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Variability of load and net load in case of large scale distributed wind power

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***Abstract*—Large scale wind power production and its variability is one of the major inputs to wind integration studies. This paper analyses measured data from large scale wind power production. Comparisons of variability are made across several variables: time scale (10-60 minute ramp rates), number of wind farms, and simulated vs. modeled data. Ramp rates for Wind power production, Load (total system load) and Net load (load minus wind power production) demonstrate how wind power increases the net load variability. Wind power will also change the timing of daily ramps.**

***Index Terms*—ramp rates, reserves, wind power, variability**

I. Introduction

WIND turbines experience changes in power generation due to wind turbulence and gusts. These are not correlated over longer distances and are therefore smoothed out with increasing area and number of turbines [1]. What is of greater concern for the power system is the variation due to large scale weather systems (synoptic scale weather systems) moving over wind power production areas and affecting the large scale wind power production.

There is lot of literature on the variation of wind speed or wind power production at individual sites, but what is of relevance for this paper is the variation in large-scale wind power (previously in [1]-[4]). In comparison to those, this article uses recent data from multiple countries.

When wind power is added to a power system, the system has to integrate the variation and prediction errors inherent in the wind power generation. However, electricity demand already has variation and prediction errors and hence wind power will add to the existing variability and prediction errors. It is the combined variation of wind and demand that matters for the power system operation, the net load.

The increase in extreme variability can be used to estimate the adequacy of operating reserve capacity [5]. The size of net load forecast errors will also influence the need for slower reserves (tertiary reserves). Prediction errors and the associated reserves are not within the scope of this article (see [6] for more). We concentrate in analysing the variation within the scheduling period.

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The results in this article are based on several sets of synchronised data from several wind power plants or wind speed measurements that cover the analysed region in sufficient density to yield robust results on the variation of large-scale wind power. Results and analyses are presented for wind power and net load variations. The paper will present comparison between the datasets, looking at smoothing effect due to area size and number or data points as well as due to time scales (hourly and sub-hourly data). Wind power generation also varies inter-annually [7], and this can have impact on the variability as well – as the variability is usually greatest at higher winds, also the high wind year variability is higher than that of a low wind year. The impact of different penetration levels to variability of net load is studied – can it be said that there is a threshold wind penetration level below which the variability of wind is absorbed by the variability of load?

In Section 2 the methods and data used in this paper for assessing and comparing variability are described. In Section 3 the results for wind power production are presented, in section 4 the results for the net load are presented. Finally, Section 5 concludes.

II. Data and methods used

Variability can be assessed with several different yardsticks. A comprehensive evaluation would require the use of several different timescales and the presentation of frequency distributions of variations. Statistical information can also be used. This article shows figures of frequency distribution of ramp rates in the form of duration curves as well as wind power penetration dependant net load ramp exceedence levels (0.1 % and 1%).

Variability of wind power depends also on the applied spatial scale. One metric for the spatial dimension is the diameter of the analysed area, or dimensions for a rectangular area. This is relatively easy to calculate and understand. However, a more accurate method would take actual dispersion into account. Wind power can be heavily concentrated within the analysed area, which would decrease the actual smoothing. A better metric would require data of the wind farm locations.

Wind power variability also depends on the time of the year and time of the day. As this is meaningful for power systems, the variation is also presented using a so called 'magic carpet' plot, which informs when steep ramps take place.

Best data for wind power variation comes from operating wind farms. The future variability can differ somewhat to what is experienced by current turbines: larger turbines reach higher more stable winds, the relation between rotor swept area and generator size are changing, and new wind

regimes like offshore are exploited. What is even more crucial is that historical data may have too few turbines or too little geographical diversity. There is a saturation effect in the smoothing of variability – if there are already tens of sites and hundreds of turbines covering a certain area, adding more turbines will not noticeably decrease the variability. If there is data from enough sites and turbines, then it should be safe to upscale the production without disturbing the representativeness of the data: at least 50 sites are needed to provide robust estimates according to [8].

A. Case Study Data

The wind production data available for the analyses comes from different sources and is listed in Table 1. Most data are from wind power plants, but we have also included some data from wind speed measurements model wind data converted to wind power to enable comparisons.

The Denmark wind and load data is from the TSO Energinet.dk. Energinet.dk has online measurements available for half of the wind capacity and the rest is calculated by online estimation. The estimation is done in 23 regions and is based on online measurements from selected wind turbines with similar properties as the non-measured.

The Finland data is from hourly measurements of most of the wind farms in Finland, covering 20-30 sites and 94-104 turbines (increasing from year start to year end) along the South and West coast and Lapland. The 10 minute data was available from 10 sites, and only covering the West coast of Finland. The load data is from the TSO Fingrid.

The German wind data is from the four German TSOs Tennet TSO GmbH, Amprion GmbH, EnBW Transportnetze AG and 50Hertz Transmission GmbH. The wind power feed-in is based on an online up-scaling algorithm using real measurements of nearly 160 spatially distributed wind farms which cover about 20 % of the total installed wind power capacity [9]. The algorithm integrates the coordinates and capacities of all wind turbines installed in Germany to represent the actual installation status. The German load data are obtained from ENTSOE.EU [10].

The simulated wind power generation data for Germany is based on the COSMO DE data set with a point to point resolution of 2.8 km provided by the German met office [11]. 1400 wind power sites (turbines or wind farms) in the data set is modeled individually, to produce a time series for 24680 MW wind power, and this was up-scaled slightly (1.07) to reach the average installed capacity in 2010. The wind to power conversion is based on a wind speed interpolation of the four surrounding COSMO data points considering surface roughness length, topography and turbine characteristics for on- and offshore facilities [12].

The Ireland data covers the period 2002 to 2010, starting from 17 active wind farms to measure the output of 126 wind farms by the end of 2010. The data is collected from energy meters at 15 minute resolution by the system operator, EirGrid, and is converted to average power. The majority of wind generation is situated on the western Atlantic coast.

The Netherlands data is from 18 wind speed measurements at 10 m height up-scaled to 90 m then extrapolated to 36 sites and converted to power [13].

The wind and load data from Portugal was obtained through the TSO REN. 47 wind power plants (60% of the wind generation, 2511 MW) have their power individually monitored and REN extrapolates the whole Portuguese wind production (195 wind parks, 4304 MW, by mid 2011) based on the remote energy counting data of the remaining 40%.

The Spanish wind and load data is from Red Eléctrica de España, REE. All wind power information is collected by the system operator REE as 10 minute mean values. Data is measured for peninsular area (excluding Canary Islands and Balearic Islands), for the wind farms representing 98.6% of installed capacity while the rest of wind power (1.4%) is estimated. As another data set, 9 wind farms (282 MW) located in the North and East of Spain are considered and compared with all Spain data.

The US wind and load data is from the Electric Reliability Council of Texas (ERCOT) and Bonneville Power Administration (BPA). The ERCOT data consists of time-stamped 1-minute (snap shot) real power output from all large wind power plants within ERCOT balancing area and the corresponding system demand from 2008, 2009 and 2010. The BPA data set consists of 5-minute (average) real power output from all wind power plants within BPA control area (3372 MW end 2010) and are available from BPA web site. For this analysis, hourly average values were computed from the 1-minute and 5-minute data.

TABLE I. DATA FOR THE CASE STUDIES

Case study	**No of sites**	**No of WTs**	**Width of area**	**Disper-sion of data**	**Time reso-lution**	**Year**
Denmark	50 % measured	>5000 WTs	300 x 300 km	very well dispersed	1 hour	2010
Finland 60 min data	30 sites	110 WTs	300 x 800 km	well dispersed	1 hour	2010
Finland 10 min data	10 sites	34 WTs	300 x 600 km	some concentration	10 min	2010
Germany	160 sites measured	~21000 WTs	600 x 900 km	very well dispersed	15 min	2010
Germany	COSMO to 1400 sites	wind speed to power	600 x 900 km	very well dispersed	1 hour	2010
Republic of Ireland	17 – 126 sites	>800 WTs	165 x 450 km	well dispersed	15 min	2002-10
The Nether-lands	18 data to 36 sites	wind speed to power	250 x 300 km	Some concentration	15 min	2004-05 (1 year)
Portugal	60 % measured	~2000 WTs	195 x 530 km	very well dispersed	15 min	2009
Spain	98 % measured	>18000 WTs	900 x 800 km	very well dispersed	10 min	2010
Spain	9 sites	374 WTs	784 km max distance	Some concentration	10 min	2007
US Texas	78 sites	6253	750 x 780 km	well dispersed	1 hour	2008-10
US BPA		>3000 WTs	500 x 200 km	well dispersed	1 hour	2007-10

III. Variability of Large Scale, Distributed Wind Power

Examples from existing wind power production data from several countries/areas with 10-15 min measured data have been processed to compare the variability – the difference in power level between consecutive time steps. All data in MW, for different penetration levels in the country cases, is first up-scaled to present 20 % penetration level (from yearly electricity consumption, the load). The variability is then presented in relation to the average load in the country, to give a common point of comparison.

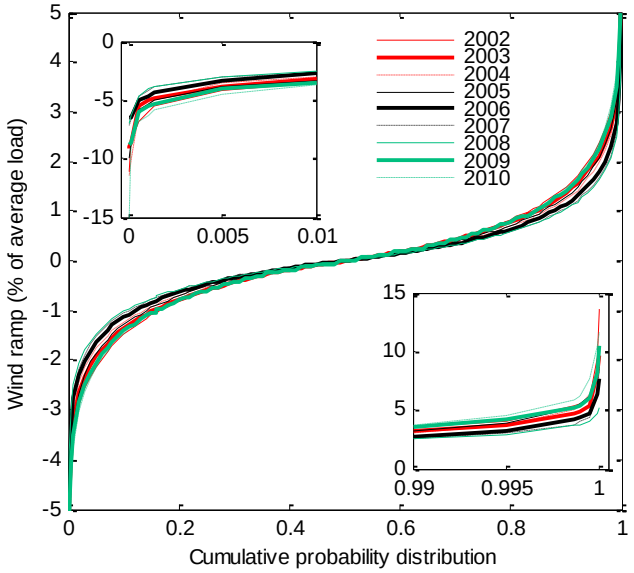

Fig. 1. Wind ramps from 15 minute data, from multiple year data (2002-10) from Ireland. The tails of the duration curves are presented as insets.

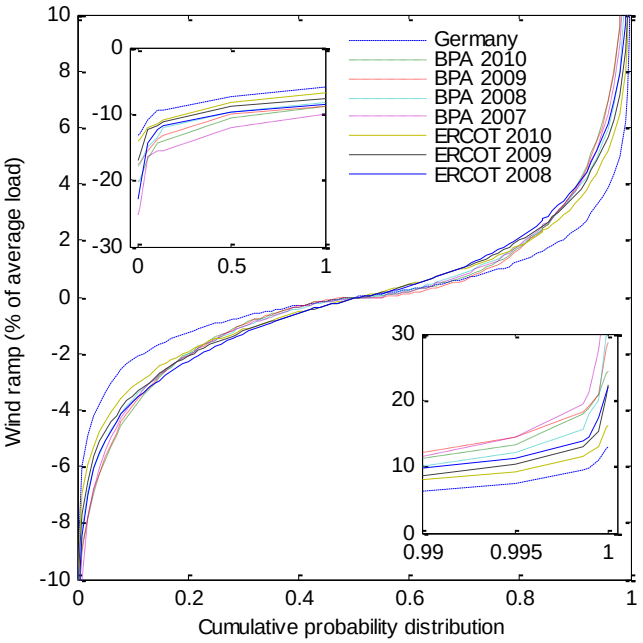

Fig. 2. Wind ramps from hourly data, from multiple year data (2007-10) from US. The tails of the duration curves are presented as insets.

Most obvious comparison of wind ramps would have been based on per units of installed capacity. However, the variability would have been clearly greater in regions with high capacity factor than in regions with low capacity factor. Hence, it was decided that a better comparison is to scale wind power in each region to present 20% of electricity consumption and compare the ramps against the average load in each region (% of average load). This also helps to process real data which includes wind turbines that are built during the year. A time series of generation as % of capacity needs an estimate of wind capacity with an hourly time step.

The first comparisons show the difference between yearly data when looking at the variability. Fig 1 shows a comparison of 15 min ramp rates calculated from one year data taking 9 years of data from Ireland. Even if the curves are basically quite similar, the extreme variability does experience some differences in different years. As the wind power capacity has increased during the years, part of the differences can be from better smoothing effect (less severe ramps) in recent years. This is clearly seen in Fig 2 for Texas ERCOT data, where the hourly ramping is less severe every year. However, for US BPA data and Ireland data the ramping has been more severe in 2010 than in earlier years.

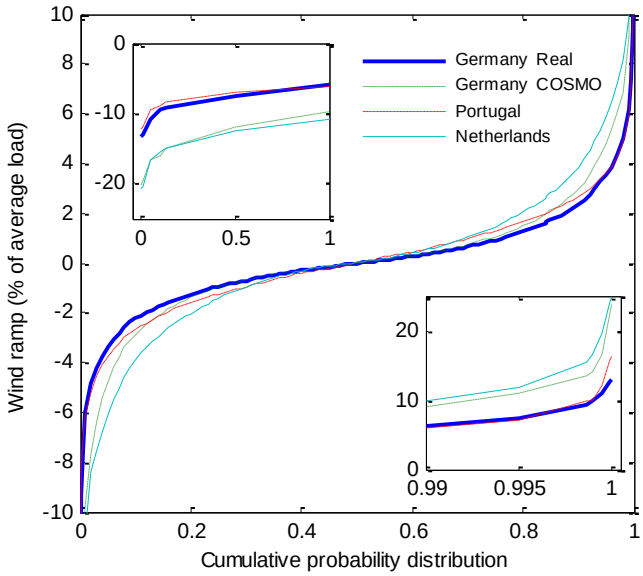

Fig. 3. Wind ramps from hourly data, year 2010 for Germany and 2009 for Portugal and 2004-05 for Netherlands data. The tails of the duration curves are presented as insets.

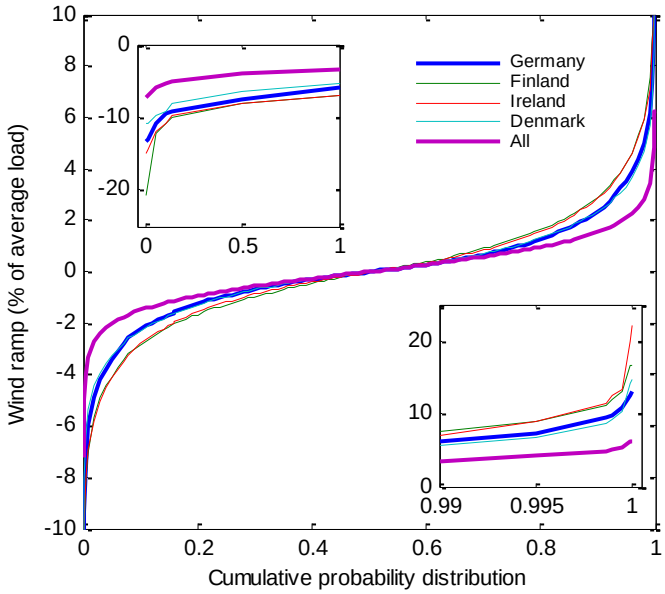

Fig. 4. Wind ramps from 60 minute data from North-European wind power year 2010, example case where the amount of wind generation in Ireland, Denmark and Finland is half of that in Germany.

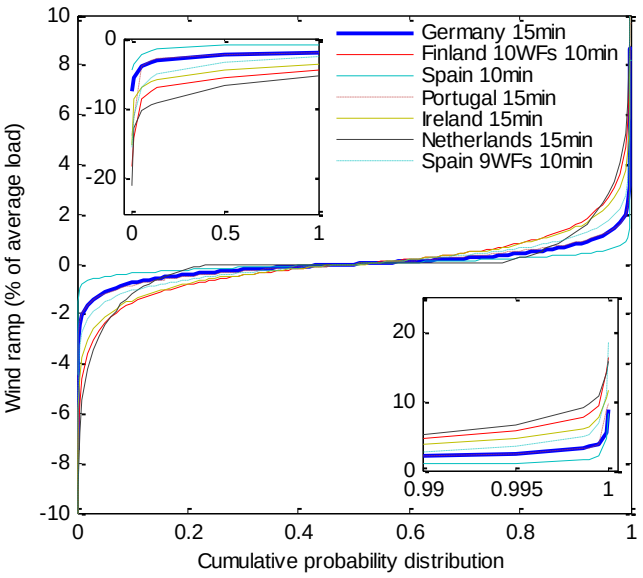

Fig. 5. Wind ramps from 10/15 minute data, year 2010. The tails of the duration curves are presented as insets.

Fig 3 shows a comparison of real data to model data – the Netherlands data gives highest ramp rates – but is also a quite small area. COSMO model data for Germany gives significantly higher ramp rates than the actual measured data, even though the model based data has been carefully prepared to take into account the dispersion of wind power. This is probably caused by the higher correlation of the wind speeds at the grid points in the weather model than in reality.

In Figs 3 and 4, Germany, Portugal and Denmark have less severe ramp rates than the other regions. Ireland is a smaller area (and wind power is probably more concentrated than in Denmark) and Finland data has less number of turbines than the other countries which explains the somewhat higher variability even if the area is larger. In US data sets the highest ramps are larger than in the European data sets. Fig 4 shows also a North-European case, where the hourly data sets we have for year 2010 have been summed from 4 countries. Smaller countries (Ireland, Denmark and Finland) have been scaled to 50% of the wind power production and electricity consumption of Germany. The larger area decreases variability clearly.

Fig 5 shows the ramp rates in 10 or 15 minute data. Comparing the hourly and 10-15 min ramp rates we can see how much the variability decreases when the time scale decreases. The hourly ramp duration curves show that about 60 % of time the ramping is ± 1 % of average load, and for 10-15 data this is about 80 % of time. In 15 min time scale the Netherlands simulated data shows different characteristic as the real measured power production data – less variability most of the time but higher extreme ramps. Also Finland, with only 10 sites of data, shows more extreme variability than the others.

IV. Combining Wind and Load Variability

Next step is combining the wind data with and load data and looking at the net load data: Load consumption minus wind power production time series.

A. *Increasing ramps for the system*

Net load time series for one year have been calculated so that wind penetration level has been increased, scaling the same wind time series from 0 %, 1%, 2% etc penetration levels, up to 50 % penetration level (energy penetration, wind energy from yearly consumption). From these 50 time series, the maximum variability has been calculated as the 0.1/99.9 and 1st/99th percentile values (separately for positive up-ramps and negative down-ramps) and they are shown as before, relative to average load. The probability distribution of the net load ramps of the 50 time series has been summarized in Figs. 6-9 with focus on the highest ramps. The plots show the dependence of the quantiles on the wind penetration level: 0.001 (negative), 0.01 (negative), 0.99 (positive), 0.999 (positive). As the original data has not been thoroughly checked for outliers due to data collection and processing, the maximum ramp levels are not shown (except for Texas data).

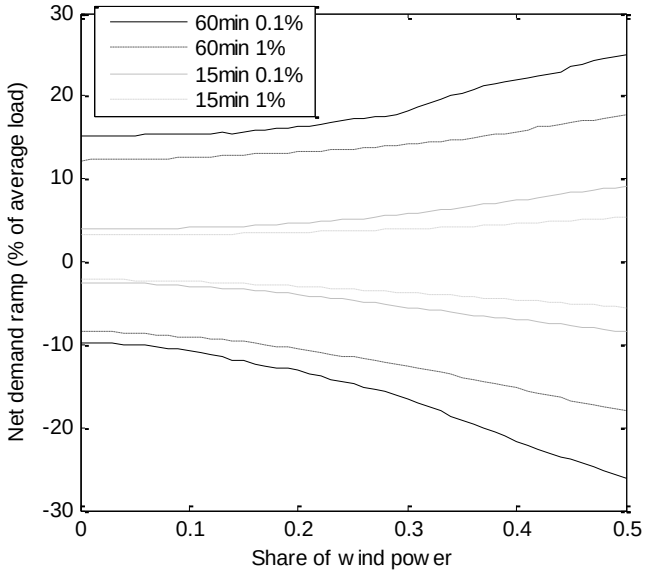

Fig. 6. Maximum ramps in net load with increasing wind penetration level in Germany. Comparison between 15 min and 60 min data. Positive and negative ramps presenting 0.1 % and 1 % of exceedence level are shown.

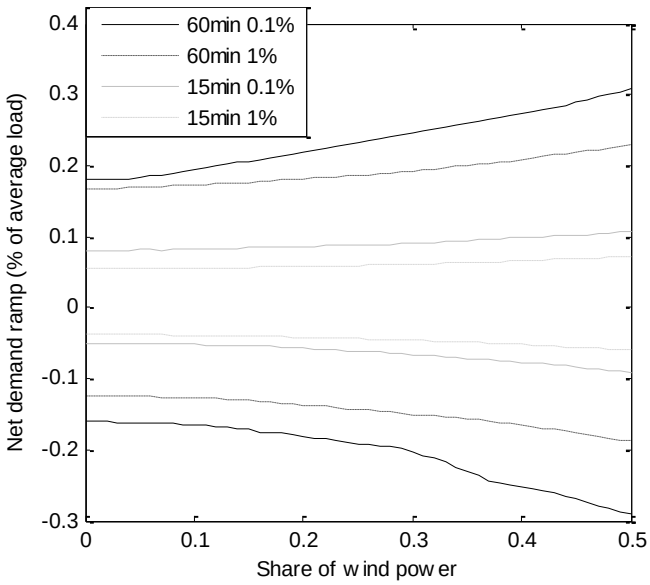

Fig. 7. Maximum ramps in net load with increasing wind penetration level in Portugal. Comparison between 15 min and 60 min data. Positive and negative ramps presenting 0.1 % and 1 % of exceedence level are shown.

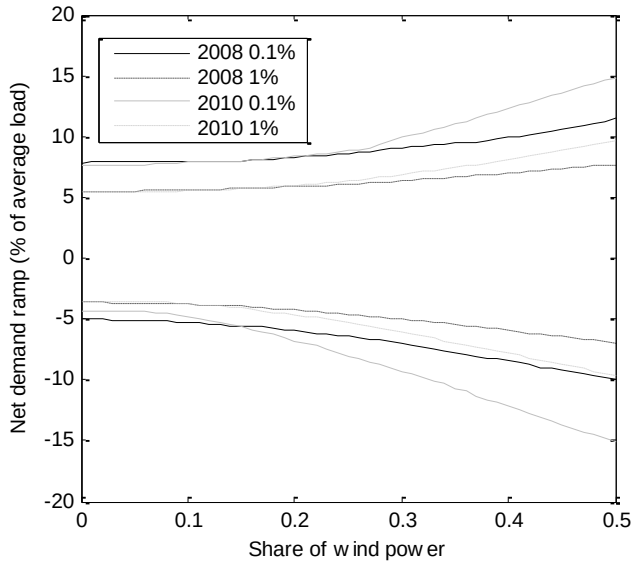

Fig. 8. Maximum ramps in net load with increasing wind penetration level in Ireland. Comparison between 2008 (lowest variability in the data set) and 2010 (highest variability year) using 15 min data. Positive and negative ramps presenting 0.1 % and 1 % of exceedence level are shown.

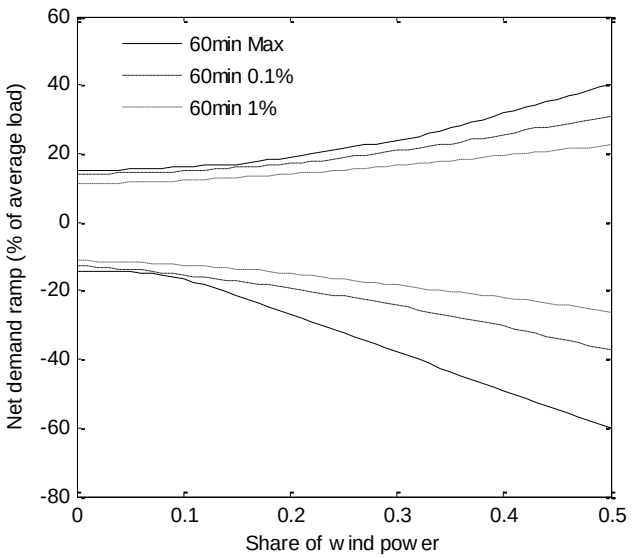

Fig. 9. Maximum ramps in net load with increasing wind penetration level in Texas (Ercot). Maximum ramp values as well as positive and negative ramps presenting 0.1 % and 1 % of exceedence level are shown.

What can be seen from these graphs is that the impact of wind on the maximum net load ramps is relatively small at smaller penetration levels and only after penetration levels of 5-10 % maximum ramping increases more. This is of course depending on the system (load and wind data), and in some systems there is a clearer threshold point after which the maximum ramps start increasing more with increasing penetration level. Also it can be seen that the impact on 15 min ramping starts at higher penetration levels than for hourly ramping. It appears that the wind variability will smooth out more when the time scale is reduced, compared with load variability.

B. Timing of large ramps

Adding wind power can impact the timing of largest ramps in the system. Analyses of the timing of the largest upward ramps (so called "magic carpet" graphs) are shown in Figs 9-12, with 24 hours of the day in the x-axis and 12 months of the year in the y-axis.

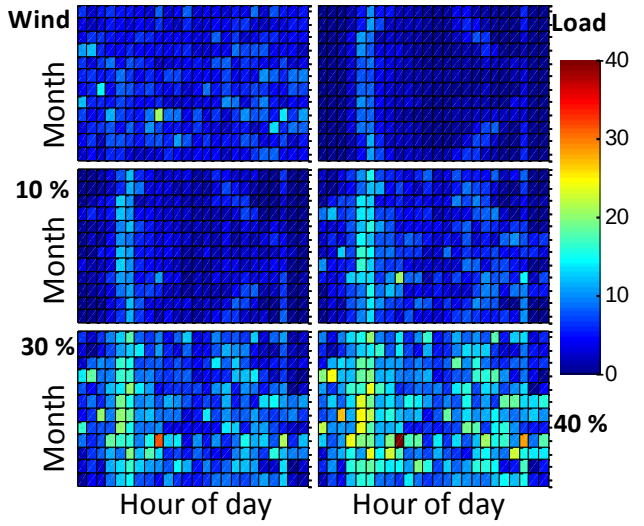

Fig. 9. Diurnal and monthly occurrence of high up-ramps in 2010 in Finland (as % of average load) for wind and load and 4 net load cases.

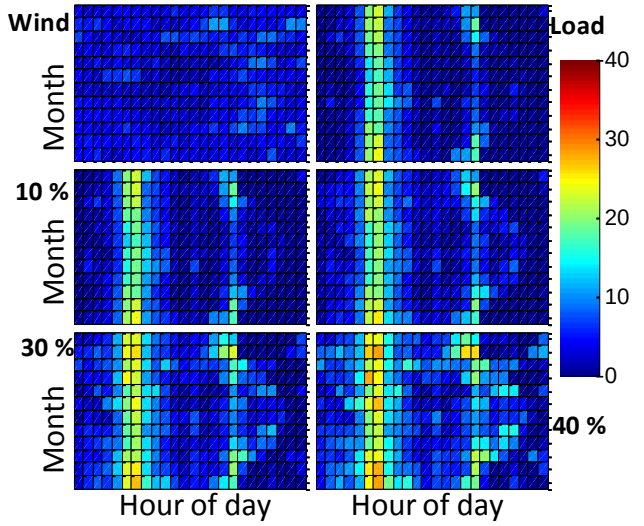

Fig. 10. Diurnal and monthly occurrence of high up-ramps in 2010 in Denmark (as % of average load) for wind and load and 4 net load cases.

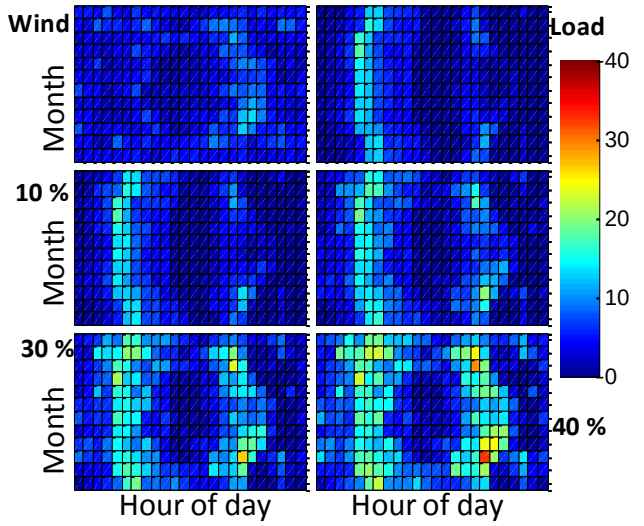

Fig. 11. Diurnal and monthly occurrence of high up-ramps in 2010 in Germany (as % of average load) for wind and load and 4 net load cases.

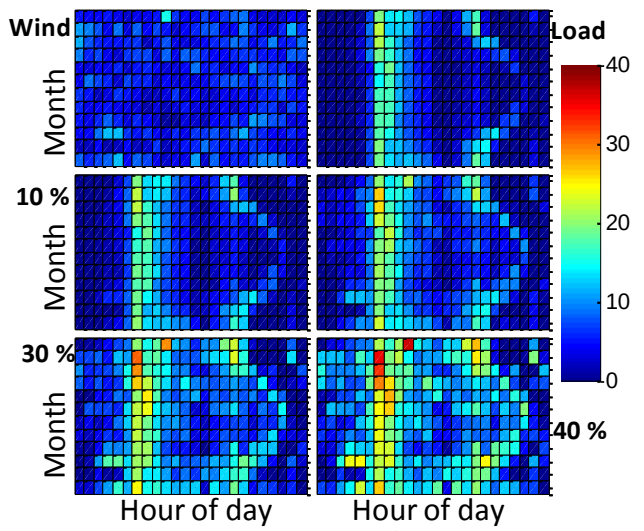

Fig. 12. Diurnal and monthly occurrence of high up-ramps in 2009 in Portugal (as % of average load) for wind and load and 4 net load cases.

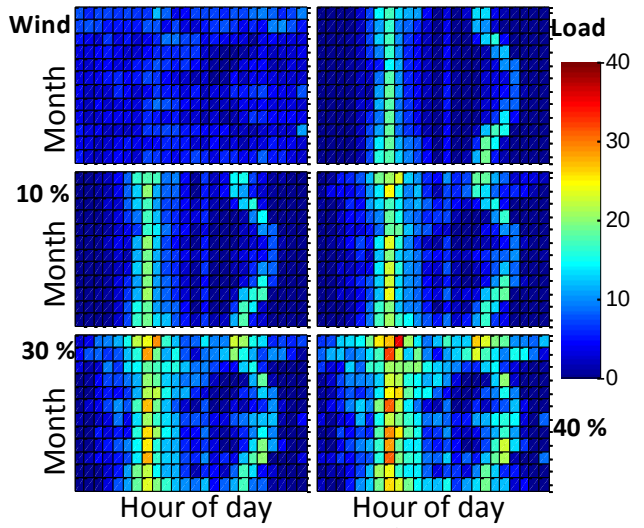

Fig. 13. Diurnal and monthly occurrence of high up-ramps in 2010 in Ireland (as % of average load). for wind and load and 4 net load cases.

The results should be treated with caution as the original data has not been thoroughly checked for outliers.

Load variability experiences the highest upward ramps in the morning hours around the year, and during the winter evenings. 10 % wind penetration will already cause visible differences in the ramps. At 20 % wind penetration largest ramps are clearly increased and further increase of wind power penetration will see large ramps occurring at times not experienced today.

V. Conclusions

Large scale wind power production and its variability is one major input to wind integration studies. This paper presents results of wind and net load variability from different countries with real large scale, dispersed wind power data.

Comparisons to different time scale variability show that ramp rates of wind power are significantly smaller in 10 or 15 minute data than in hourly data. Comparisons also show that using less wind farm data (10-30 sites in a large area covering several hundred kilometers East-West and North-South) will overestimate the variability. Also simulated data show more variability than measurements of generation.

According to our analyses, the impact of wind on the maximum net load ramps is relatively small at smaller penetration levels and only after penetration levels of 5-10 % maximum ramping increases more. Also it can be seen that the impact on 15 min ramping starts at higher penetration levels than for hourly ramping. It appears that the wind variability will smooth out more when the time scale is reduced, compared with load variability.

Analyses of the timing of largest ramps show that at 20 % wind penetration largest ramps are clearly increased and further increase of wind power penetration will see large ramps occurring at times not experienced today.

VI. Acknowledgment

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