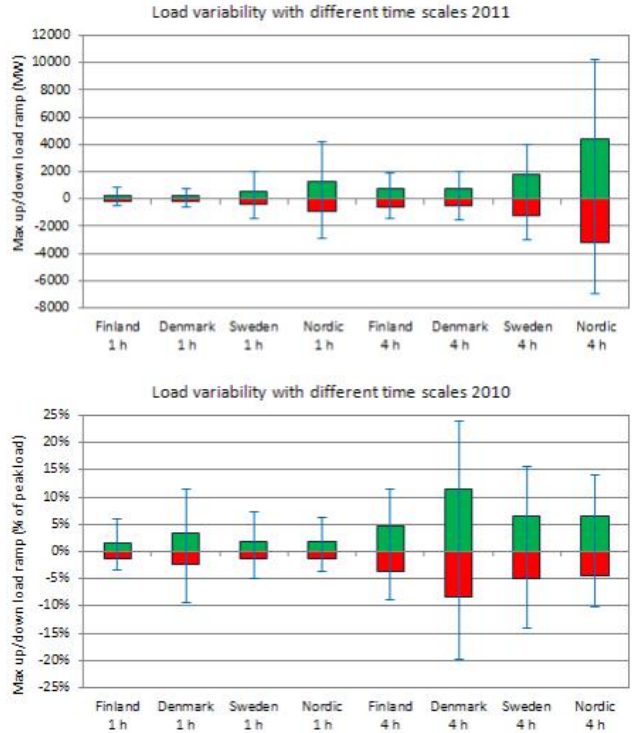

Figure 6.   Average 1 hour and 4 hour load up-ramps (green bars) and down-ramps (red) during 2010. Range of variations is shown with blue error bars. Upper graph shows absolute MW values and lower graph relative to peak load.

VI. COMBINED VARIABILITY OF WIND AND LOAD

A. Correlation between the Nordic countries

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 would be 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 IV). 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 IV). Therefore it is not probable that the largest variations would occur simultaneously for both of them.

TABLE IV. 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

B. Selecting statistical parameter for analyzing impact of wind power

Since measured time series data might include erroneous points, absolute maximum values may be misleading, especially when they only occur a few times per year. Therefore it is more reasonable to derive appropriate confidence intervals from the distribution of the hourly variations. The distributions are asymmetrical with more pronounced up-ramps.

TABLE V. Hourly variability of load (relative to peak load) and wind power production (relative to installed capacity), year 2010.

	FI	DK	SE	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				
max up-down	18,1 % -22,5 %	18,4 % -9,4 %	11,5 % -9,4 %	7.8 % -7.3 %
±3sigma	8,4 %	7,4 %	5,3 %	4.1 %
99 % exceedance	8,2 % -7,7 %	6,8 % -6,4 %	4,9 % -4,3 %	3.7 % -3.4 %
99,9 % exceedance	13 % -11,7 %	11,5 % -11,3 %	7,3 % -6,5 %	5.5 % -4.9 %

For load variations, using 3 times standard deviation (3sigma) 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 3sigma. The 99 % exceedance level covers approximately 80 % of the maximum variation, and the 99.9 % exceedance level approximately 90 % (Table V).

For wind power production, both 3sigma and 99 % exceedance level lead to substantially smaller values than the realized maximum variations. This shows that wind power variability does not follow a normal distribution but

can have larger extreme variations, as has been reported from previous work as well [2].

C. Implications to operating reserve requirements

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 (Table VII) 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 to note 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).

TABLE VI. Magnitudes of load 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 %

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 VI both as MW numbers and as relative to installed wind capacity.

D. Timing of largest load and wind production ramps

For all Nordic countries, largest load ramps upward occur from 6 to 9 in the morning and largest ramps downward around midnight. In Denmark there is also a considerable up-ramp from 17 to 18. For wind production in all countries, upward and downward ramps cancel out each other in the long run, making the average ramp approximately zero. However, maximum ramps in both directions can still be large and occasionally happen in the opposite direction compared to load ramps. For example, up-ramps in Finland and Sweden mostly occurred during the day when load ramping is not so severe, but the largest up-ramps occurred in the evening and midnight hours.

Wind production variability is more dependent on the initial current production level than the time of day. The largest variations occur when the production is approximately 30-70 % of installed capacity, since any change in the wind speed is magnified by the power curve when the turbines are operating within this region. In contrast, the variability of production is low at small winds and also at high winds when the turbines operate at rated power (Figure 10).
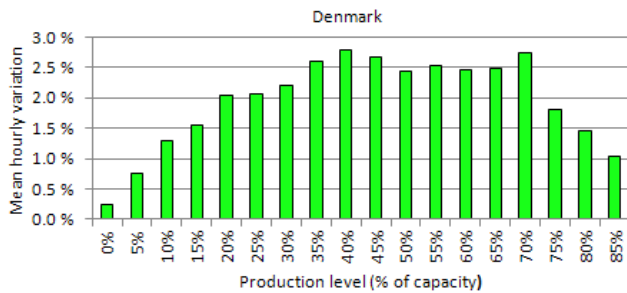

Figure 7.   Average absolute hourly variation with different production levels in Denmark, year 2010.
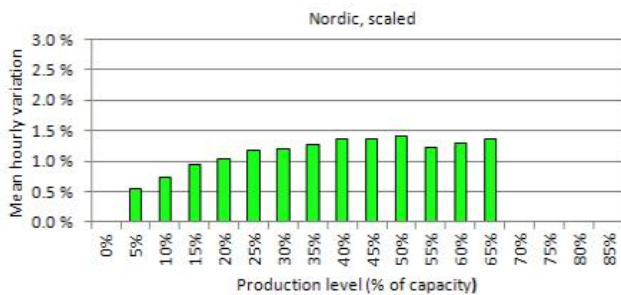

Figure 8.   Average absolute hourly variation with different production levels in Nordic countries, year 2010.

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 (Figure 9 and 10). Again, this impact is not as strong in the Nordic level as for one country.
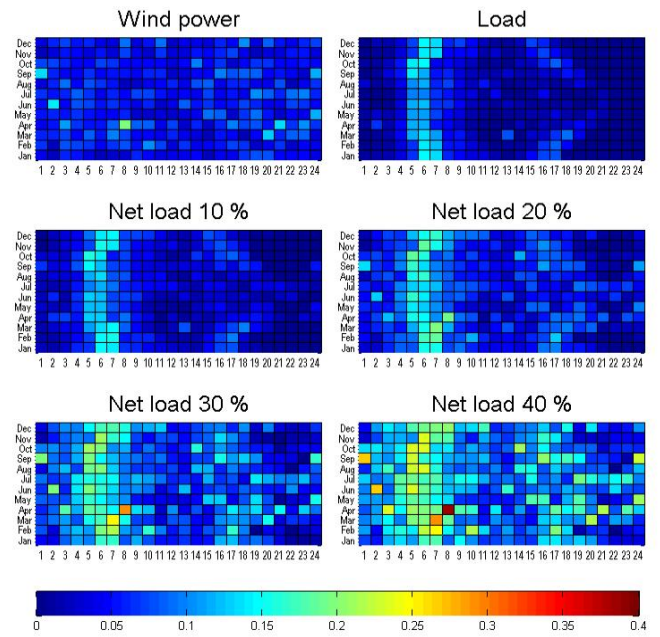

Figure 9.   Timing of largest up-ramps in Finland with different wind penetration levels, year 2011. Magnitudes of the ramps, relative to the average load, are depicted in colours (highest ramps in red). 24 hours of the day are on the x-axis and 12 months of the year on the y-axis in plots.
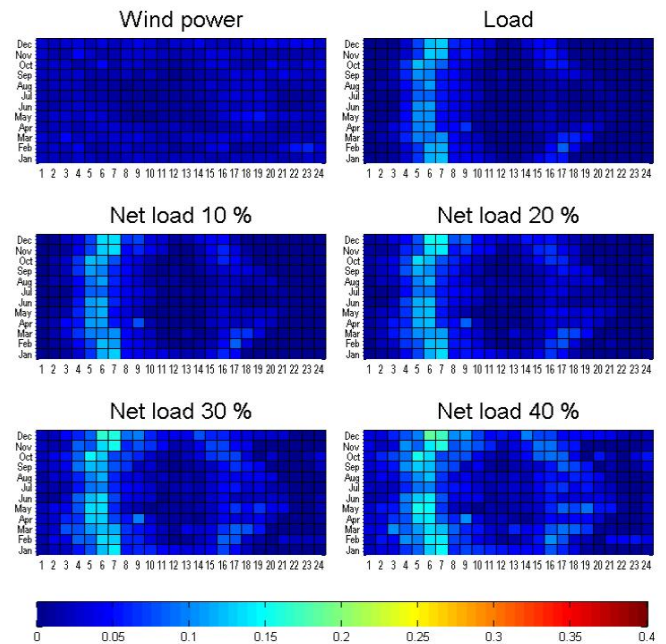

Figure 10. Timing of largest up-ramps in the Nordic region with different penetration levels, year 2011. Magnitudes of the ramps, relative to the average load, are depicted in colours (highest ramps in red).

VII.   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 [3], [4]. 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.

A. High production during low load

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 % (Figure 11). There is not so much difference in the three years of analysis for Nordic data as for single countries.
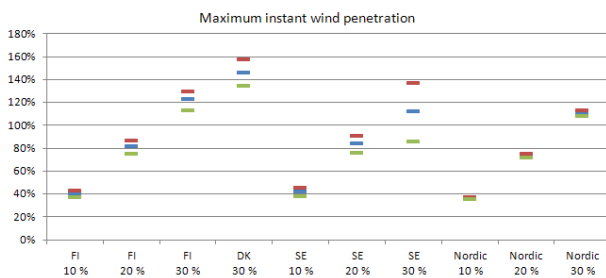

Figure 11. Maximum instant wind penetration (wind share of load during one hour) reached during 2009-11 with different yearly wind shares.

B. Low production during peak load

In the Nordic countries peak loads occur during the wintertime, and are directly dependent on the outside temperature in Finland, Sweden and Norway. Data from the three year period already shows how the figures can differ substantially on yearly basis (Figure 12). One of the years (but different one for each country) showed a very low wind power production level during peak load, and two of the years in each country had one low production occurrence during 10 highest peaks.
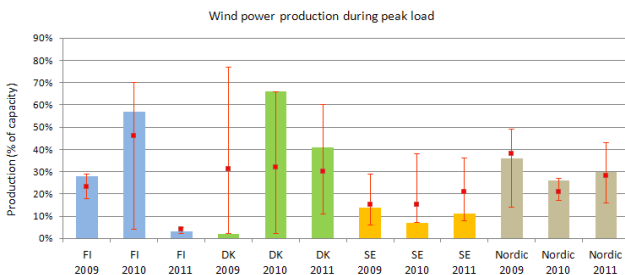

Figure 12. Wind power production during peak load. Each bar shows the production, as % of installed capacity, during the single highest peak load hour. Minimum, maximum and average production during 10 highest peaks are shown with red error bars.

C. Length of low and high wind periods

The amount of low (Table VII) and high wind (Table VIII) periods show also considerable smoothing effect from single countries to Nordic wide data. For example, during 2009-11

Nordic data had only 4 occurrences of low wind periods that lasted for 24 to 47 hours and no occurrences of 70 % production lasting over 24 hours.

TABLE VII. AMOUNT OF PERIODS WHEN WIND POWER PRODUCTION WAS LESS THAN 5 % OF INSTALLED CAPACITY, YEARS 2009-2011.

length	FI	DK	SE	Nordic scaled
24-47 h	17	36	7	4
48-71 h	3	9	2	1
72-95 h	3	2	1	0
96-120 h	1	0	0	0
Max 2009	98 h	64 h	82 h	70 h
Max 2010	72 h	63 h	24 h	15 h
Max 2011	79 h	80 h	35 h	41 h

TABLE VIII. LENGTH OF PERIODS WHEN WIND POWER PRODUCTION WAS OVER 70 % OF INSTALLED CAPACITY, YEARS 2009-2011.

	FI	DK	SE	Nordic scaled
periods > 24 h	3	5	0	0
Max 2009	16 h	33 h	18 h	21 h
Max 2010	25 h	28 h	6 h	0 h
Max 2011	28 h	32 h	19 h	10 h

VIII. CONCLUSIONS

Analysis on the variability of the Nordic wind power production show that the hourly variations decrease significantly when measured over a larger area with more distributed wind power, such as a single country or the Nordic region as a whole. Correlations of production variations between the countries are weak or non-existent. The results can be used to derive estimates on the amount that the required reserve power needs to be increased to cover extreme situations during a year, and on how the daily pattern of net load ramps will change, with varying wind penetration levels.

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