TEMPORAL FORECAST UNCERTAINTY FOR RAMP EVENTS

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Summary

As the penetration of wind energy continues to increase around the world, the impact of wind energy on the management of electrical grids is becoming increasingly evident. The challenge for the grid operator of integrating wind energy, or for the energy trader to maximise the market value of the energy, is toughest during periods of rapid change in wind farm production, or ramp events. These events are also tough to forecast accurately, and it is therefore essential to understand the uncertainty of forecasting such events.

To date the majority of work on the uncertainty of wind energy forecasts has been focused on the possible amplitude of wind production that might occur at a given time. However, there has been limited investigation into effectively defining the possible timing of significant wind energy events.

This paper aims to focus on methodologies for generating temporal forecast uncertainty for rapid changes in wind farm production. The first challenge is to define ramp events, secondly the forecast uncertainty needs to be calculated and finally this information needs to be presented clearly to the end user. This paper covers these three areas, with a focus on the method of calculating forecast uncertainty using multiple NWP inputs, statistical processing and adaptive algorithms.

The results are based on GH Forecaster services for both individual and portfolios of wind farms. The outcome of the investigation demonstrates that temporal forecast uncertainty can be calculated and clearly presented to indicate the likely timing and amplitude of wind energy ramp events.

Key words: Wind power forecasting, ramp events, grid integration

1. Introduction

A ramp event is a large change in the power production of a wind farm or portfolio of wind farms over a short period of time. There are two ways in which variation in wind speed can result in a rapid change in power production, illustrated in figure 1 below. At ramp up wind speeds the power output of a wind turbine is highly dependent on wind speed, and rapid changes in wind speed will therefore cause rapid changes in power. At high wind speeds a smaller increase in wind speed can trigger high wind speed shutdown, causing a rapid drop off in power production. The majority of ramps are caused by rapid changes in ramp up wind speed, but high wind speed shutdown events are also significant.

Ramp events occur rarely, but unexpected rapid changes in power from wind farms can be problematic for grid operators, and the impact of ramp events grows as the penetration of wind energy continues to increase. The difficulties presented by periods of rapid change are also passed on to energy traders in the form of financial penalties or a lowered overall market value of wind energy [1]. With accurate prior warning of a large ramp event, energy from other sources may be scheduled in order to mitigate a steep rise or drop in wind energy. This means the accurate forecast of ramp events and quantification of ramp forecast accuracy is crucial to the large-scale integration of wind energy into electricity grids, and also to help traders better understand the risk involved in trades at times of high variability.

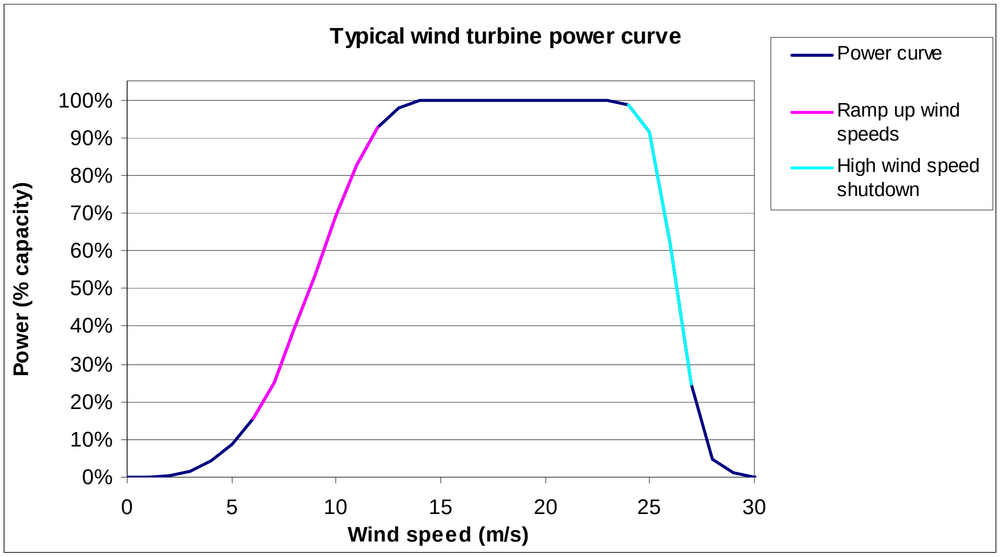

Figure 1- A typical wind turbine power curve

Forecast uncertainty is typically provided by forecast providers to enable end users such as grid operators and energy traders to make informed decisions about energy scheduling and how much energy to trade ahead of time. To date the majority of work on the uncertainty of wind energy forecasts has been focused on the possible amplitude of wind production that might occur at a given time, with limited investigation into effectively defining the timing of significant wind energy events. In the calculation of conventional uncertainty, temporal uncertainty is taken into account over the entire forecast, but the rarity of large rapid changes means that current forecast optimisation methods are not sensitive to the timing of ramp events. A new method to calculate and present the temporal uncertainty of ramp event forecasts is therefore required.

There is no established definition of the minimum change in power production or maximum time period over which a change must occur for it to constitute a ramp event. Hence, the first aim of this paper is to define a ramp event so as to identify changes in power, which are considered to be significantly large and rapid..

The second objective of this work is to calculate temporal forecast uncertainty to provide a clear indication of the likely timing of wind energy ramps, which must be presented clearly to the end user. It is also necessary to consider that some ramp forecasts may not result in a ramp event and some ramp events may not be forecast.

2. Method

2.1 Frequency of ramp events and definition of a ramp event

There are two features that define a change in power production, the size of the ramp (the amount of change in power production that occurs, as a percentage of wind farm or portfolio capacity), and the length of time over which the change occurs, or the duration of the change. Ramp events are characterised as having large sizes and short durations, the larger the size and shorter the duration, the more extreme the event.

In this paper a ramp is defined as a variation in power output exceeding a minimum size, s_{min}, over a duration less than or equal to a maximum duration, d_{max}, figure 2 shows the frequency of events with varying size and duration constraints. The data used is measured power data from a number of wind farms in the UK, with each farm being considered individually, not as part of a portfolio. It can be seen that the frequency of events decreases approximately exponentially with increasing size and also decreases with decreasing duration, i.e. that larger and more rapid changes are less common.

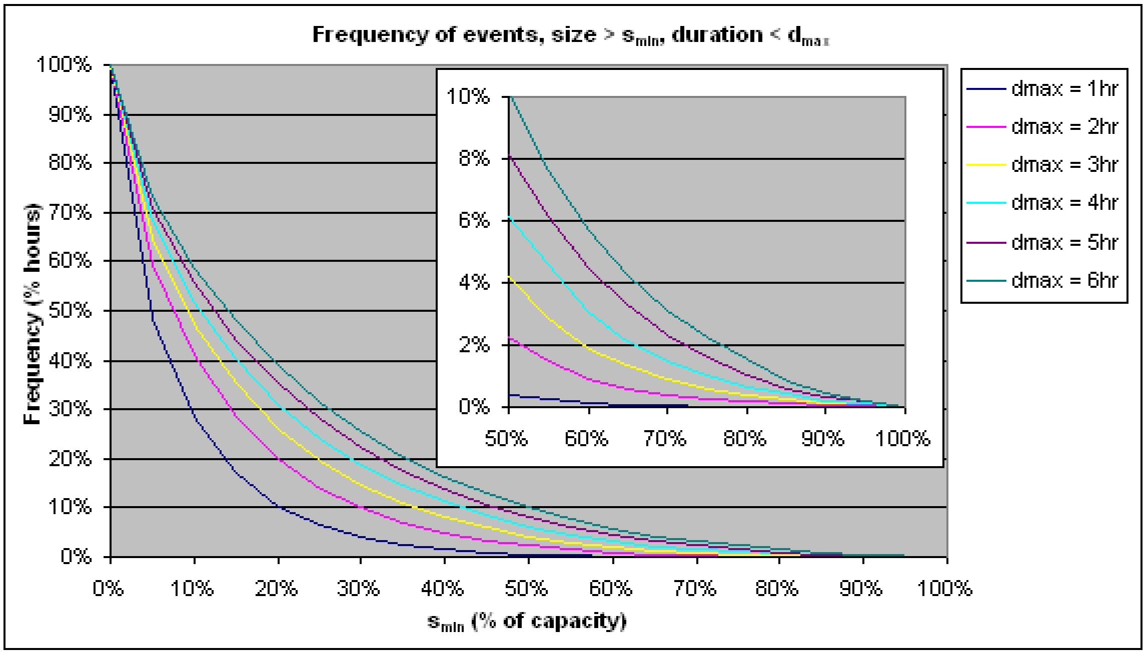

Figure 2- Frequency of power changes with varying size and duration constraints

For the purpose of analysing forecast accuracy for ramp events, a ramp event is taken to be a change in power of 50% of capacity or more over a period of 4 hours or less. This definition of a ramp event is the same used in other work such as [2]. From figure 2, it can be seen that events in which the power changes by 50% of capacity or more over 4 hours or less occur approximately 6% of the time. A maximum duration of 4 hours ensures that variations are rapid and that sufficient events with minimum ramp size of 50% of capacity are identified for analysis.

2.2 Current forecasting method

The GH forecasting modelling method incorporates input data from Numerical Weather Prediction (NWP) sources of appropriate resolution, and from on-site data.

The physical aspect of the modelling methodology is primarily provided by the NWP input. This input is enhanced through the application of multi-parameter statistical regression routines.

The creation of power output forecasts within GH Forecaster is a two-stage process. First, through the statistical adaptation of the physical NWP input, there is the creation of site-specific meteorological forecasts for a pre-defined reference point, such as a site met mast. These meteorological forecasts are then transformed, via site-specific power models, to power output forecasts. To enable the meteorological model to be both auto-regressive and adaptive, feedback data from the site is also required.

Further details of the forecasting method used can be found in [1] and [3].

2.3 Ramp forecasting

Historical data from GH Forecaster services for forecast power and measured power production were used to identify forecast and measured ramp events. A measured ramp event is defined as a change in power of 50% of wind farm capacity or more over a period of 4 hours or less. The variability of forecast power was compared to that of measured power, and a forecast ramp was defined in such a way as to best forecast ramp events in measured power for individual wind farms. The same definition of a forecast ramp was used throughout this work. The time at which a ramp occurred was taken to be the central point of the ramp.

2.3.1 Total accuracy

The total accuracy of the ramp forecast is based on the frequencies of the three possible outcomes of ramp forecasting illustrated in table 1. This gives two measures of the accuracy of ramp event forecasting, forecast accuracy and ramp capture, as defined in equations 1 and 2 below. Both of these are important for producing a useful and meaningful ramp forecast.

Table 1- Outcomes of ramp forecast

	Measured ramp event	**No measured ramp event**
Forecast ramp event	True forecast	False forecast
No forecast ramp event	Missed ramp	

$$\text{forecast accuracy} = \frac{\text{true forecasts}}{\text{true forecasts} + \text{false forecasts}} \qquad (1)$$

$$\text{ramp capture} = \frac{\text{true forecasts}}{\text{true forecasts} + \text{missed ramps}} \qquad (2)$$

A true forecast is taken to be a forecast ramp with a measured ramp of the same direction (either up or down) within ±12 hours of the time of the forecast ramp. Each forecast ramp is only associated with one measured ramp and each measured ramp is only associated with one forecast ramp. Where two or more measured ramps fall within ±12 hours of a forecast ramp or vice versa the closest is taken.

By expanding the time period of association between forecast and measured ramps it would be possible to obtain results where all forecast ramps correctly predict a measured ramp, but this would lead to the association of forecast and measured ramps so far apart in time that they do not represent the same meteorological event. However, allowing only the very closest forecast ramps to measured ramps to be considered true forecasts would not allow the full temporal distribution to be analysed. Garrad Hassan has found a maximum time difference of ±12 hours to give sufficient data for temporal uncertainty analysis whilst maintaining a realistic connection between forecast and measured ramp events.

Total accuracy values were calculated for individual wind farms within the UK, a portfolio of wind farms in Ireland, and individual wind farms in the US for short and medium forecast horizons. In order to determine the effect of NWP sources on ramp forecasts, total accuracy values were calculated for a single wind farm for two forecasts each using a different NWP source and for a forecast from the two NWP feeds combined.

2.3.2 Temporal uncertainty

For all true forecasts, a statistical analysis of temporal accuracy of forecasting the midpoint of a ramp event was made. Temporal uncertainty analysis was carried out for data from a number of wind farms within the UK, and wind farms in the US for short and medium forecast horizons.

It is important for the resulting information to be presented in a way that accurately yet simply provides a visualisation of the temporal uncertainty of ramp event forecasts. Various methods of presentation were considered and the best was chosen to give a clear presentation of temporal uncertainty for the end user.

2.4 Sites analysed

2.4.1 Individual UK sites

Forecast and measured power data from 12 wind farms in the UK were analysed, covering the same 15 month period for each farm, with a combined forecast period of approximately 121 wind farm months. The farms range in capacity from 3MW to 90MW.

2.4.2 UK Portfolio

The ramp frequency and ramp forecast accuracy for a portfolio of wind farms were analysed. The portfolio consists of 6 wind farms ranging in capacity from 3MW to 72MW with a combined capacity of 139.5MW. The data used for analysis was for the same 15 month period as taken for the analysis of individual sites.

In general, forecasts for portfolios of wind farms are significantly more accurate than forecasts for individual wind farms, especially for large changes in power production. This is illustrated in figures 3 and 4 which compare time histories of forecast and measured power for a portfolio of wind farms and a single wind farm that is part of the same portfolio over the same time period.

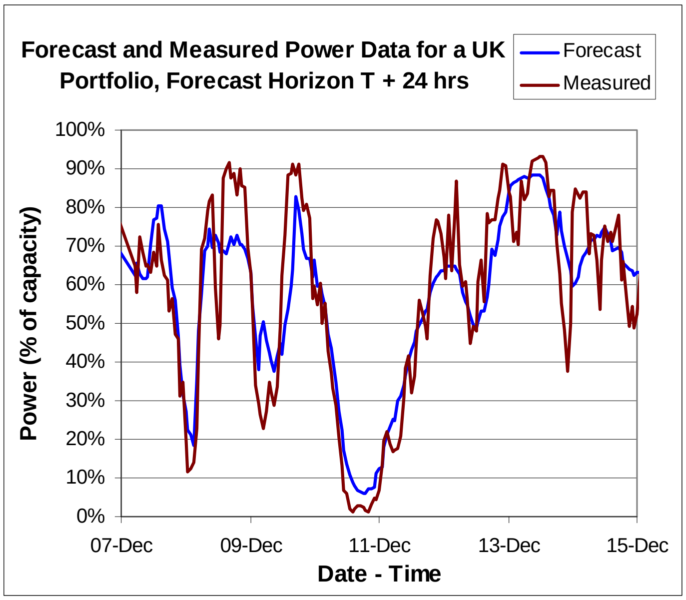

Figure 3- Time history of forecast and measured power for a portfolio

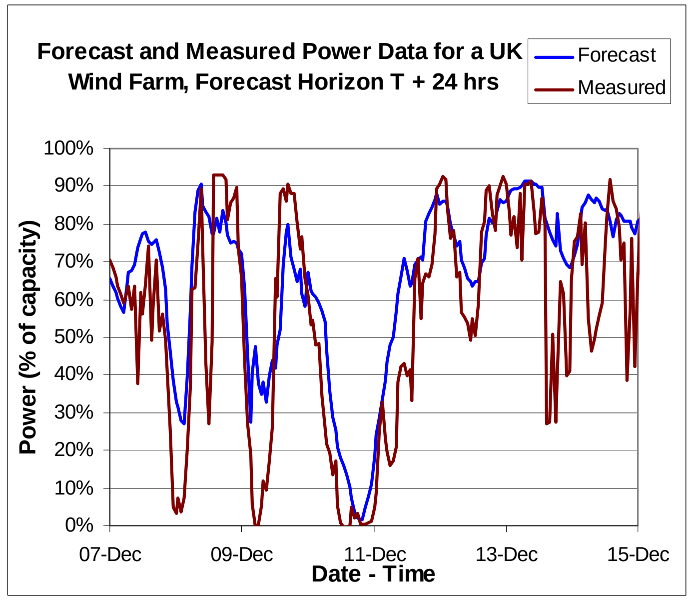

Figure 4- Time history of forecast and measured power for a single wind farm

Due to the higher accuracy of portfolio forecasts for the timings of changes in power, it is expected that temporal uncertainty of ramp forecasts will be significantly reduced for portfolios compared to individual sites.

2.4.3 US sites

Data from six individual wind farms in the US were analysed, ranging in capacity from 37.5MW to 240.8MW, with a combined forecast period of approximately 42 wind farm months. It is noted that the capacities of the wind farms analysed in the US are much higher than those in the UK.

3. Results

3.1 Frequency of ramp events and total forecast accuracy

Table 2 shows the frequencies of forecast and measured ramp events from the individual UK wind farms for forecast horizons of 3 and 24 hours.

Table 2- Ramp frequencies and forecast accuracies for individual wind farms and portfolios

Wind farms	Individual UK sites		UK Portfolio		Individual US sites	
Forecast horizon (hrs)	3	24	3	24	3	24
Number of true forecasts	894	700	21	18	384	323
Number of false forecasts	436	484	43	30	266	236
Number of missed ramps	1099	1300	21	24	699	769
Forecast accuracy (%)	67.2%	59.1%	32.8%	37.5%	59.1%	57.8%
Ramp capture (%)	44.9%	35.0%	50.0%	42.9%	35.5%	29.6%

3.1.1 Individual UK sites

Ramp forecasts with a horizon of 3 hours have a ramp capture (measured ramps correctly forecast to within ±12 hours) of 44.9%, and ramp forecast accuracy of 67.2% (i.e. if a ramp is forecast, there is a 67.2% probability that a measured ramp will occur within ±12 hours of the forecast time.) Ramp forecasts with a forecast horizon of 24 hours have a ramp capture of 35.0% and a forecast accuracy of 59.1%. The increased accuracy of ramp forecasts for individual UK wind farms at shorter forecast horizons compared to longer horizons is expected, as general forecast accuracy typically also decreases with increasing horizon.

3.1.2 UK Portfolio

Typically, portfolios of wind farms experience fewer ramp events than individual wind farms. The geographical spread of wind farms means that the times at which large rapid weather events occur at different wind farms will be staggered, or that weather events affecting some sites will not affect others. This has a smoothing effect on the overall power production, so that large changes in power production occur over longer periods of time, and rapid changes in power are typically of a smaller size relative to the total portfolio capacity. The frequency of events with varying size and duration constraints for a portfolio is compared to that for individual wind farms in figure 5. It can be seen that far fewer large events (changes greater than 50% of capacity) occur in portfolios than in individual wind farms.

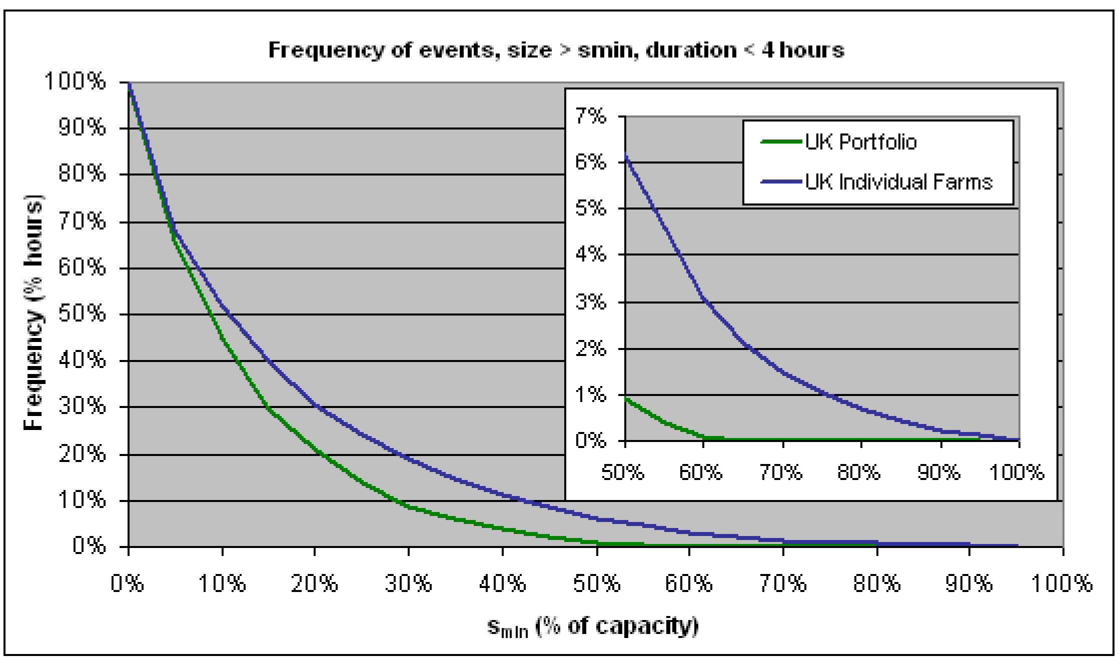

Figure 5- Frequency of 4 hour events with varying minimum size for portfolio and individual wind farms

The frequencies of the forecast and measured ramp events from the UK portfolio for forecast horizons of 3 and 24 hours are shown in table 2 above.

For forecast horizons of 3 and 24 hours the portfolio ramp forecast has a higher ramp capture, predicting more of the measured ramp events than the forecast for individual wind farms. However, more false forecasts of ramps are made, with a 32.8% probability of a ramp occurring given a forecast ramp for a 3 hour horizon, and a 37.5% probability of a ramp occurring given a forecast ramp for a 24 hour horizon. The reason for the poor accuracy of portfolio ramp forecasts is that ramp events in the portfolio forecast data are identified using the method designed to identify forecast ramps for individual wind farms. This method is better suited to individual wind farms than to a portfolio.

Although the forecasting of ramp events using this method is less accurate than for individual wind farms, the overall forecasts are accurate enough to give good warning of upcoming changes in portfolio power production, as illustrated in figure 3 in section 2.4.2 above.

Figure 6 shows one case in which the method used to forecast ramp events predicts that a ramp may occur on the 10th December, but the measured change in power is not rapid enough to constitute a ramp event based on the definition used. Although the ramp forecast is technically incorrect, the forecast predicts the timing of the change in power well. This serves to illustrate the fact that further work to refine the method by which ramp events are predicted based on forecast power is necessary for portfolios.

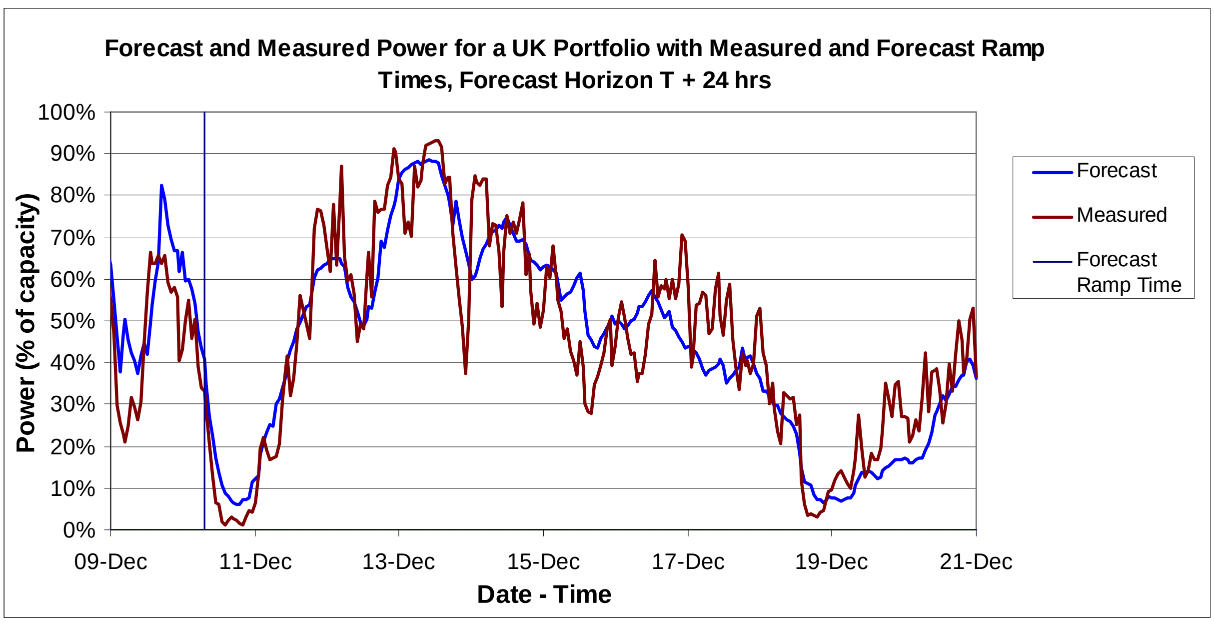

Figure 6- Power time history for a portfolio of wind farms with a forecast horizon of 24 hours, with a forecast ramp

3.1.3 US sites

The frequencies of forecast and measured ramp events for individual US wind farms are shown in table 2 above. The accuracy of individual US site forecasts is lower than for individual UK site forecasts for forecast horizons of both 3 hours and 24 hours, with ramp captures of 35.5% and 29.6% respectively and forecast accuracies of 59.1% and 57.8%.

This work also shows ramp events to be more common in the US wind farms analysed than in the UK, it should be noted that the US wind farms were located within one state, so these results should not be interpreted as a comparison of all US and UK wind farms. Data from UK wind farms show an average measured ramp frequency of 0.54 ramps per day, compared to 0.85 ramps per day for US wind farms.

3.2 Temporal uncertainty

The probability distributions of the time differences between forecast and measured ramp events for individual UK wind farms and individual US wind farms are shown in figure 7 and 8 below.

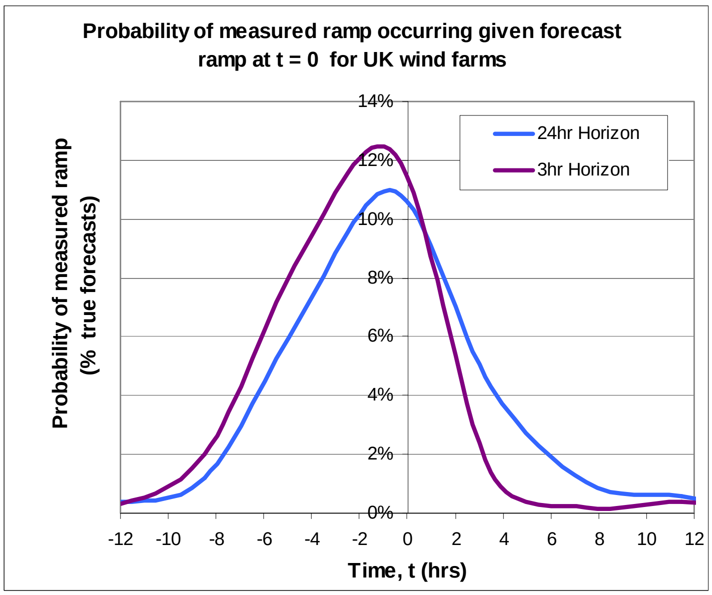

Figure 7- Probability of measured ramp occurring given a forecast ramp at t = 0

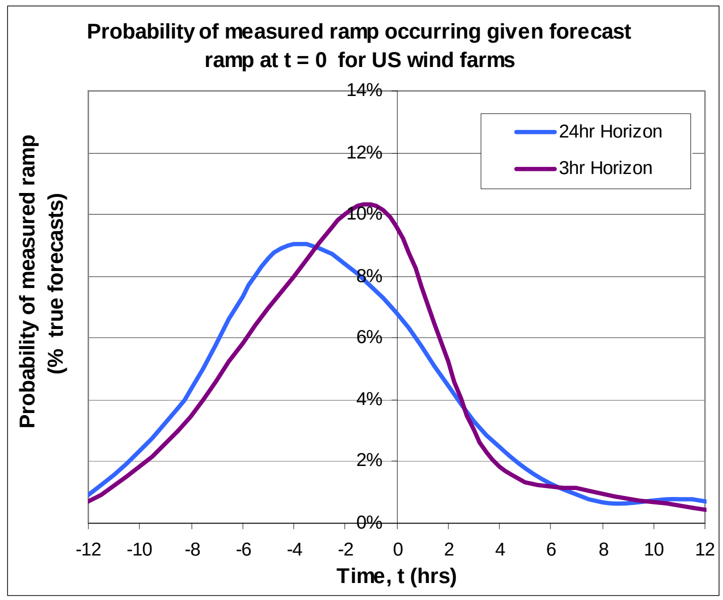

Figure 8- Probability of measured ramp occurring given a forecast ramp at t = 0

3.2.1 UK Sites

It can be seen in figure 7 that the temporal distributions of measured ramps around the associated forecast ramps approximate normal distributions, with a smaller spread for a 3 hour forecast horizon than for a 24 hour horizon. The negative bias of the distributions can be explained by the use of feedback data in the forecasts. Measured ramps may affect the forecast after they occur, but not before, leading to a greater number of late forecast ramps than early forecast ramps.

3.2.2 US Sites

Figure 8 shows similar temporal distributions to those shown in figure 7 for UK sites, which approximate normal distributions, but with a wider spread, which is in line with the lower forecast accuracies measured. Both distributions, but particularly that for the 24 hour forecast horizon, are somewhat skewed due to the smaller data set used for US farms, having approximately 34% of the number of wind farm hours used for the UK sites.

3.2.3 Presentation of temporal forecast uncertainty for ramp events

Of the different presentation styles investigated by GH the best method for displaying temporal uncertainty on a plot of forecast power is shown below in figure 9. The probability of a ramp event occurring at a given time is presented as a temporal distribution around the forecast time for the ramp.

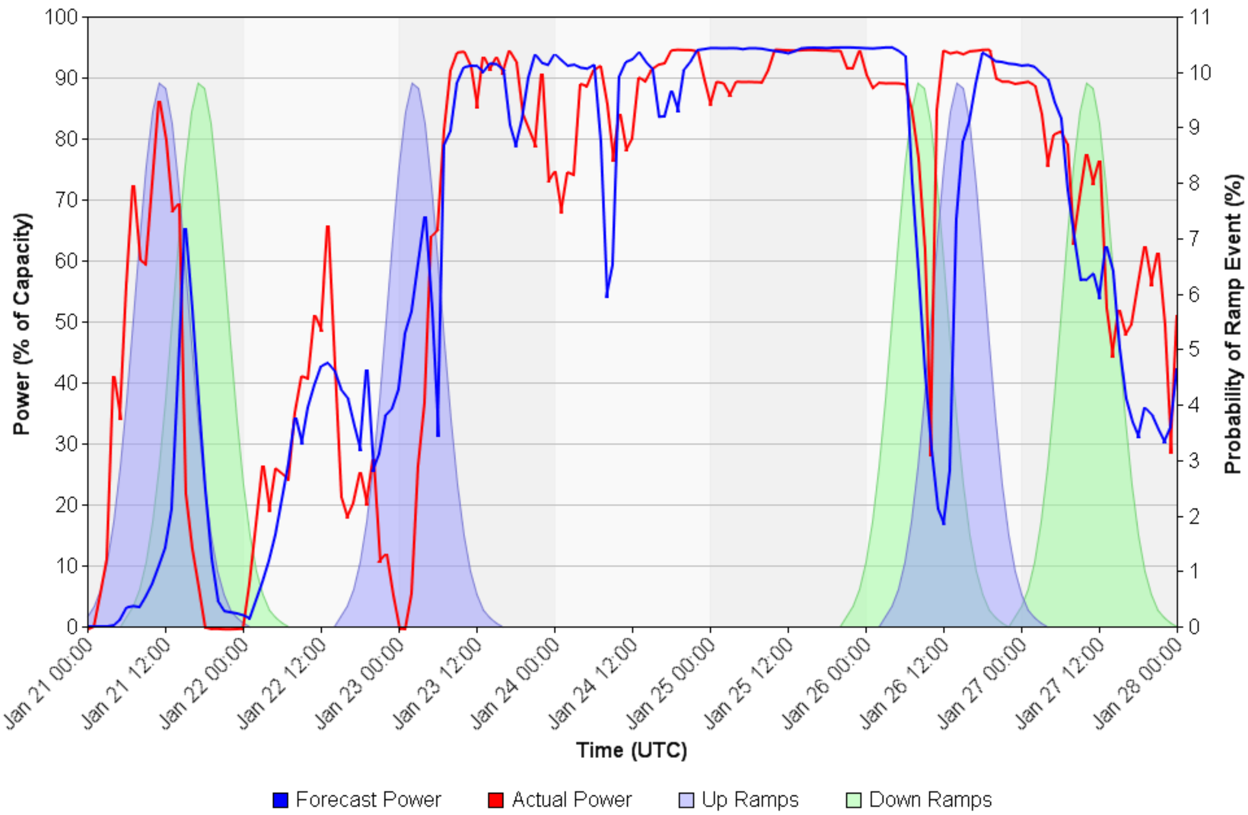

Figure 9- Forecast power with ramp event temporal uncertainty for a horizon of 24 hours

3.3 NWP combination

Table 3 shows the ramp frequencies and forecast accuracies of three forecasts for a wind farm in the UK with a capacity of 72MW. The forecasts cover the same time period, and consist of two forecasts from separate NWP data sources and one forecast from the two sets of NWP data combined.

Table 3- Ramp frequencies and forecast accuracies for forecasts for a single wind farm based on individual and combined NWP sources

NWP source used	NWP1	NWP2	Combined
Number of true forecasts	78	97	80
Number of false forecasts	67	79	65
Number of missed ramps	127	108	125
Forecast accuracy (%)	53.8%	55.1%	55.2%
Ramp capture (%)	38.0%	47.3%	39.0%

It can be seen that by using current intelligent methods for NWP combination the forecast accuracy is slightly better than that for either NWP forecast used on its own, but that the better NWP forecast has a ramp capture nearly 10% higher than the combination and the other NWP forecast.

It is generally understood that combining NWP data from different sources will improve the accuracy of forecasts, and this is usually the case if minimising the overall error of a forecast (e.g. the mean absolute error, MAE) is the primary aim. However, this work shows that if the accurate prediction of ramp events is considered to be more important than minimising the MAE, the combination of NWP feeds using the current method will not necessarily give the best forecast.

For future improvements to ramp forecasts, identifying which are the better NWP feeds for forecasting ramp events and tailoring the combination of NWP data to optimise ramp forecasting could significantly improve the accuracy of ramp event forecasting.

4. Conclusions

The temporal uncertainty of ramp event forecasting using the current forecasting method is approximately a normal distribution around the mean time difference between forecast and measured ramps. For a collection of UK wind farms this distribution has a standard deviation of 4.0 hours for a forecast horizon of 24 hours, and 3.3 hours for a forecast horizon of 3 hours. The mean value of time difference between forecast and measured ramp events is negative. This is more pronounced for the shorter forecast horizon, and is most likely due to the effect of feedback data. There is variation between individual sites, but due to the rarity of ramp events, the data set used is not large enough to quantify the differences between wind farms and factors that may affect this.

The best method of presenting temporal uncertainty data to give warning of possible ramp event timings is shown in figure 11 in section 3.3.3 above.

For single wind farms, the forecast accuracy falls in the range 59-67%, which represents the probability of a ramp occurring in measured data within ±12 hours of a forecast ramp. However, many measured ramp events were not forecast, with a ramp capture of only 34-47%. Ramp event temporal forecasting was found to be more accurate at a shorter forecast horizon than at a longer horizon, which is in agreement with trends in general forecast accuracy.

Despite the high accuracy of portfolio forecasts, the method used to predict ramp events for individual sites is not optimal for portfolios, as the ramp forecasts had low forecast accuracy for the UK portfolio and low ramp capture for the US portfolio.

5. Future work

Conducting further tailoring of the forecasting method for ramp forecasting is likely to achieve improved capture of ramp events, so further work on improving ramp forecasting for individual wind farms and portfolios is required. Further work on ramp event forecasting for portfolios is important, as the best method for identifying forecast ramp events for individual wind farms does not also give the best ramp forecast for a portfolio. Different definitions of a forecast ramp event should be considered.

The analysis of separate and combined NWP data shows that although the combination of NWP data using current methods reduces the overall error of forecasts, ramp event forecast information may be lost through the combination. One step towards improving ramp event forecasting is the optimisation of NWP combination for predicting ramps, including further work with ensemble NWP data.

As improvements are made to ramp event forecasting, further discussion with end users is necessary to guide what is most useful in a ramp forecast. Grid operators and energy traders will be consulted to optimise the forecast to be useful for informing energy scheduling and energy trading. This will help to improve both the ramp event prediction of the central forecast and the presentation of temporal uncertainty.

6. References

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