Nordic Wind Power Forecast Errors: Benefits of Aggregation and Impact to Balancing Market Volumes

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***Abstract*— Increasing wind power penetration in the Nordic power system will increase the day-ahead forecasting errors, which will evidently increase the amount of balancing needed in the power system. However, having a large synchronous power system has its benefits, since it is possible to aggregate production and consumption imbalances from a wide geographical area to ease balancing. In this study the effect of how the forecasting errors will smooth in different Nordic areas were studied. For Mean Absolute Errors the errors will reduce down to 3% from over 10% when looking at the whole Nordic as a balancing area instead of a single area.**

Two case studies were carried out to see how the day-ahead forecasting errors will affect the balancing need. For Finland wind power penetration was up scaled from 0.6% to 5 and 10% and the balancing need was estimated. It was noticed that the amount of up and down regulation need increased as the penetration level increased. However, when the balancing need in the whole Nordic was studied the net balancing need only increased for up regulation, and for down regulation the balancing need decreased when the penetration increased from 3.5 (mainly DK) to 10% (dispersed for Nordic).

Keywords-forecasting; regulating power; forecast errors

I. INTRODUCTION

The Nordic countries have a synchronous power system that can be balanced in a coordinated manner. This means that the possible disturbances such as outages of conventional power plants and variability of variable generation can be balanced in a large geographical area. Limitations for balancing imbalances in the whole synchronous area are set by the bottlenecks in the transmission system. In the case of bottlenecks Nordic power system will separate into predefined price areas and the TSOs balance their imbalances respectively.

Variable generation has its unique characteristics compared to conventional generation such as variability of the source and uncertainty of the future production. As the share of variable generation increases in the power system one of the most evident consequences is the increase in balancing power. In the Nordic countries the share of wind power capacity has more than doubled between years 2000 – 2013. The capacity in 2013 was 15% from the Nordic peak demand and the energy 6% of the gross demand [1]. The share of variable generation will keep on growing in the Nordic power system, which will make the characteristics of variable generation even more pronounced. West Denmark is not part of the Nordic synchronous power system, but in this paper we consider the aggregate Denmark data.

Having a large interconnected power system will help integrating variable generation to the power system, since large geographical dispersion of variable generation will reduce the total variability and uncertainty. The total balancing need for a large interconnected area is dependent on the size of the balancing area, how the variable generation is dispersed into that area and how forecast errors and variability from variable generation and load combine.

Variability of wind power and load has been studied in several publications [2][3][11]. The basic principle of smoothing is that the pressure systems as a driving force of wind have a limited size and as the distance between two points is increasing it is more probable the points are not seeing the same wind variation at the same time. In [10] it was shown that in Germany the correlation of hourly variations over two point's decades exponentially with distance and the correlation over distances of 400 km and more is less than 0.3.

Many forecasting errors are phase errors when the timing of a front is miscalculated or level errors when there is an error in the amplitude of a forecast. Over time there could be a correlation in these errors in different places but looking at one moment in time, these errors in a large geographical area are mostly uncorrelated. Spatial-temporal correlation of forecasting errors have been also studied and smoothing of forecast errors have been studied in several publications [6][7]. In [11] it was also shown the correlation coefficient of forecasting errors is decreasing exponentially as the distance increases. For distances over 100 km the correlation coefficient is less than 0.3 for day-ahead forecasts. So far these studies have often been made for a small area by using the same forecasting model to create the wind power forecasts. In the Nordic countries wind power producers and Transmission System Operators (TSOs) are creating their own wind power forecasts, which create more independence between forecasts made at different countries. Balancing need due to wind power variability is often analyzed in integration studies, but impact of forecast errors is often discarded due to lack of representative data. This paper presents day-ahead forecast error data from the four Nordic countries, from historical data for 2011, with analyses on the aggregation impact of forecasting errors in Nordic countries and how the day-ahead errors impact on balancing need. In the future studies also other time horizons, especially intraday will be studied.

II. DATA

This section presents the data that was used in this study.

A. *Forecasting data*

Forecasting error time series were acquired from the four Nordic countries. Actual operational day-ahead forecasts were received from Swedish and Danish TSOs. In Finland day-ahead forecasts were created by using Numerical Weather Predictions (NWPs) from Foreca and turned into wind power forecasts based on VTT's forecasting model. The data to fit the forecasting model was provided by Finnish Energy Industries from different wind turbine sites. Norway's forecasting error dataset was created from NWPs from Met Norway and forecasting from Kjeller Vindteknikk based on historical wind power production data available from Norwegian Water Resources and Energy Directorate (NVE). The dataset contains year 2011, forecasts day-ahead (for the electricity market, 12-36 hours ahead) and the resolution of the dataset is one hour. After removing all the outliers and missing data points the synchronous data set contained 7707 values.

Since the forecasts are made by using different forecast models in different countries, the forecast accuracy can vary between countries. Denmark has been developing power system level forecasts for a couple of decades, which means that it is reasonable to assume that their forecast model is more advanced than the ones in other Nordic countries. However, also the differences on the area sizes and terrain complexity have an effect on the forecasting accuracy. In Table I the relevant country statistics are presented. Area sizes are estimated based on the electricity market price areas. In Finland wind power capacity is concentrated on four spatially separated areas. Therefore, the area size of Finland is calculated as a sum of these three areas. For Sweden and Norway price areas were used instead. In Denmark the wind power capacity is more evenly distributed in the whole country and the price areas can be used as a good estimate. Number of turbines Sweden and Denmark are based on actual statistics [4][5]. However, the number of turbines in each price area is estimated based on the installed capacities. Currently the amount of wind power in Norway and Finland is almost negligible compared to the wind power capacities in Sweden and Denmark. Therefore, in order to study combined wind power forecast errors wind power capacities in Finland and Norway were up scaled to half of Denmark's wind power capacity.

TABLE I AMOUNT OF WIND POWER AND AREA SIZE. SCALED VALUES ARE MARKED WITH PARENTHESIS

Country	***Statistics***		
	Area [km^2]	***Number of turbines***	***Installed wind Capacity MW***
FI	**187144**	**(1945)**	**200(1556)**
SWE1	115297	130	153
SWE2	126736	370	436
SWE3	141699	938	1106
SWE4	49358	610	720
SWE	**433090**	**2039**	**2403**
NO2	50223	(389)	(311)
NO3	69304	(778)	(622)
NO4	107463	(778)	(622)
NO	**324546**	**(1945)**	**511(1556)**
DK1	34872	3923	2526
DK2	12252	907	591
DK	**47124**	**4830**	**3111**

Calculating the area size by giving more weight to the locations of wind turbine plants would give a number that is more reflecting how concentrated/dispersed wind power is built – and how much aggregation benefit can be expected. However, to calculate this kind of metrics, detailed information is required to know how the wind power plant sites are distributed spatially (coordinates) and what are their sizes in MWs.

B. *Nordic market data for balancing*

In 2011 Nordic market area was divided into 10 different price areas, Figure 1 (at the moment there are 15 prices areas). In the end of 2011 Sweden was separated into four different price areas instead of one. The synchronous balancing area spans all Nordic countries with the exception of West-Denmark.

FIGURE 1 PRICE AREAS IN NORDIC POWER MARKET IN 2011

During hours of bottlenecks imbalances must be dealt with inside the price area since the transmissions lines are constrained. In 2011, only 35 % of the time the Nordic market area was sharing the same market price. However, The price difference was mainly caused by the bottlenecks between the price areas in Norway, where only 38 % of the time Norway had the same market price. On the other hand Finland and Sweden share the same market price 95 % of the time, which indicates that only 5% of the time there is a bottleneck between these areas. In this article, when aggregating wind power data, we only look at a theoretical situation where there are no limitations in the transmission network.

Increasing the share of variable generation in the power system has an impact mainly on load following/balancing reserves, which are manually activated in 15 minutes during the delivery hour [8]. Nordic TSOs have their joint balancing market (Nordic Regulating Power Market) where participants can place up- and down regulation bids up to one hour before delivery, that contain volume, price and location of the regulation. Sweden and Norway, who are responsible for maintaining the power system balance, activate regulation bids to keep system balance in the whole Nordic synchronous area, during delivery hour. The location of regulation is an important factor since during bottlenecks balancing must be activated in each balancing area and most cost-effective units may not be able to participate if they are located outside the balancing area where balancing is needed. The balancing volumes from the Nordic Regulating Power Market are publicly available from the Nord Pool Spot webpage [9]. For the Finnish scenario in chapter IV, imbalance data from the Finnish TSO's was used, which is also publicly available [12].

III. AGGREGATION BENEFITS OF FORECASTING IN NORDIC COUNTRIES

In this chapter forecast errors are analyzed for different sizes of areas in Nordic countries.

A. Forecast Error Comparison

Typical metrics to analyze the accuracy of wind power forecasts are Mean Absolute Error (MAE), Root Mean Squared Error (RMSE) and bias. In order to compare different areas it is typical to give all the metrics as values normalized by the wind power capacity. In Figure 2 these statistics are shown for different combinations of the areas in Nordic countries. The overall trend is that as the area size increases relatively more accurate forecasts are acquired. In the lower figure the logarithmic density distributions of forecast errors in different areas are shown. Since number of sites and turbines from Norway and Finland were much lower, the distributions tails are much heavier than for other areas. Again, as the area size is increased forecast error distributions are getting tighter, which shows that the forecast accuracy is higher for a larger area.

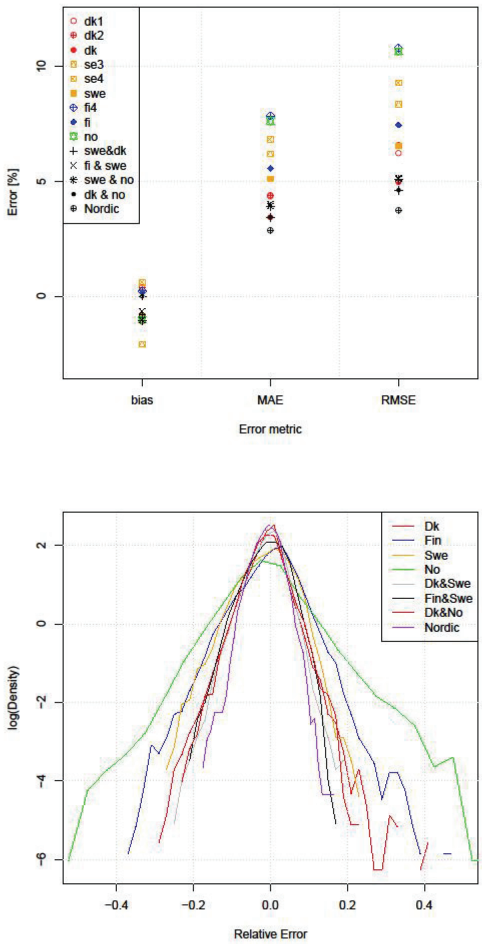

FIGURE 2 NORMALIZED BIAS, MAE AND RMSE IN DIFFERENT AREAS IN THE NORDIC COUNTRIES (UP) AND LOGARITHMIC DENSITY FORECAST ERROR DISTRIBUTIONS OF DIFFERENT AREAS (DOWN)

In Figure 3 is shown how the MAE changes as the size of the area or the number of turbines in an area increases. Although the area sizes are not wind power weighted areas, it can still be seen that forecast errors are reduced as the area size or number of turbines increases. The main reason for this is the spatial smoothing of forecast errors. Forecast errors tend to decrease the size of the area increases. The different forecast models in different countries may also contribute to smoothing effect.

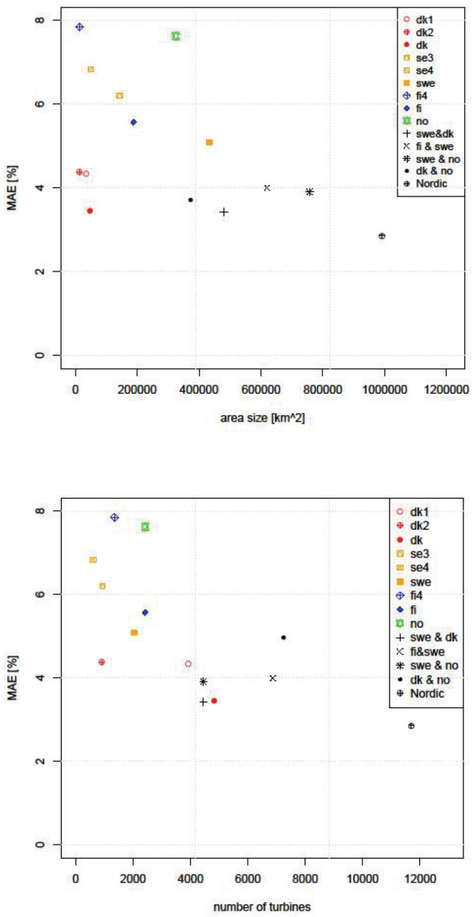

FIGURE 3 MAE OF FORECAST IN DIFFERENT SIZES OF AREAS AND DIFFERENT NUMBER OF TURBINES IN AREAS

Forecast errors have power dependent characteristics. This is due to the nonlinear wind to power conversion. In Figure 4 forecast errors in Denmark are shown in relation to generated power level. The form of a tilted parallelogram just indicates that power forecasting is a bounded problem, as neither forecast nor production can exceed the installed power or get below zero. For the whole Nordic countries the range of realized forecasts errors is lowered for all power levels.

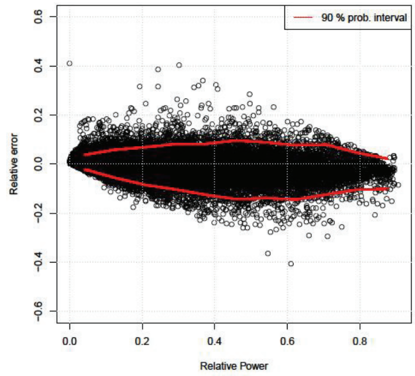

FIGURE 4 POWER DEPENDENT FORECAST ERRORS IN DENMARK

IV. IMPACT OF FORECAST ERRORS TO BALANCING NEEDS

During the bottleneck situations each of the TSOs are responsible for balancing their own balancing area. During these situations balancing power must be activated in order to balance wind power forecast errors and outages of conventional power plants. In 2011 Finland share the same market price with Sweden 364 hours before Sweden divided into four different price areas, which is roughly 5 % of the time. In this case we study first Finland as its own balancing area and see how much the total system imbalance will increase as the wind power penetration increases. Then we do the same analyses for the whole Nordic area. This is a theoretical study, mainly intended to show how much the aggregation benefits are moving from one country to Nordic wide area. Both of the wind power scenario are based on the assumption that wind power capacity is built exactly to the same location where the current wind data is located and the capacity is up scaled so that the energy penetration 4.5 and 10 % for the Finnish case study, and for Nordic case 10 % from the gross demand.

A. Finland

Production and consumption imbalance data from 2011 were used to analyze the total system imbalances in Finland. In Figure 5 the duration curves for production, consumption and total imbalances are presented for the 2011 data. The amount of wind capacity in Finland was 200 MW in 2011, however in this study forecasts from 130 MW were available.

TABLE II INCREASE IN IMBALANCE ENERGY FOR FINLAND FOR TWO WIND POWER SCENARIOS, 4.5 % AND 10% PENETRATION LEVEL (WIND POWER PENETRATION IN FINLAND WAS 0.6 % OF GROSS DEMAND IN 2011)

	1556 MW Wind Power (4.5 %)		**3400 MW Wind Power (10 %)**	
	Down	**Up**	**Down**	**Up**
Net imbalances [TWh]	0.88	-0.47	1.21	-0.87
Increase in system net imbalances [TWh]	0.10	0.15	0.43	0.55
Relative increase in total imbalances	18 %		47 %	
Relative increase in balancing energy	13 %	88 %	55 %	170 %
System imbalance increase relative to produced wind energy	3 %	4 %	5 %	6 %
Produced wind energy [TWh]	3.85		8.41	
Wind forecast errors [TWh]	0.38	-0.43	0.82	-0.94

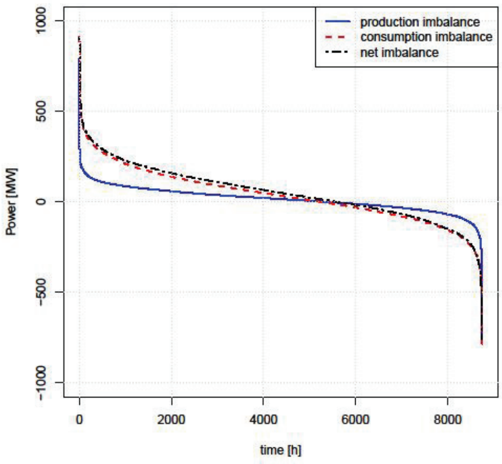

FIGURE 5 DURATION CURVES OF PRODUCTION (0.45 TWH) IMBALANCE, CONSUMPTION (1.03 TWH) IMBALANCE AND TOTAL IMBALANCE (1.1 TWH) IN FINLAND FOR 2011 (0.6 % WIND SHARE). POSITIVE VALUES ARE DOWN REGULATION AND NEGATIVE VALUES ARE UP REGULATION.

Consumption uncertainties exceed production uncertainties and consumption imbalances are biased to downward regulation. The same bias can also be seen from the duration curves in Figure 5.

It was assumed that the wind capacity is built exactly at the same locations as the current wind farms . Normalized time series of prediction errors from whole Finland were multiplied with the desired wind power capacity and then added to the production imbalances without any wind. It was also assumed that the forecasting accuracy remains in the same level as it was 2011. So these assumptions are conservative, both increased dispersion and improved accuracy would result in lower forecast errors for the larger amounts of wind. In Table II results for the two different wind scenarios are presented. The imbalance energy clearly increases in relative terms as the wind power capacity is increased in the power system. The increase in per cents is larger for up regulation since the imbalance energy before wind is biased for down regulation direction and wind forecasts do not have any significant bias. For down regulation the increase is quite moderate for 4.5 % share of wind, whereas for 10 % wind share both the up and down regulation are increased significantly, if only day-ahead forecasting is used and errors are not corrected before hour of delivery.

When looking at the imbalance increase per wind power produced energy the increase in the imbalance energy is only 3-6%. In Figure 6 the duration curves for imbalances for the 4.5 % and 10 % wind power penetrations are shown. Consumption imbalances are still greater than the production imbalances for 4.5 % wind share but with 10 % share production becomes greater than the uncertainty of consumption – if day-ahead forecast errors of wind are not corrected closer to real-time operation, and forecasting accuracy was as it was for the sites in 2011.

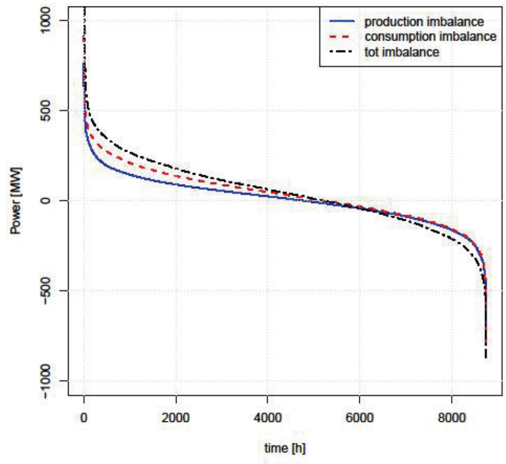

FIGURE 6 DURATION CURVES FOR PRODUCTION, CONSUMPTION AND TOTAL IMBALANCE FOR 10 % WIND PENETRATION IN FINLAND . POSITIVE VALUES ARE DOWN REGULATION AND NEGATIVE VALUES ARE UP REGULATION.

B. Nordic case

For the Nordic system production and consumption balances are not separated since the only available data for the whole Nordic system was activated balancing volumes, reflecting the total system imbalances. Wind power capacity is assumed assumed to be in the same location as the actual data, which is mainly in Denmark and South-Sweden. The total capacity is 7263 MW, which is 3.5% from the gross demand. Simulated scenario for the future Nordic wind power was 10 % energy penetration 10 % energy penetration, 23025 MW. In order to compare the Nordic balancing increase to the Finnish area study, forecasting errors were subtracted from the Nordic net imbalance data in order to look situation without wind power. In Table III results for the future Nordic wind power scenario are shown.

TABLE III INCREASE IN BALANCING NEED FOR NORDIC COUNTRIES WHEN WIND PENETRATION INCREASES FROM 0 TO 10 %

type	2011	
	Down	**Up**
System imbalance for 0 % wind [TWh]	1.99	-1.24
System imbalance for 10 % wind [TWh]	1.58	-1.72
increase in balancing [TWh]	-0.41	0.48
Relative increase in total imbalances	2 %	
Relative increase in balancing energy	-20 %	39 %
System imbalance increase relative to produced wind energy	-1 %	1 %
forecast error for 10 % wind [TWh]	1.30	-2.26
produced wind energy (10 % wind) [TWh]	33.59	

It is possible to see from Table III that by increasing wind energy share of consumption from 0 to 10 % the day-ahead forecast errors would decrease the amount of down regulation by -0.41 TWh whereas the amount of up regulation would increase by 0.48 TWh. Forecast errors of wind power are weakly, but negatively correlated with the balancing need from consumption and other production. This can mean that the balancing power, resulting from system total net imbalances is sometimes decreasing due to day-ahead forecast errors of wind power. Therefore, the total down regulation need will decrease although the forecast errors are increasing. Also, the differences between wind power forecast errors and in net imbalance biases will reduce the total net imbalance need. The base case of year 2011 has wind power from mainly Denmark and South Sweden, and the aggregation benefit from adding Finland and Norway would result in reduced forecast errors. The total increase in balancing energy is only 2 % of the total produced wind energy. In Figure 7 duration curves of 2011 total system imbalances for the original data (including 3.5 % share of wind) and up-scaled wind power to 10 % share are shown.

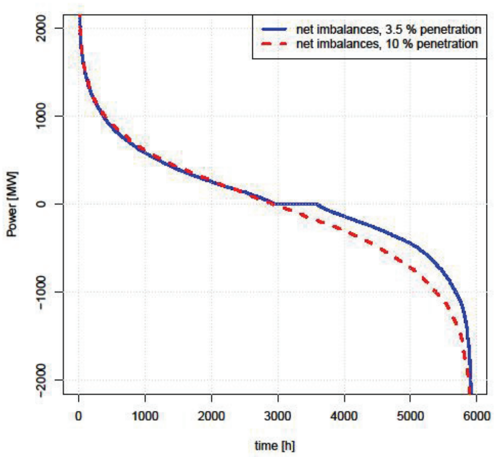

FIGURE 7 DURATION CURVES OF TOTAL SYSTEM IMBALANCES IN 2011 WITH DAY-AHEAD FORECAST ERRORS OF 3.5 % AND 10 % WIND PENETRATION

V. CONCLUSIONS

There are clear benefits from having a large interconnected area since the wind power forecast errors are reduced significantly. For instance the MAE of forecast errors can be more than 10 % for a small area but reduces to below 3% combining the forecast errors in the Nordic area. This can reduce the need for balancing power if there are no bottlenecks in transmission.

Our analysis used real forecast data for 4 Nordic countries for year 2011 and system imbalance data from the Nordic countries. A simple up-scaling of wind power generation to reach 10 % penetration level was made to see how day-ahead forecast errors would impact total net imbalances in Finland and Nordic countries. This simple up-scaling will overestimate the future forecast errors of wind and it assumes no improvement of forecast accuracy and only using same sites for the wind power plants than in 2011.

In Nordic countries, the day-ahead forecast errors of wind would result in system total net imbalances of 1.72 TWh and 1.58 TWh for up and down (total 3.23 TWh) at 10 % penetration, compared to 1.24 TWh up and 1.99 TWh down (total 2.6 TWh) without wind. In Finland, total system net imbalances would be 1.2 TWh down and 0.9 TWh up (total 2.1 TWh) with 10 % wind, up from 0.8 TWh and 0.3 TWh (total 1.1 TWh) with 0.6% wind penetration. Increases in imbalance energy are not very large in relation to total produced wind energy, but are high compared to total imbalance energy today. Wind power day-ahead forecast errors would result in very high impacts on a single country balancing area, where as the impacts Nordic wide are more moderate. As consumption imbalances seem to be highly biased towards down-regulation to start with, the impacts of wind power are more dramatic towards up-regulation needs. Impacts from wind power day-ahead forecast errors are significant enough at 10 % penetration level to call for mitigation from both improved forecast accuracy and intra-day trade to correct the largest errors before real time balancing market is used,

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