

Technical University of Denmark



Assessment of storm forecast

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Publication date:
2011

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Cutululis, N. A., Hahmann, A. N., Huus Bjerger, M., Gøttig, A., Hansen, L. H., Detlefsen, N., & Sørensen, P. E. (2011). Assessment of storm forecast. www.twenties-project.eu.

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“Assessment of storm forecast”
Deliverable n°: 6.1



EC-GA n° 249812

Project full title: Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions



Assessment of storm forecast

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Assessment of storm forecast

Document info sheet

Document Name:	Assessment of storm forecast
Responsible Partner:	Risø DTU
WP:	6
Task:	6.1
Deliverable n°	6.1
Revision:	01
Revision Date:	
Author:	Nicolaos A Cutululis

Diffusion list

All Partners

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Documents history

Revision	Date	Main modification	Author
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Assessment of storm forecast

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EXECUTIVE SUMMARY

When wind speed exceeds a certain value, wind turbines shut-down in order to protect their structure. This leads to sudden wind plants shut down and to new challenges concerning the secure operation of the pan-European electric system with future large scale offshore wind power.

This task aims at analysing the ability of existing forecast tools to predict storms at the Horns Rev 2 wind farm. The focus will be on predicting the time where the wind turbine will need to shut down to protect itself, e.g. the time where wind speed exceeds 25 m/s. At the same time, the planned shut-down should cost as little lost wind energy as possible. Therefore, the planned shut down time should be as close as possible to the time where the wind turbine itself would shut down, but still reliable. The forecast systems available to ENERGINET.dk will be applied.

The forecast tools ability of accurately predicting storms was analysed based on historical meteorological data available at Risø DTU and dynamically down-scaled to the Horns Rev 2 wind farm level. This solution was chosen due to the lack of measurements. Moreover, since the project started, there were four events during which Horns Rev 2 wind farm stopped, completely or partially, producing due to extreme wind speeds. Wind speed and power measurements from those events are presented and compared to the forecast available at Energinet.dk. The analysis looked at wind *speed* and wind *power* forecast.

The main conclusion of the analysis is that the wind *speed* forecasts are not very reliable in predicting when Horns Rev 2 wind farm will stop producing due to a storm. One of the reasons for that is the fact that there is no clear and precise definition of Extreme Wind Period (EWP) at wind farm level (how many wind turbines should stop producing in order to consider it an EWP) and that the available wind speed forecasts are given as a mean wind speed over a rather large area. At wind *power* level, the analysis shows that prediction of accurate production levels from a wind farm experiencing EWP is rather poor. This is partially because the power curve typically used to transform wind *speed* into *power* has not been optimised for high wind speeds. This means that today, the wind *power forecast error* that the TSO's control room is facing when dealing with EWPs is around 1 p.u.

1 INTRODUCTION

This report is presenting the work done in the TWENTIES project work package 6, Task 6.1: Storm forecasting [1]:

This task will analyse the ability of existing forecast tools to predict storms at the Horns Rev 2 wind farm where the demonstration will take place. The idea is to assess the uncertainty in a way that will enable a planned wind farm shut down, which has a high reliability of not being “bypassed” by wind turbine protection. The performance of existing forecast tools has been analysed in many studies, but using performance indicators such as RMSE (root mean square error) and MAE (mean average error). These indicators are useful for normal operation, but much less relevant for storm forecasts. There, focus will be on predicting the time where the wind turbine will need to shut down to protect itself, e.g. the time where wind speed exceeds 25 m/s. At the same time, the planned shut down should cost as little lost wind energy as possible. Therefore, the planned shut down time should be as close as possible to the time where the wind turbine itself would shut down, but still reliable. The forecast systems available to ENERGINET.dk will be applied.

The work done in work package 6 aims at preparing the framework for demo #4, STORM MANAGEMENT, whose objectives described in [1] are:

The occurrence of storms will raise new challenges when it comes to secure operation of the whole European electric system with future large scale offshore wind power. With the present control schemes, storms will lead to sudden wind plant shut downs, which in turn is a threat to the whole system security, unless standby reserves are ready to take over power demands under very short notice. The challenge that this demo is addressing is to balance the wind power variability, operating the transmission grid securely during such storm conditions. The more specific objectives of the demodemonstration is to:

- *Demonstrate secure power system control during storm passage, using hydro power plants in Norway to balance storm shut down of Horns Rev 2 wind farm in Denmark.*
- *Use existing forecast portfolio available to the TSO to monitor and plan the down regulation of large scale offshore wind power during storm passages.*
- *Provide more flexible wind turbine and wind farm control during storms.*

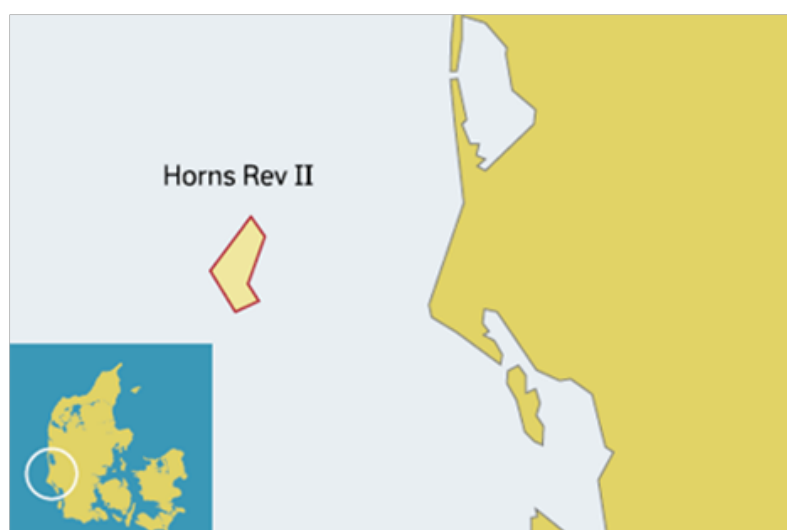


Figure 1 Horns Rev 2 wind farm, source [2]

The demo #4 will be done at Horns Rev 2 offshore wind farm, located off the west coast of West Denmark, see Figure 1.

The wind farm is owned by DONG Energy and the turbines are supplied by Siemens and are of the type SWP 2.3-93. Each wind turbine has a capacity of 2.3MW. With a total of 91 wind turbines the wind farm has an overall capacity of 209MW [2]. The wind farm became fully operational in September 2009. The connection to shore, realised by Energinet.dk is given in and presented in

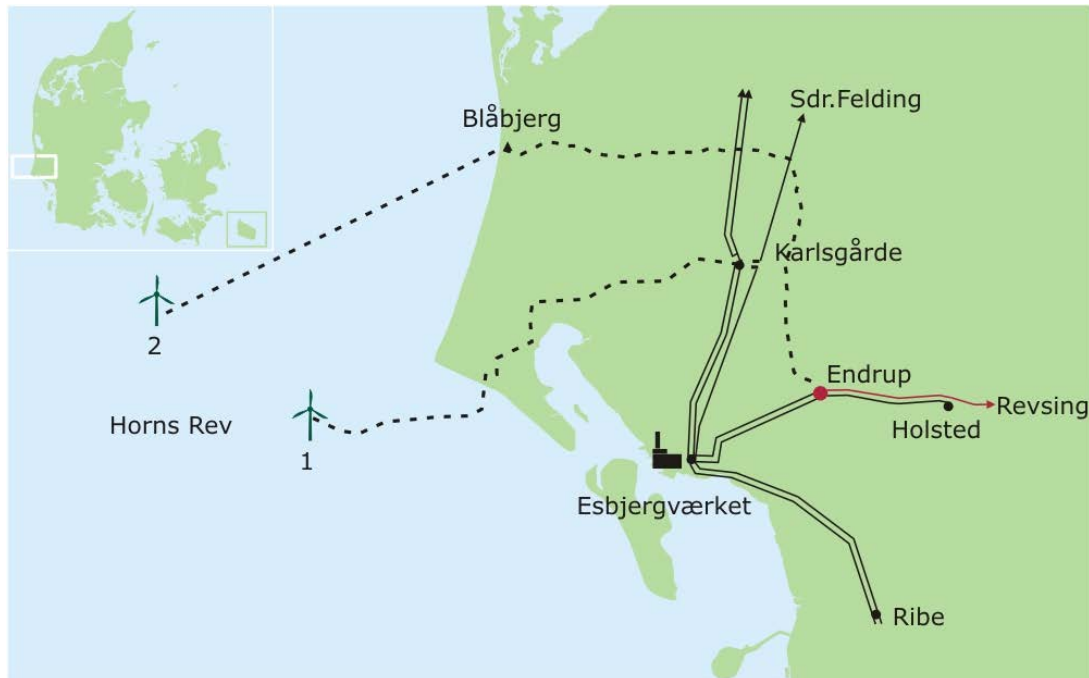


Figure 2 Connection to shore, source [3]

The main barrier encountered in our analysis is the lack of measured data. The wind farm has been fully operational for only a little longer than a year. This was overcome by using historical meteorological data available at Risø DTU.

After the brief description of how Energinet.dk is using the wind speed and power forecasts in the next section, the definition of the extreme wind periods (EWP) and a description of the used historical data are given in chapters 3 and 4 respectively. The analysis based on the historical data is done for wind speed and wind power forecasts, separately, in chapters 5 and 6. Since the start of the project, a number of EWP's have been recorded at Horns Rev 2 wind farm and they are analysed in the final section of the report, which concludes with a conclusion chapter.

2 FORECASTING SYSTEM USE

For a secure operation of power systems even when the share of energy produced by wind is not very significant, i.e. more than 5-10%, forecasting of wind power has become an indispensable tool. The Danish Transmission System Operator (TSO) Energinet.dk is no exception to that.

Energinet.dk, as TSO, is responsible for the transmission and permanent balance between production and consumption, even if it does not own or operate directly any generating or consuming facilities. All production and consumption entities plan their production or consumption and are obliged to send in detailed schedules. These schedules are continuously updated.

Based on the schedules Energinet.dk calculates the systems imbalance and can trade this in the regulating power market. If production facilities deviate from the schedules, which is often the case in a storm situation, Energinet.dk will see a sudden imbalance that has to be taken care of, either by slow manual reserves or by automatic reserves. Energinet.dk has meteorological forecasts available and calculate their own wind power forecasts optimized to minimize the aggregated wind power imbalances. Meteorological forecasts from DMI's Hirlam model are updated every 6 hours.

If a storm is forecasted correctly, then it will be possible to do a controlled action to prevent severe imbalances. In this case there are several options for calling for this controlled action. The owner of the wind farm can choose to reduce power gradually before the storm or the TSO can call for a gradual reduction of power output. If the wind farm's output is reduced there will be some lost power. The challenge in this situation is to define the strategy for taking action (based on the forecast) in such a way that the lost power is minimized and the safety of the entire scaled future system is maintained.

3 EXTREME WINDS PERIOD

When wind speed is becoming too strong, wind turbines are shutdown to prevent damage due to extreme mechanical loads. The typical power curve of a modern wind turbine is presented in Figure 3. The wind turbine will shut down when the average wind speed reaches a certain value denoted V_4 in the Figure 3. When the average wind speed drops below the shutdown value, the wind turbine starts again. To prevent frequent restarts and shutdowns, hysteresis is often applied, so that the wind turbine starts up only when the average wind speed reaches a value V_3 lower than the shutdown wind speed.

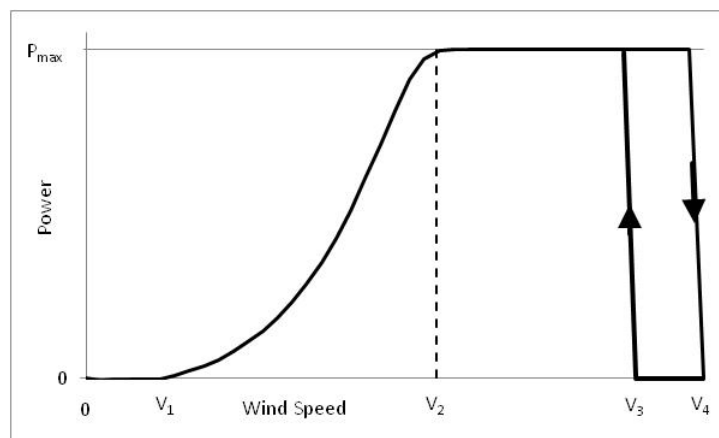


Figure 3 Typical wind turbine power curve

The typical value for which a wind turbine will initiate shut-down is when the 10-minute average nacelle anemometer wind speed reaches 25 m/s (V_4) and they will restart when the measured wind speed drops below 20 m/s (V_3). Consequently, an extreme wind period (EWP) is defined to be the one in which the storm control is active and is considered to occur when the wind speed exceeds the cut-out speed and lasts until the wind speed drops below the cut-in speed.

The meteorological forecasts are given as the average value over an area defined by the grid points distance (15km spatial resolution for the meteorological forecast at Energinet.dk) and with hourly resolution. This means that the forecasted wind speed values will not give proper results if used for predicting when individual wind turbines will initiate shut-down due to large wind speed. Instead, they should be used to assess the ability to predict storms at wind farm level.

A question that arises naturally is what are the values that characterize an EWP when looking at a large offshore wind farm as a whole. This subject was analysed based on measurements coming from Nysted wind farm and the result was that most of EWP's occur when the average wind speed over the whole wind farm is in the range [18 22.5] m/s. Therefore, this is the pair of wind speeds that, in the following, define an EWP.

4 HISTORICAL MODELLED DATA

The meteorological data come from a climate simulation using the Weather Research and Forecasting (WRF) model and the dynamical downscaling technique developed by Hahmann et al [5], but using Newtonian relaxation terms toward the large-scale analysis (also known as grid or analysis nudging). Initial and boundary conditions and the gridded fields used in the nudging are taken from the NCEP reanalysis [6] at $2.5^\circ \times 2.5^\circ$ resolution. The sea surface temperatures are obtained from the dataset of Reynolds et al [7] at 0.25° horizontal resolution and temporal resolution of 1 day. The simulation covers the period from 1 January 1999 to 31 December 2010 with hourly outputs. The model is run on an outer grid of spatial resolution of 45 km and a nested grid of 15km, respectively. The data from the inner domain, which covers most of Northern Europe, is used in this study. Additional details can be found in Peña and Hahmann [8].

We decided to use historical modelled data due to the lack of consistent measurements, covering a period of time large enough to have a statistical relevance in the attempt of assessing the performance of forecasts to predict EWP. The most consistent and lengthy data set available to the project partners comes from Nysted wind farm, located in the Baltic sea [1]. The data consists of the 10-minutes average wind speeds recorded by the anemometers on the nacelle of the individual wind turbines. What is interesting in this context is the wind farm average wind speed. Therefore, the mean wind speed over the whole wind farm was calculated as the average speed of all wind turbines in the wind farm. Further, the hourly mean wind speed was calculated and compared to the historical data. The data cover the period 2007 – 2010. The average wind speed, over the whole period, as well as the standard deviation for both measurements and historical data are given in Table 1.

Table 1 The statistics of measured and historical model data

	Measurements	Model
Average [m/s]	8.2	8.9
Standard deviation	3.34	4.25

The mean wind speed resulting from the down scaling of WRF data (the wind speed historical model data) is slightly higher than the one resulting from the averaging of the nacelle measurements. The variability of the time series is also different, with the historical data again having a larger standard deviation. The differences can be regarded as acceptable, especially if it is taken into account the fact that the measurements are from the nacelle anemometers situated on the individual wind turbine and behind the rotor.

Figure 4 shows measured versus historical model wind speed time series. There is a good match between them.

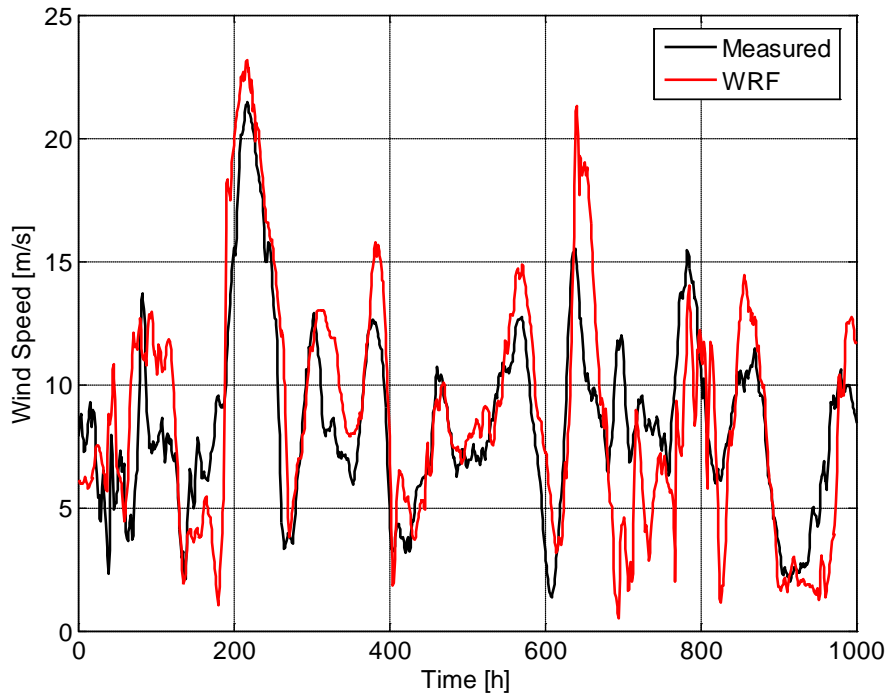


Figure 4 Measured versus historical model data

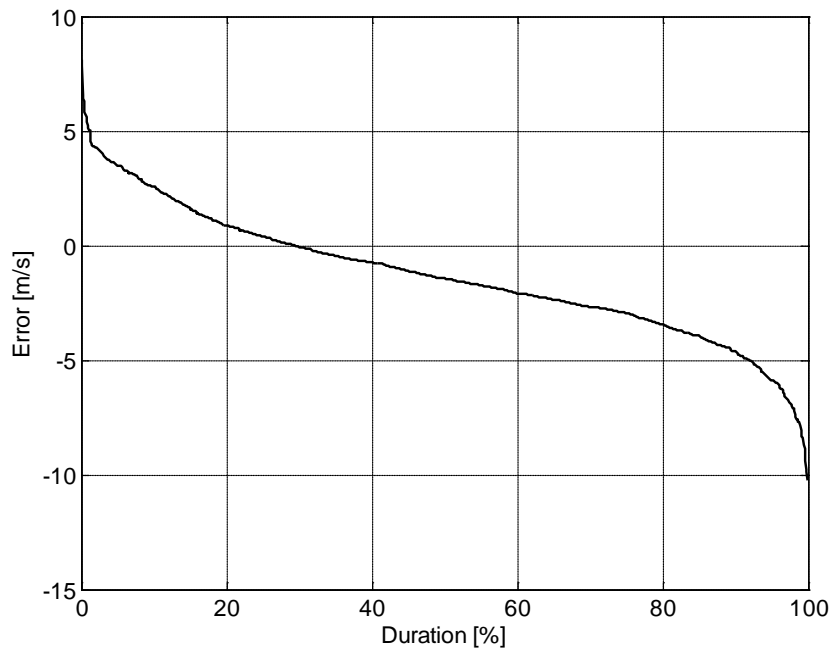


Figure 5 Distribution of the error between measured and historical modelled wind farm mean speed

The distribution of the error between the measured and the historical modelled wind farm mean wind speed is given in Figure 5. As expected, the error, which is defined as measured minus historical model, is more time negative, thus historical model values are bigger than the measured ones. This

is, partially, due to the fact that the available measurements are from the wind turbine nacelles, behind the rotor.

5 WIND SPEED FORECAST ERROR

The analysis of the ability of forecasting tools to predict storms at Horns Rev 2 offshore wind farm was done based on available data covering the time period February 2007 to November 2010 (45 months). The wind speed and direction are given at 10 and 100 meters height, with an hourly resolution. The forecasts are available from Energinet.dk.

5.1 Frequency and duration of occurrences

The yearly and the total number of forecasted EWP's versus the ones seen in the historical modelled wind speeds are given in the following. The analysis is done for both heights for which forecast are available, 10 and 100 meters, respectively.

When looking at the 10 meters high wind speed, the number of identified EWP's, per year and total, are shown in Figure 6 and the duration, grouped on 5-hours bins in Figure 7.

The same graphs, for the 100 meters high wind speeds are given in Figure 8 and Figure 9, respectively.

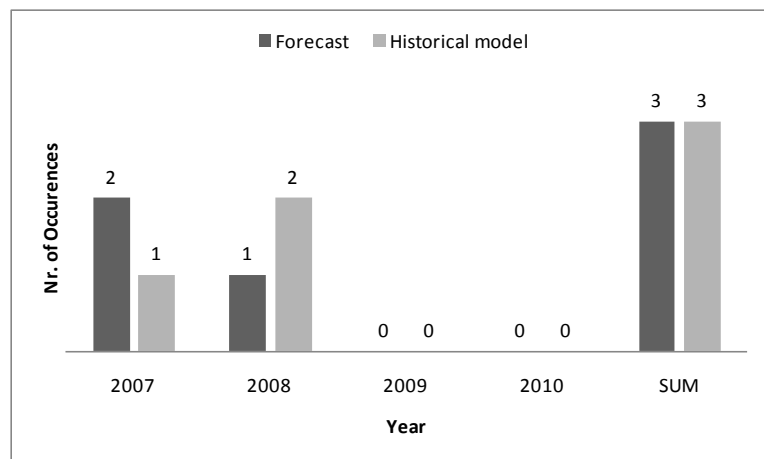


Figure 6 Number of EWP, 10 meters height wind speeds

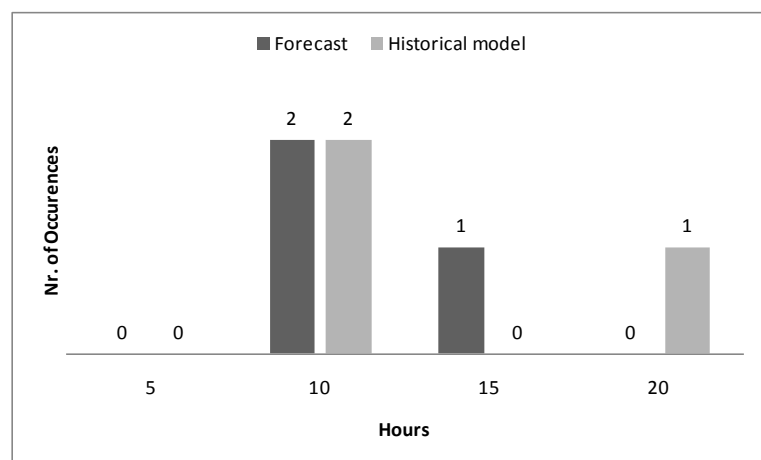


Figure 7 EWP durations with 5-hour bin. 10 meters high wind speeds

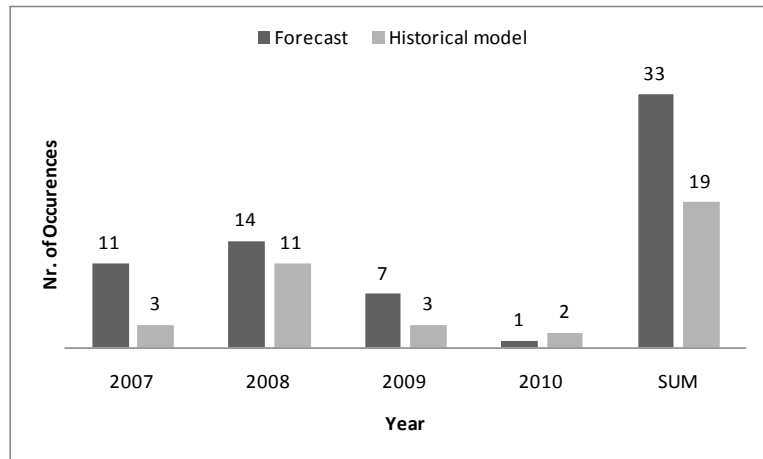


Figure 8 Number of EWP, 100 meters height wind speeds

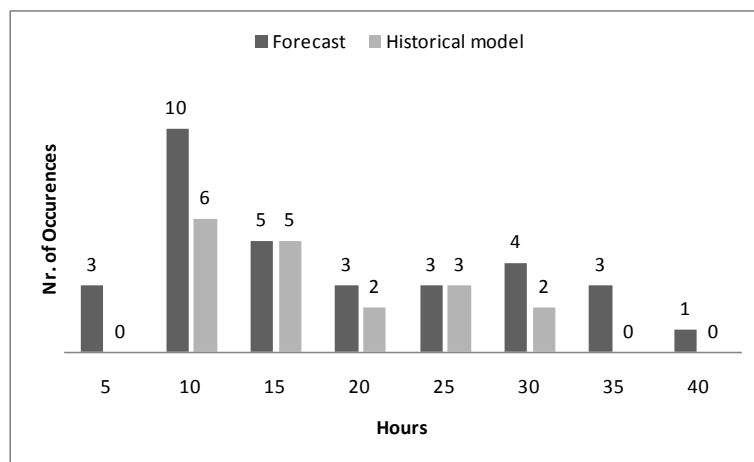


Figure 9 EWP durations with 5-hours bin. 100 meters high wind speeds

The analysis shows that there is a significant impact of the height in which the forecast is given over the number of EWPs. There seems to be a significant overestimation of the EWP by the forecast (33 forecast versus 19 resulting from the historical model data).

Besides the frequency and duration of the EWPs, it is also important to see the accuracy of the forecast. An accurate forecast, in this sense, is when an EWP did actually occurred during the day that it was forecasted. The result of this analysis is given in Table 2. It is clear that the accuracy of the forecast is rather poor, with less than 25% of the forecasted EWPs actually happening. Furthermore, when looking if the EWPs that occurred (appear in the historical model data) were also forecasted, it is observed that almost 60% of the EWPs were not forecasted at all.

Table 2 Accuracy of forecast

Historical model		Forecasted	Forecasted		Historical model
Yes	No		Yes	No	
8	25	33	8	11	19
24%	76%	100%	42%	58%	100%

5.2 Duration curves

The wind speed forecast error is defined as the difference between forecast and model wind speed, i.e. positive values of the forecast error means that the predicted wind speed is higher than the model wind speed. The duration curve of the wind speed forecast error, quantified during the predicted EWP, is given in Figure 10.

It can be concluded that there appears to be a systematic over estimation of the wind speed, in both 10 and 100 meters height, as the forecast error is positive for around 70% of the time. The forecast error is situated in the range of ± 5 m/s for most of the time.

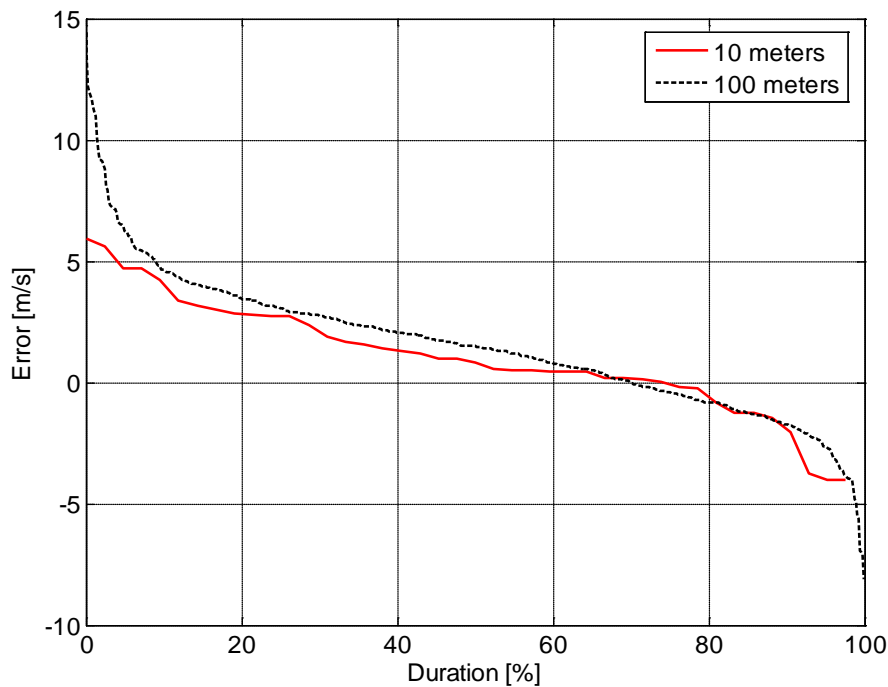


Figure 10 Duration curves of the wind speed forecast errors

6 WIND POWER FORECAST ERRORS

6.1 Power curve

The typical way of obtaining wind power production from forecast wind speeds is by using a static model of the wind turbine, namely the power curve. For a wind turbine, the power curve is defined using measured wind speed and power output values. The industry standard is to use 10-minutes averaged values. A typical wind turbine power curve is presented in Figure 11. When dealing with wind farms, one should use an aggregated wind farm power curve. The aggregated wind farm power curve for Horns Rev 2 was created by means of simulating all the wind turbines in the wind farm and then calculating the average wind farm wind speed and power. The simulations were done with the CorWind simulation model developed at Risø DTU [9], which simulates correlated wind speeds. The power produced by each individual wind turbine in the wind farm was obtained using the power curve given in Figure 11. The simulations were done with one minute time step.

The aggregated wind farm power curve was then calculated using the 1-minute, 10-minutes and 1-hour average values. This is done in order to be able to quantify the impact of the averaging interval on the power curve. The results are presented in Figure 12. The impact of the averaging period is

much more pronounced in the high wind speed area, i.e. the area where the storm control is active and it is shown in Figure 13.

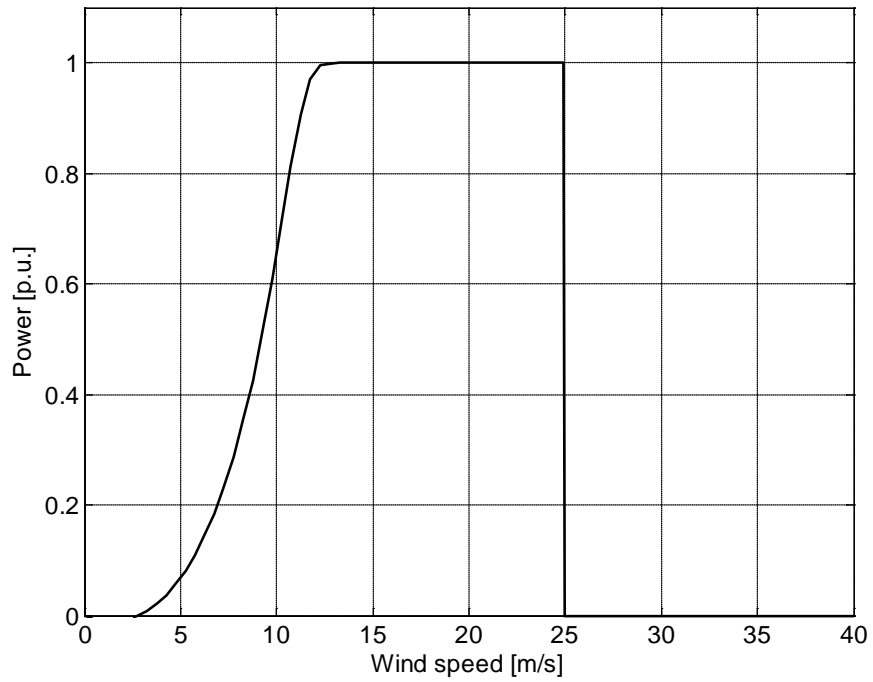


Figure 11 Wind turbine power curve

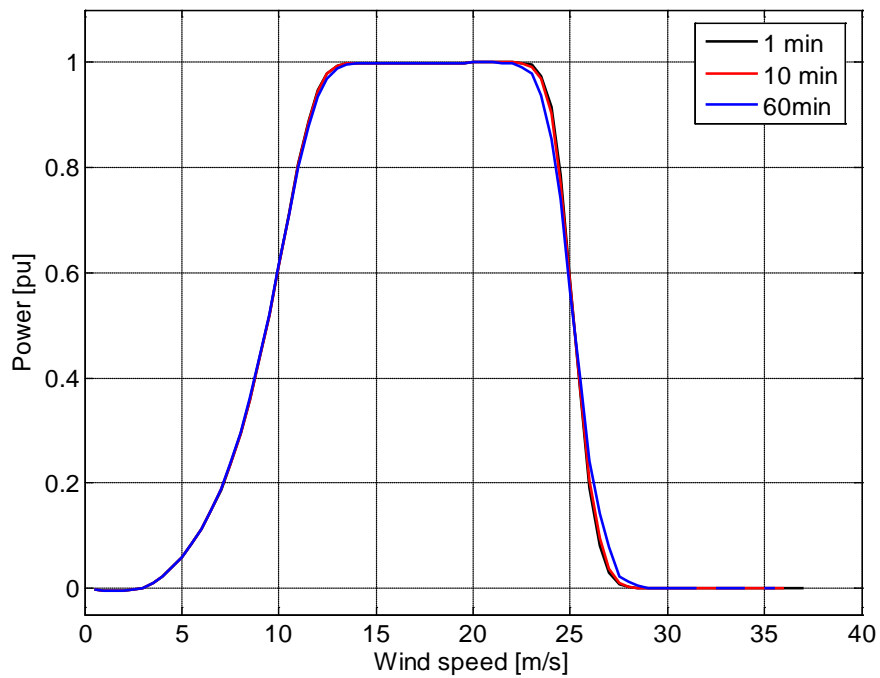


Figure 12 Aggregated wind farm power curve

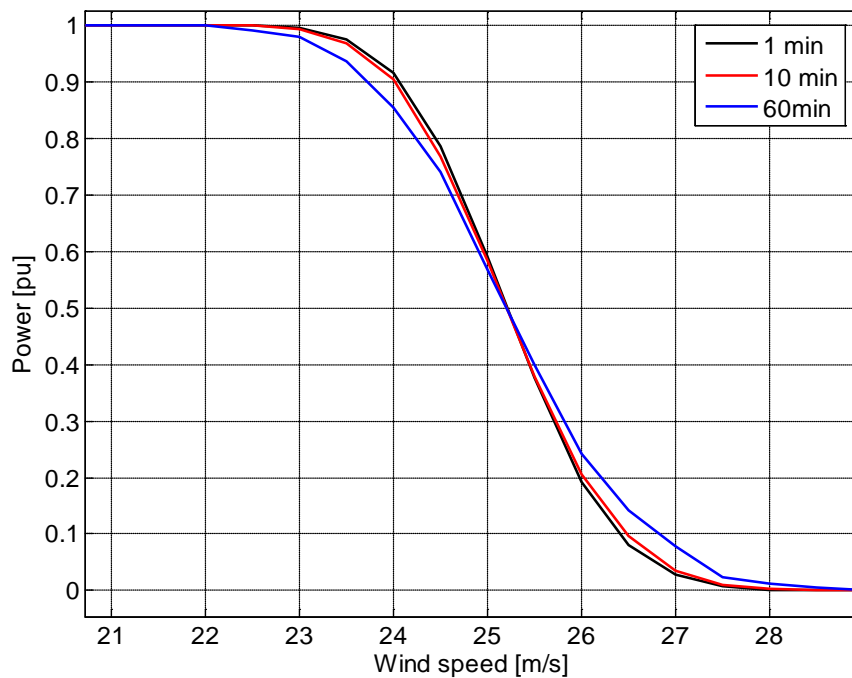


Figure 13 Detail of aggregated wind power curve

Therefore, it plays a very important role what power curve is used when predicting the wind farm power using forecast wind speeds. Today, practice says that the power curves used in the control rooms of the TSO's are optimized to best predict the power produced by the wind farm in the optimization range, i.e. wind speeds between 5 – 12 m/s. This makes sense, since the frequency of EWP's and the magnitude of the problems caused by one wind farm shutting down are rather low.

6.2 Wind power forecast errors analysis

Wind power is obtained by applying the aforementioned wind farm power curves to the forecast, respectively, historical model farm wind speed. Afterwards, the wind power forecast error is calculated as the difference between forecast and modelled power. For an easier understanding of the scale, the error is expressed in p.u.

Comparing forecasted and modelled power production, the maximum wind power forecast error, in absolute values, is given in Figure 14, for each EWP.

The duration curve of the wind power forecast error is shown in Figure 15.

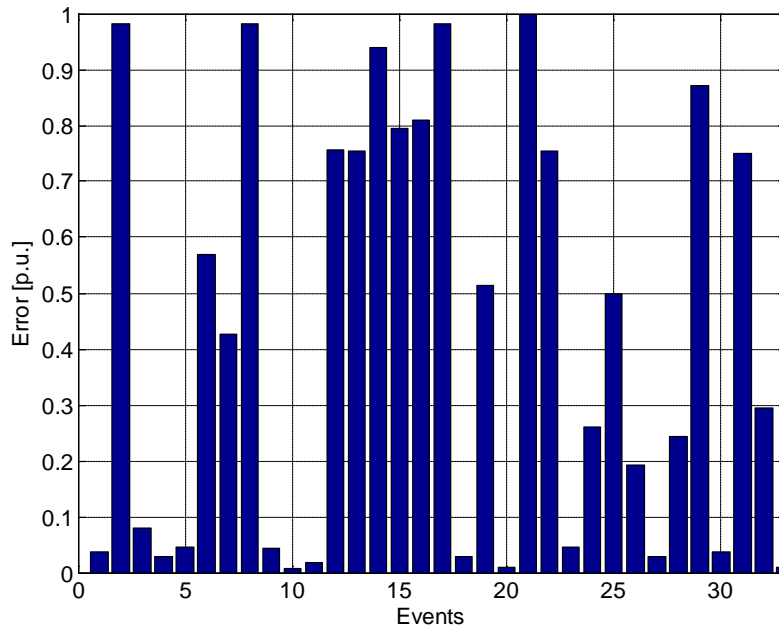


Figure 14 Maximum absolute wind power error for each predicted EWP

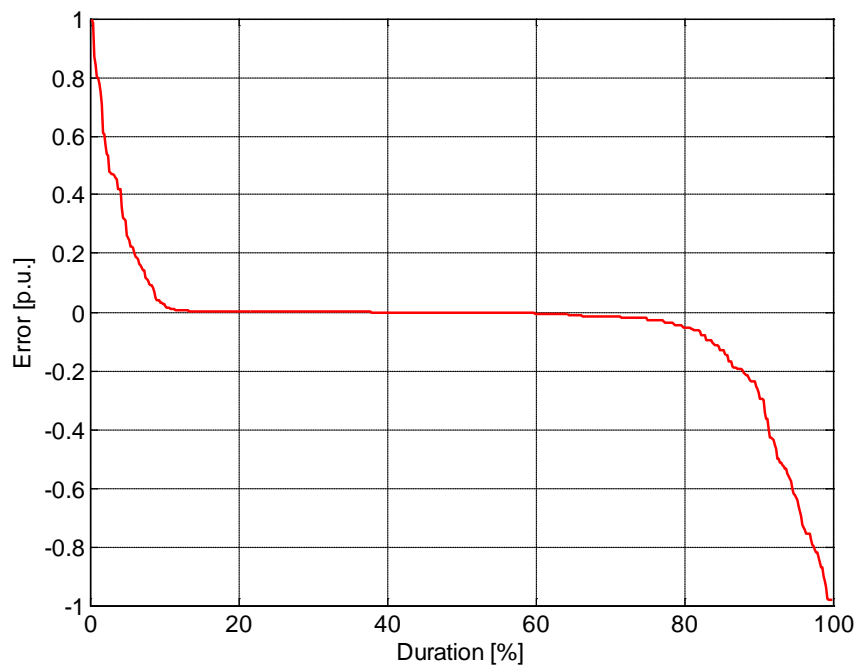


Figure 15 Wind power forecast duration curve

The analysis shows that in most cases, the wind power forecast error is in the vicinity of 1 p.u. When looking at the duration curve, it can be observed that in around 2/3 of the cases, the forecasts failed to predict the loss of power due to EWP (negative values of the error). This means that TSO's will have to deal with sudden and unexpected (not forecast) power losses of 1 p.u.

7 EXTREME WIND PERIODS IN HORNS REV 2

Since the start of the project, several EWPs have been recorded in Horns Rev 2 offshore wind farm. In the following, an analysis of those events is presented. The EWPs recorded and presented in the following are singular events and do not represent the most significant or the only possible types of EWPs. For that matter, all the EWPs recorded are rather slow, in terms of the time that it takes for the production to go from 1 p.u. to zero. This is not always the case. As an example, in a neighbouring wind farm, Horns Rev 1, an EWP recorded in 2005 and presented in [10], lead to a complete wind farm shut down in app. 3 minutes.

The layout of Horns Rev 2 wind farm, together with the numbering of the wind turbines, as used in some of the plots in the following, is presented in Figure 16

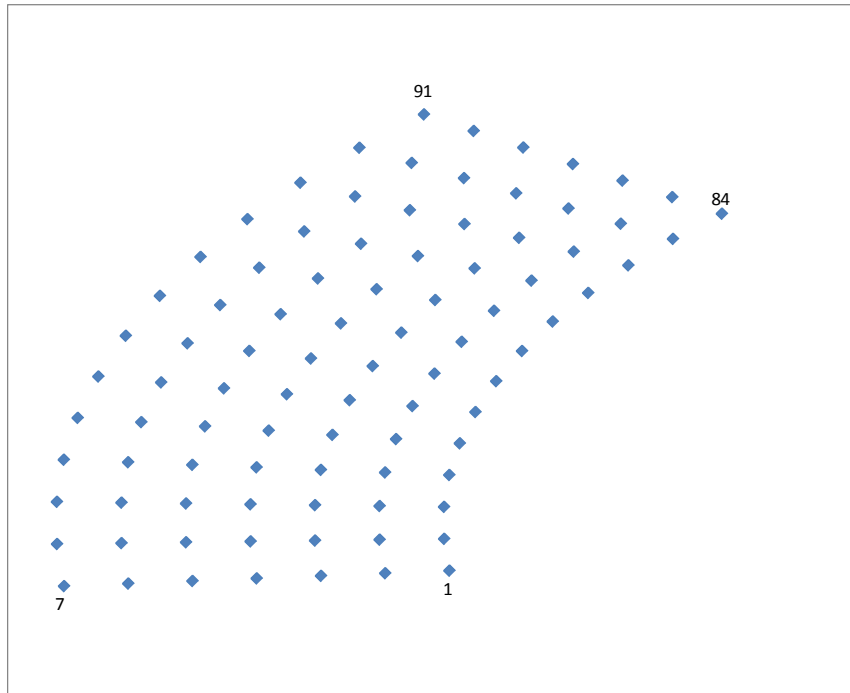


Figure 16 Horns Rev 2 wind farm layout and wind turbine numbering

7.1 11 November 2010

The first EWP occurred in the afternoon of November 11th, 2010. The weather continued to be unstable until the 12th of November. Two periods with very high wind speeds were recorded. The wind farm wind statistics of the wind speeds measured during the first period, from 16:00 to around 23:00 on November 11th, 2010, is shown in Figure 17. The sample time is 1 sec. and the wind speeds are measured on the individual wind turbine nacelle. The wind farm statistics are calculated as the mean value and minimum/maximum values of the 91 individual turbine wind speeds. The first conclusion arising is that the average farm wind speed never exceeds 25 m/s, even if some of the wind turbines experience wind speeds well above 25 m/s for several hours. This shows that, when dealing with mean farm wind speeds, the hysteresis for individual wind turbines, i.e. [20 25] m/s, is not able to predict the wind farm behaviour.

The wind speed forecast for November 11th is shown in Figure 18. The measured wind speed is the mean value of the wind turbine wind speeds, similar to the one in Figure 17, but with 1-minute sample. The forecast wind speed is the one available at Energinet.dk on November 10th at 12 AM and it is with 1-hour time step. The forecast is given in 10 m height. While there is a forecast available at 100 m height, the 10 m height forecast is shown here simply because this is the one used in Energinet.dk's wind power forecast system.

From Figure 18 it can be observed that the wind speed forecast is rather close to the measured one, but it does not exceed 22 m/s at any given time. This means that even when the proposed wind farm hysteresis of [18 22.5] m/s is used the EWP would not be predicted.

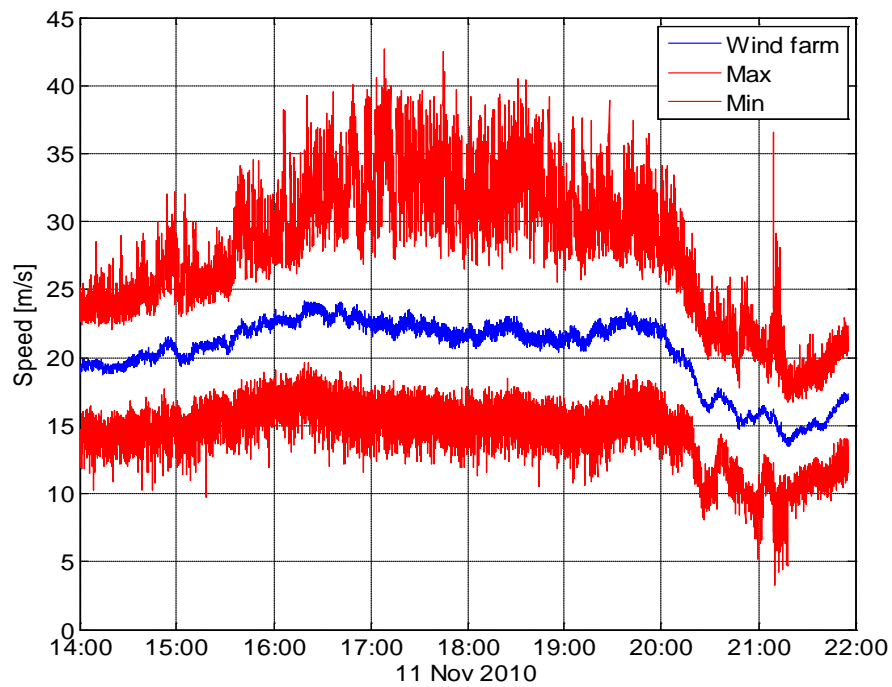


Figure 17 Measured wind speeds during 1st EWP

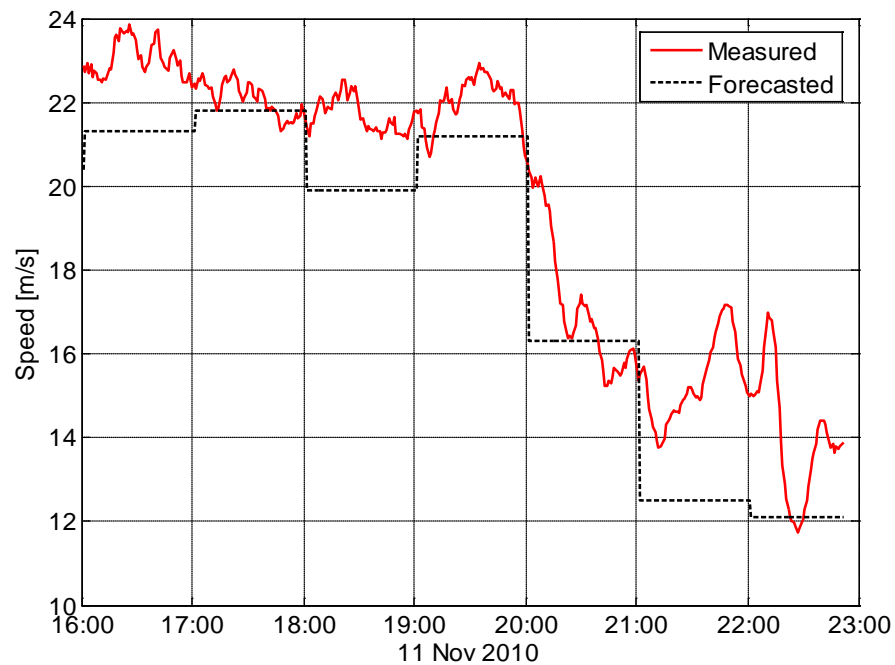


Figure 18 Horns Rev 2 wind speed forecast for November 11th EWP

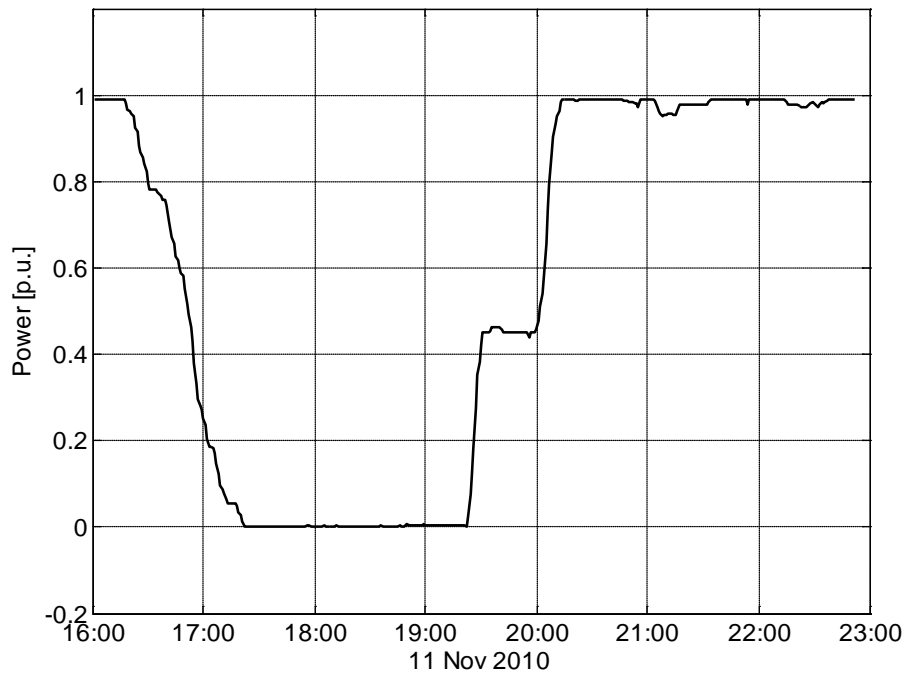


Figure 19 Power produced by Horns Rev 2 wind farm during November 11th EWP

The power produced by Horns Rev 2 wind farm during November 11th EWP is shown in Figure 19. The wind power production went from 1 p.u. to 0 in app. 55 minutes (16:17 – 17:22), which implies a ramp of app. -3.8 MW/min or -0.02 p.u./min. These values are not posing a big challenge in the operation of the West Denmark power system.

The production of the individual wind turbines in the farm, along with the overall production are shown in Figure 20.

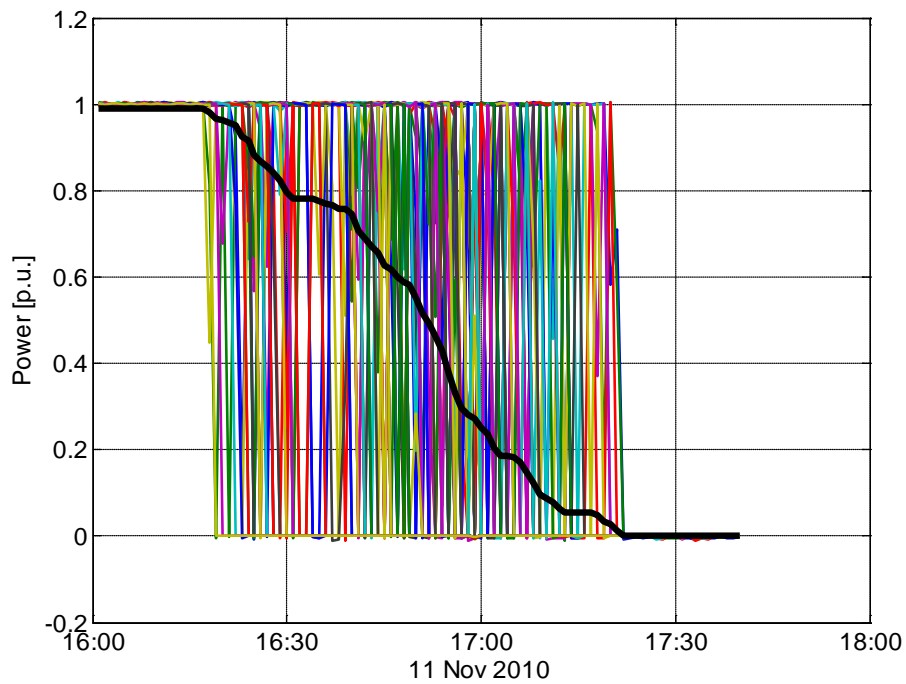


Figure 20 Wind turbine and wind farm production

The wind power forecast, based on the online measurement data and running every 15 minutes, is shown in Figure 21. The online wind power forecast has a 5-min resolution. Based on those forecasts, the control room operators will not have any prediction about the loss of wind power produced by Horns Rev 2.

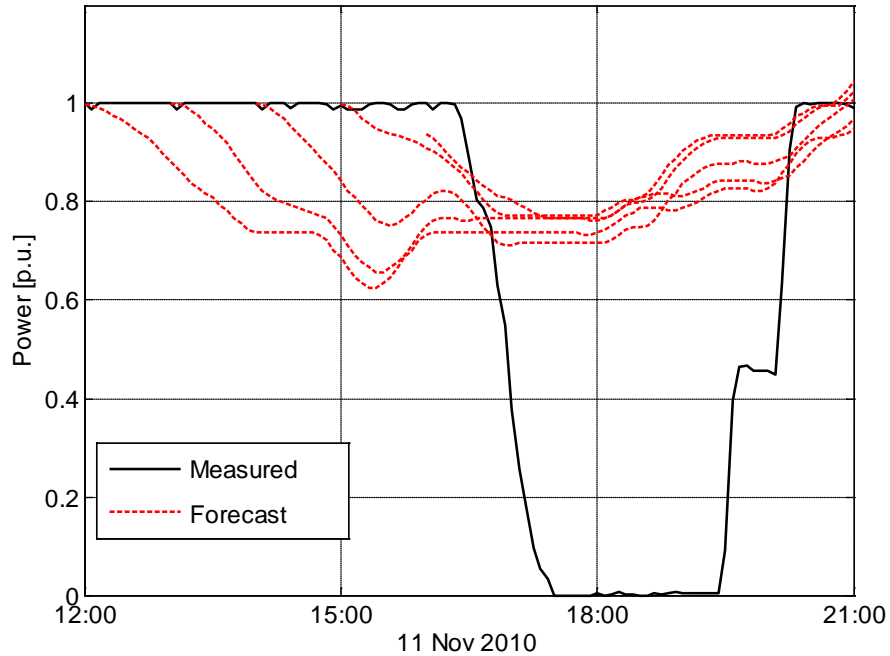


Figure 21 Measured versus hourly intra-day forecast wind power

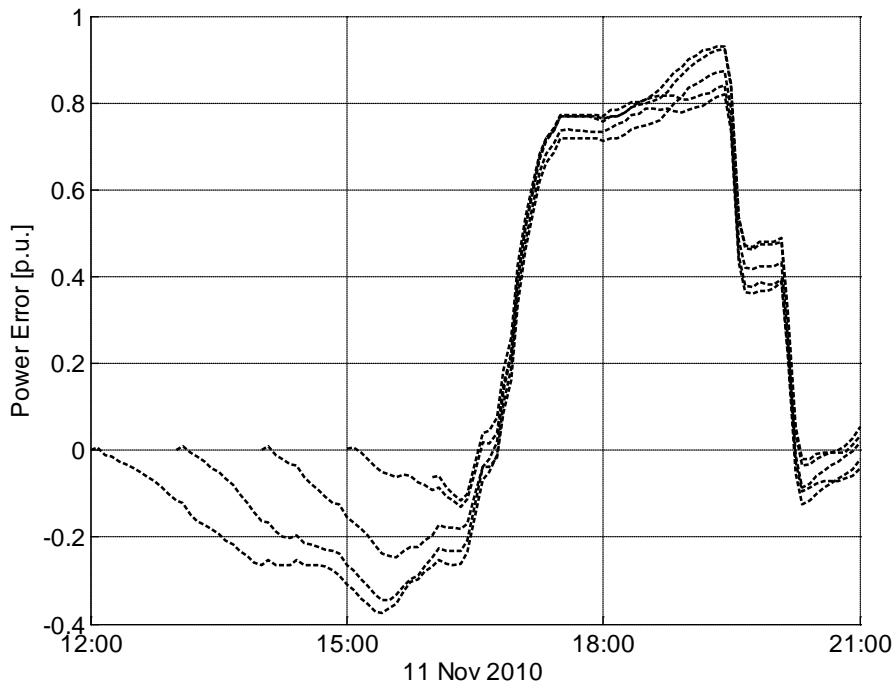


Figure 22 Wind power forecast error during November 11th, 2010 EWP

The forecast error, defined as forecast minus measured wind power production is given in Figure 22.

The impact of the EWP over the wind farm is presented in Figure 23, where the power production for each wind turbine is presented. One can note that all the wind turbines in the farm shut-down for a period of time. The way the wind turbine numbering relates to the wind farm layout is shown in Figure 16.

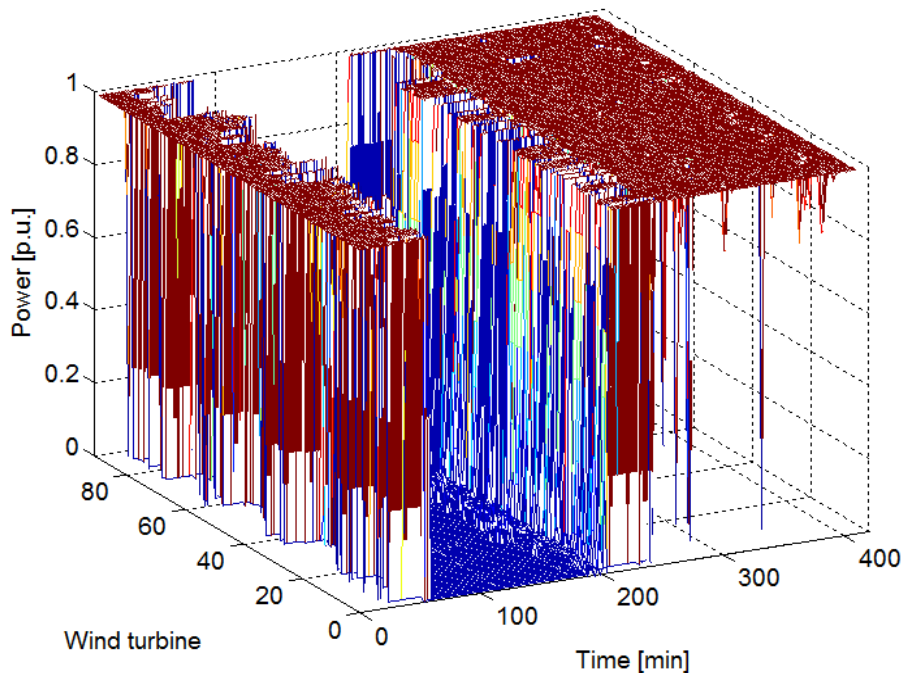


Figure 23 Horns Rev 2 wind turbine power production during November 11th EWP

7.2 12 November 2010

The second EWP occurred only a few hours after the first one, in the morning hours of November 12th, 2010, from around 06:00 to 13:00. The wind farm wind statistics of the wind speeds measured during the EWP are shown in Figure 24. The sample is 1 sec and the wind speeds are measured on the individual wind turbine nacelle. The farm wind statistics are calculated as the mean value and minimum/maximum values of the 91 individual turbines wind speeds.

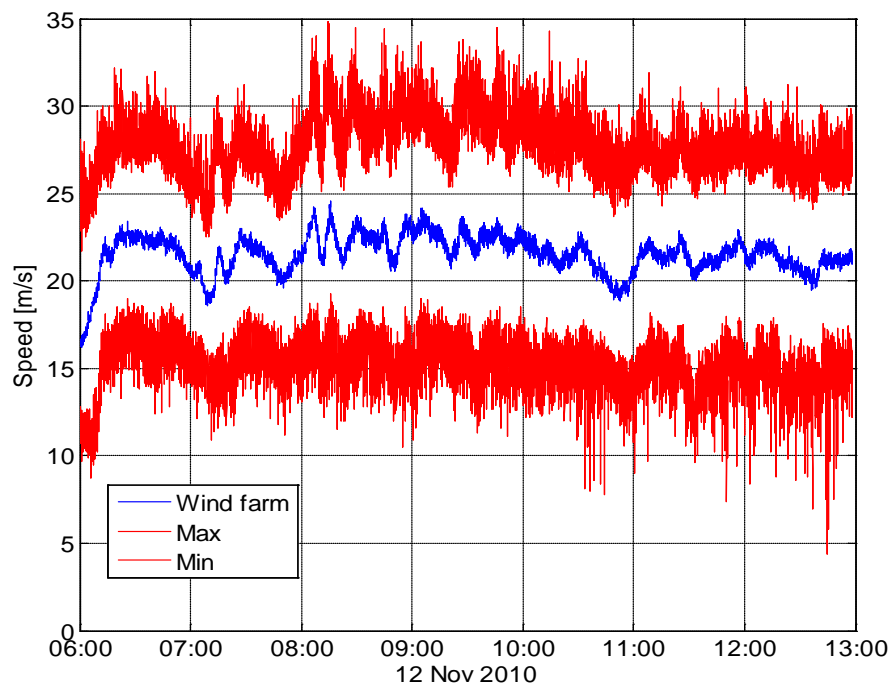


Figure 24 Measured wind speeds during 2nd EWP

Similarly to the first EWP, the mean farm wind speed does not exceed 25 m/s, but the mean wind speed values are inside the proposed wind farm hysteresis of [18 22.5] m/s.

The wind speed forecast for November 12th is shown in Figure 25. The measured wind speed is the mean value of the wind turbine wind speeds, similar to the one in Figure 24, but with 1-minute sample. The forecast wind speed is the one available at Energinet.dk on November 11th at 12 AM and it is with 1-hour time step. The wind speed forecast underestimates the magnitude and it would fail to predict the EWP even when the proposed wind farm hysteresis of [18 22.5] is used.

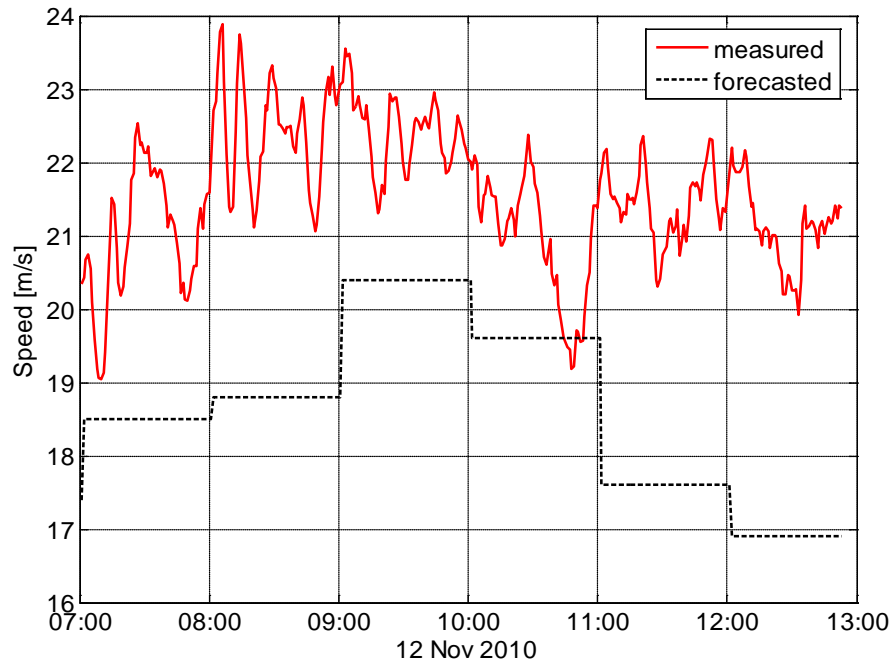


Figure 25 Horns Rev 2 wind speed forecast for November 12th EWP

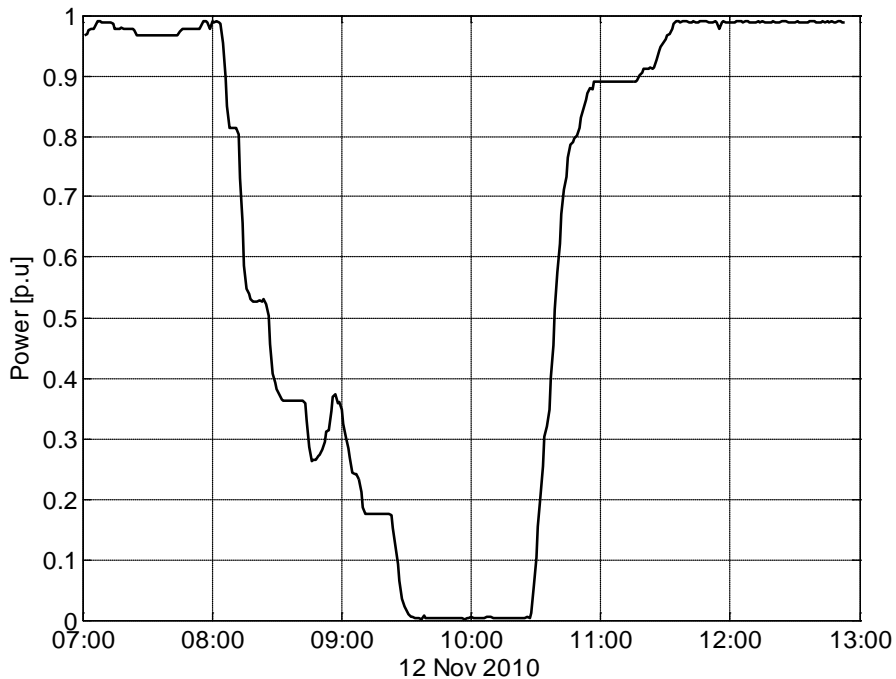


Figure 26 Power produced by Horns Rev 2 wind farm during November 12th EWP

The power went from 1 p.u. to zero in app. 1.5 hours, i.e. 8:00 to 9:37 am, which means a ramp of app -2.1 MW/min or -0.01 p.u./min. This ramp rate does not create problems for the secure operation of the West Denmark power system.

The forecast versus the measured wind farm produced power is shown in Figure 27. Again, the forecasts fail to capture the evolution of the wind farm production, leading to wind power forecast errors of almost 1 p.u. (Figure 28).

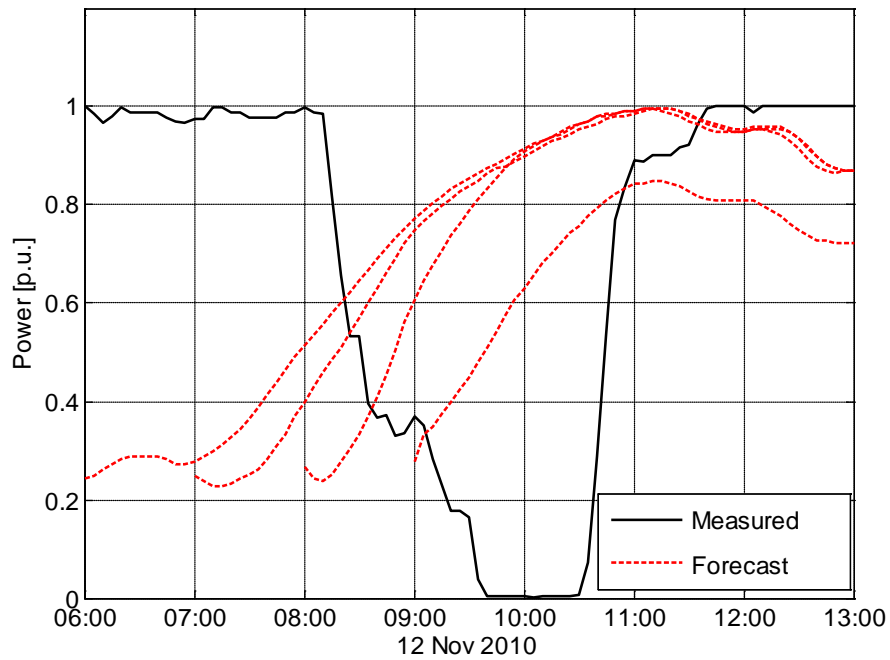


Figure 27 Measured versus hourly intra-day forecast wind power

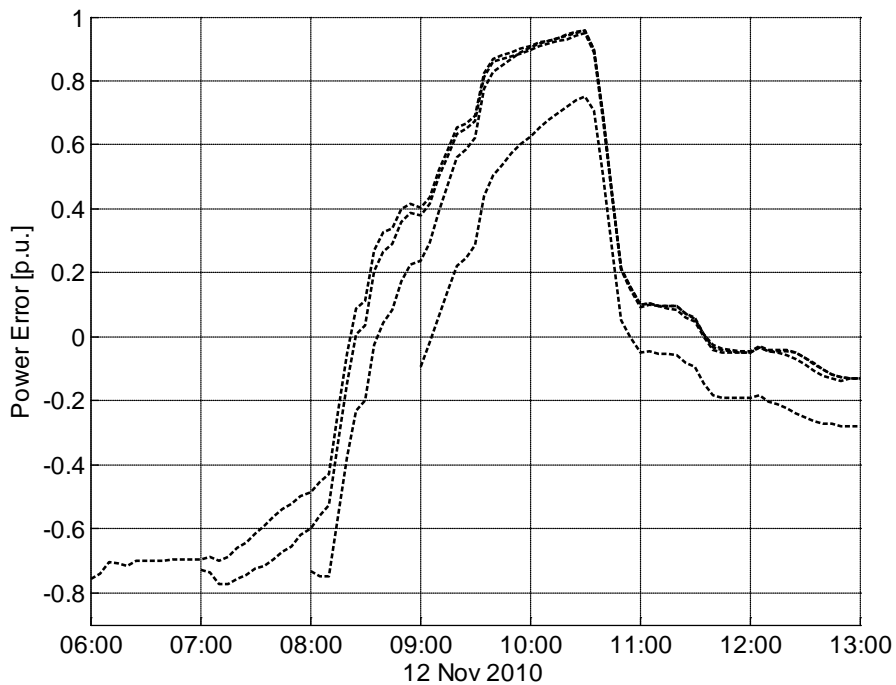


Figure 28 Wind power forecast error during November 12th, 2010 EWP

The impact of the EWP over the wind farm is presented in Figure 29, where the power production for each wind turbine is presented.

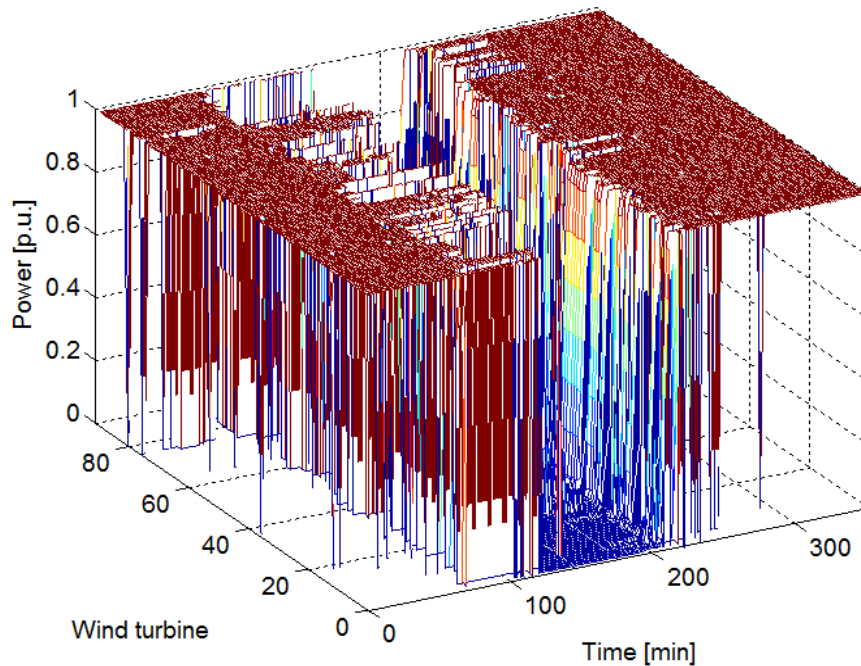


Figure 29 Horns Rev 2 wind turbine power production during November 12th EWP

7.3 7-8 February 2011

The third EWP occurred in the evening of February 7th, 2011, from around 20:00 until a little over midnight. The wind farm wind statistics of the wind speeds measured during the EWP are shown in Figure 30.

The sample is 1 sec and the wind speeds are measured on the individual wind turbine nacelle. The farm wind statistics are calculated as the mean value and minimum/maximum values of the 91 individual turbine wind speeds. In this case, the average wind speed over the wind farm exceeds 25 m/s.

The wind speed forecast for February 7-8th is shown in Figure 31. The measured wind speed is the mean value of the wind turbine wind speeds, similar to the one in Figure 30, but with 1-minute sample. The wind speed forecast is pretty accurate and it would be able to predict the EWP when the proposed wind farm hysteresis of [18 22.5] is used.

The wind power production at wind farm level is shown in Figure 32.

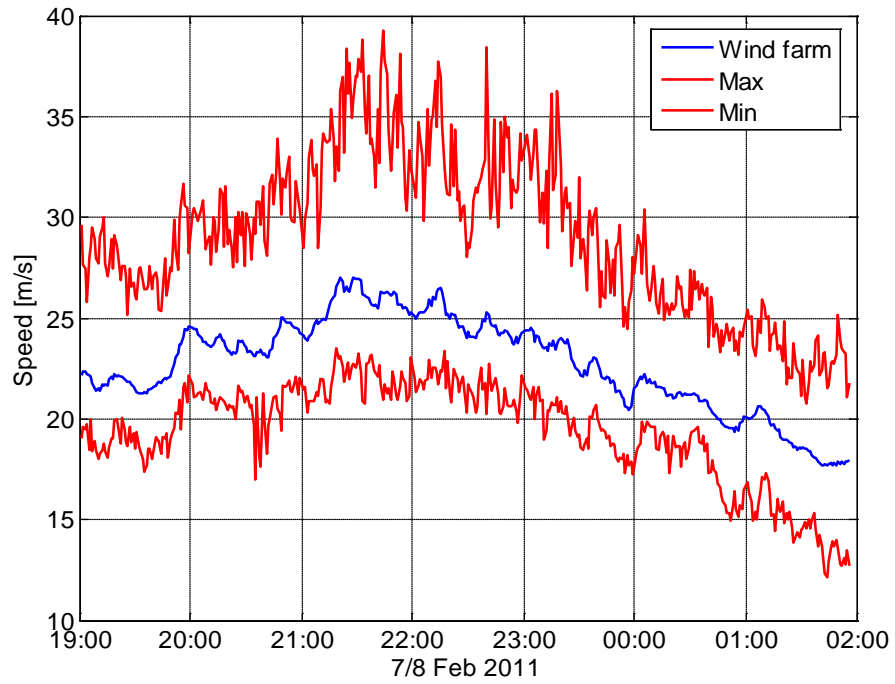


Figure 30 Measured wind speeds during 7-8 February 2011 EWP

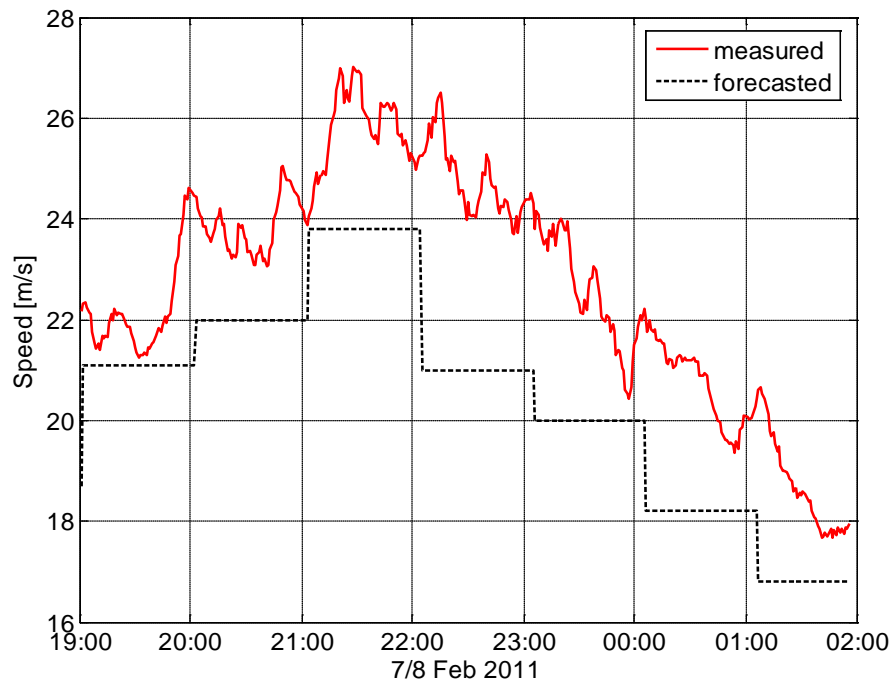


Figure 31 Horns Rev 2 wind speed forecast for February, 7-8th EWP

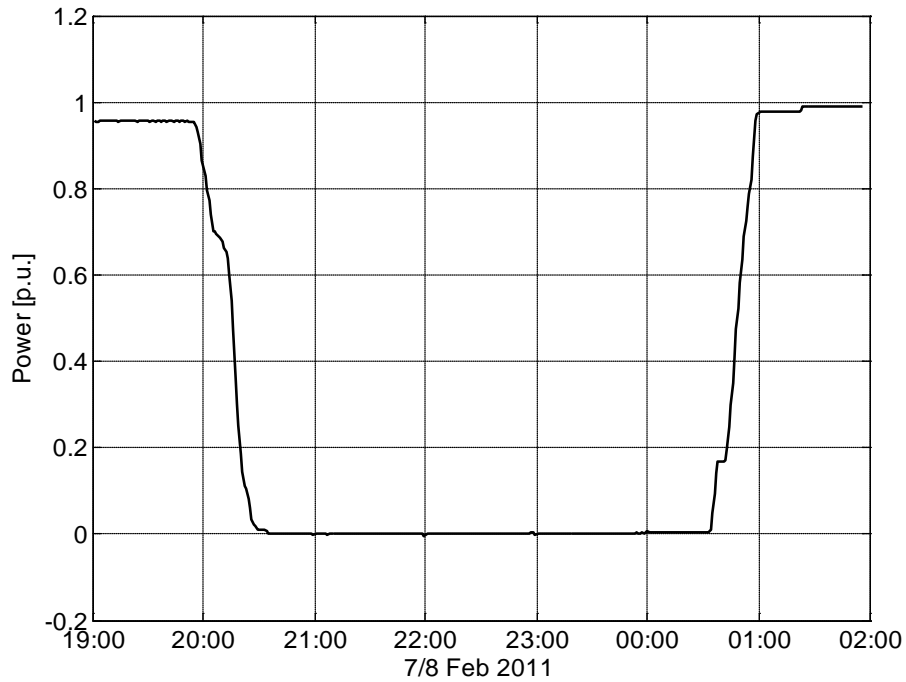


Figure 32 Power produced by Horns Rev 2 wind farm during February 7/8th EWP

The wind farm went from full production to zero in app. 40 minutes (19:55 – 20:35, February 7th) which means a ramp of app. -5.3 MW/min or -0.025 p.u./min.

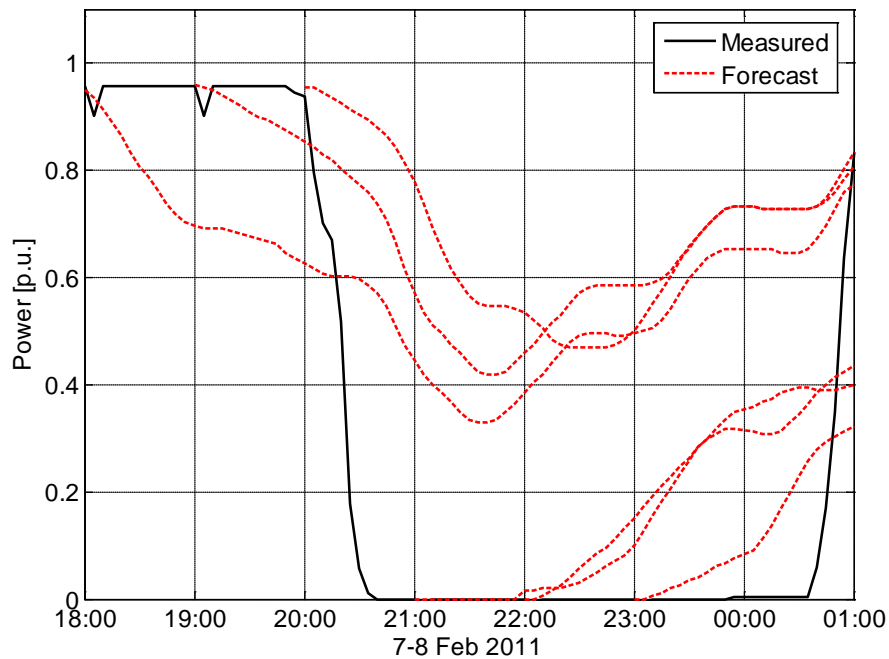


Figure 33 Measured versus hourly intra-day forecast wind power

The produced versus forecast power, during the EWP, is shown in Figure 33. Similarly to the previous EWP's, the predicted evolution of the wind power production does not reflect the wind farms shut-

down due to extreme wind speeds, even if the wind farm average wind speed exceeded the threshold of 25 m/s. This leads, once more, to wind power forecast errors of 1 p.u., as shown in Figure 34.

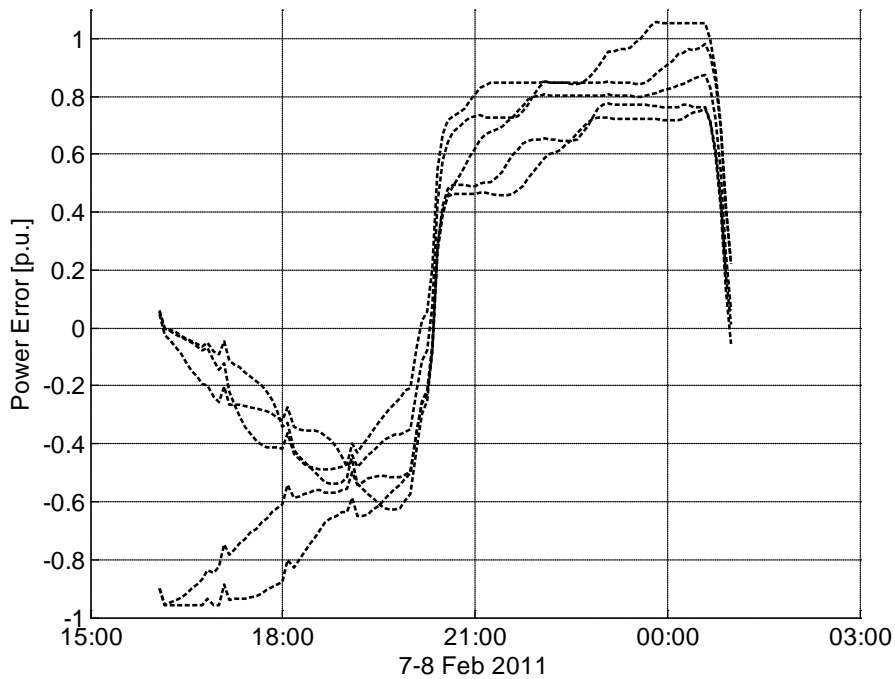


Figure 34 Wind power forecast error during February 7-8th, 2011 EWP

The impact of the EWP over the wind farm is presented in Figure 35, where the power production for each wind turbine is presented.

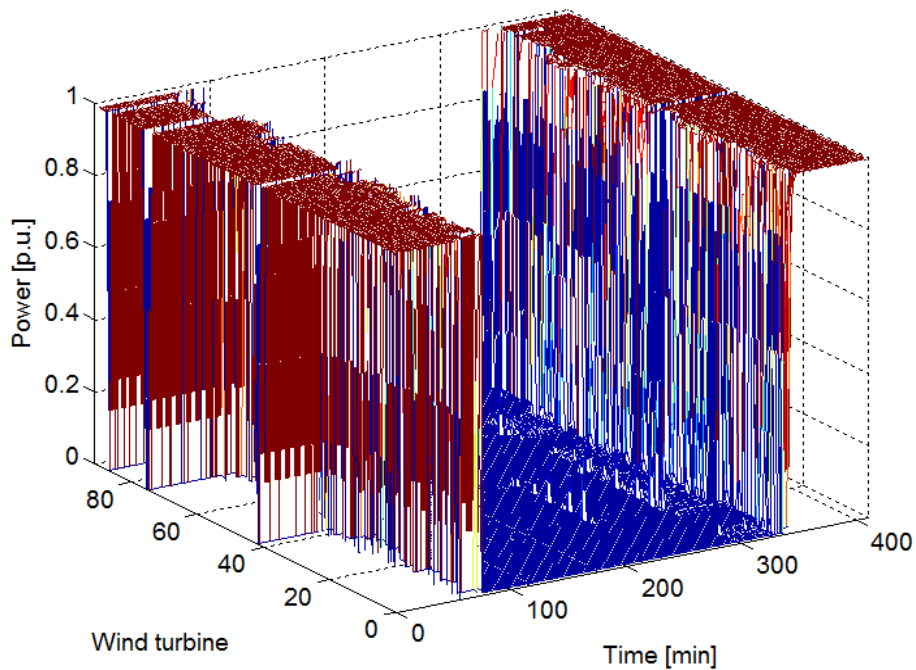


Figure 35 Horns Rev 2 wind turbine power production during February 7-8th / 2011 EWP

7.4 10 March 2011

The fourth and final EWP occurred in the evening of March 10th, 2011, from around 21:00 to 23:00. This EWP is different from the first three in the sense that the wind farm production decreased but it did not go all the way to zero, i.e. only some of the wind turbines experienced wind speeds over 25 m/s and shut-down. The wind farm wind statistics of the wind speeds measured during the EWP are shown in Figure 36. The sample is 1 sec and the wind speeds are measured on the individual wind turbine nacelle. The farm wind statistics are calculated as the mean value and minimum/maximum values of the 91 individual turbine wind speeds. As expected, the average wind speed over the whole wind farm does not exceed 25 m/s.

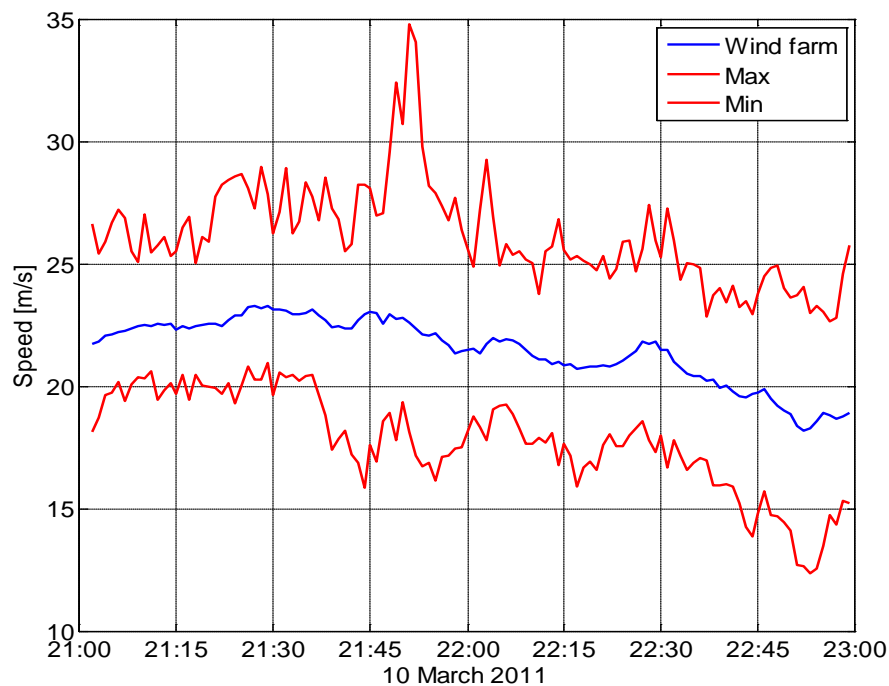


Figure 36 Measured wind speeds during March 10th 2011 EWP

The wind speed forecast for March 10th is shown in Figure 37. The measured wind speed is the mean value of the wind turbine wind speeds, similar to the one in Figure 36, but with 1-minute sample. The wind speed forecast is pretty accurate and it would be able to predict the EWP when the proposed wind farm hysteresis of [18 22.5] is used. In this case, the forecast system would have predicted that the wind farm will go to zero production, which was not the case, as it can be seen in Figure 38.

The produced versus forecast power, during the EWP, is shown in Figure 39. Similarly to the previous EWP's, the predicted evolution of the wind power production does not reflect the wind farm lower production due to extreme wind speeds. This leads, once more, to wind power forecast errors of 0.5 p.u., the maximum value of the power lost, as shown in Figure 40.

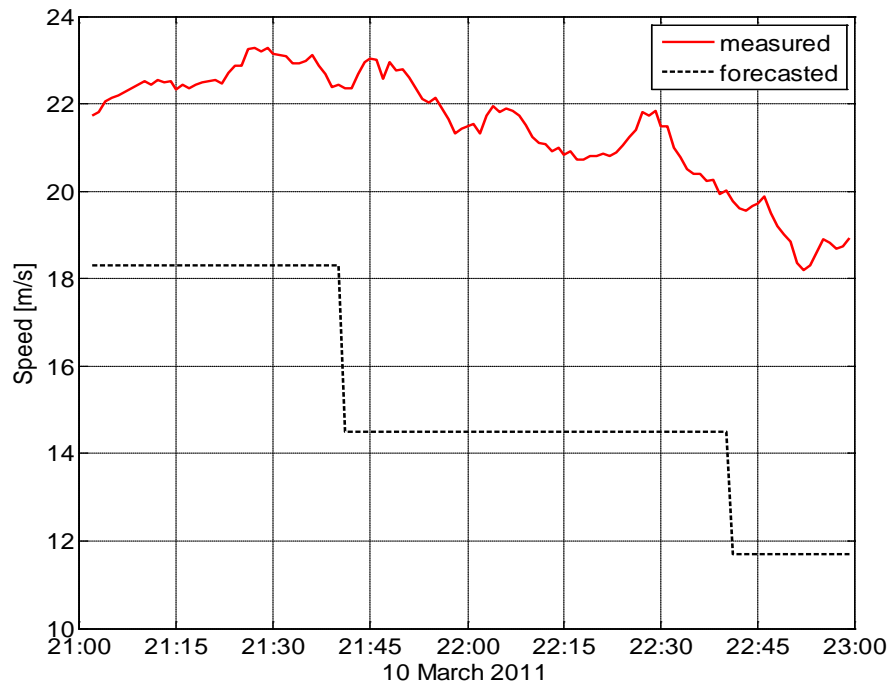


Figure 37 Horns Rev 2 wind speed forecast for March, 10th, 2011 EWP

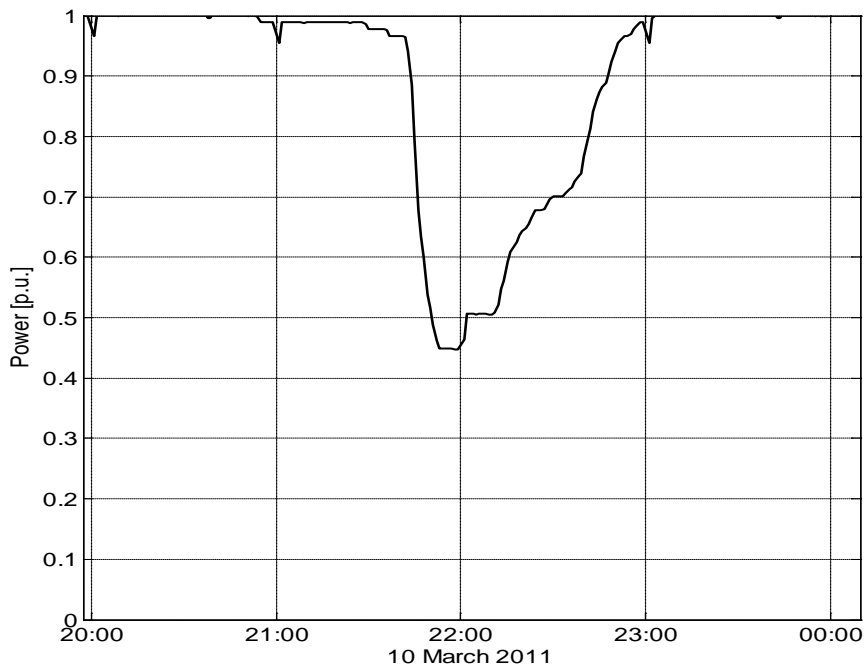


Figure 38 Power produced by Horns Rev 2 wind farm during March 10th, 2011 EWP

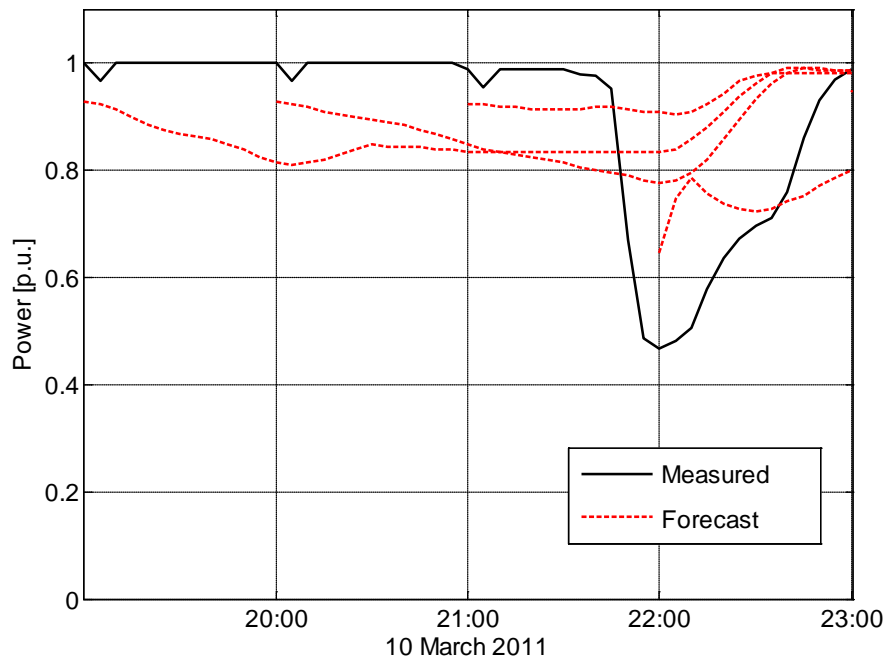


Figure 39 Measured versus hourly intra-day forecast wind power

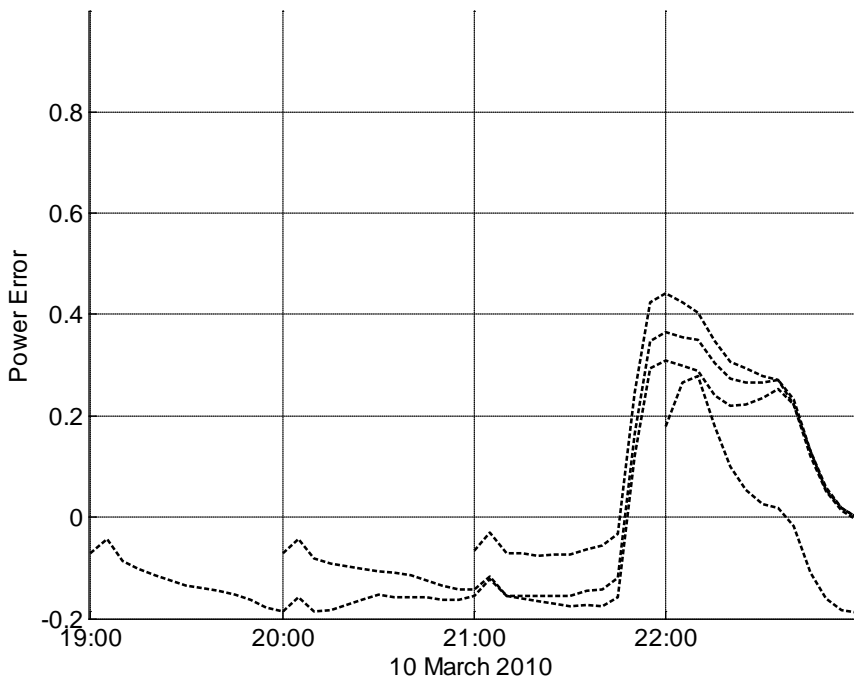


Figure 40 Wind power forecast error during March 10th, 2011 EWP

The evolution of the power produced by the individual wind turbines during the 10th of March EWP is presented in Figure 41.

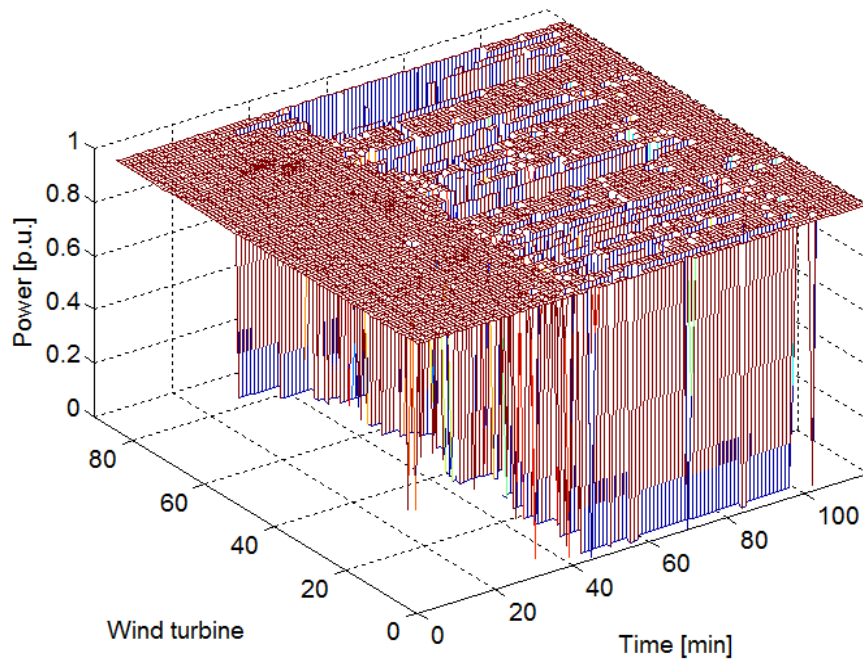


Figure 41 Horns Rev 2 wind turbine power production during March 19th, 2011 EWP

8 CONCLUSIONS

The analysis presented in this report aimed at assessing the capability of existing forecasting systems to predict EWP that would lead the whole wind farms to shut down in order to protect the wind turbines. The main barrier in performing such an analysis is the lack of historical measurements. This is even more pronounced in the case of Horns Rev 2 wind farm due to its short operational time. Therefore, model wind speed data, provided from a climate simulation using the Weather Research and Forecasting (WRF) model and the dynamical downscaling technique developed at Risø DTU, were used.

The first part of the analysis looked at model data for Horns Rev 2, comparing the wind speed model data with the wind speed forecasts available at Energinet.dk. Similarly, the wind power forecast error was analysed. In this case, the “produced” power was obtained from the model wind speed data by passing them through a static wind farm model, i.e. wind farm power curve. The analysis also aimed at quantifying the impact of how the wind farm power curve is produced, i.e. the averaging period.

The second part of the report analysed the forecasts and the measured data during the four EWPs that have occurred at Horns Rev since the project started. Even if the number of EWPs is statistically insignificant, such an analysis is useful because it is based on measured data.

Some main conclusions arise from the work done. First of all, defining a so called “storm event” at a wind farm level is not trivial. For individual wind turbines, a “storm event” is very well defined and it has as a direct consequence the emergency shut-down of the wind turbine. The shut-down procedure is initiated when the 10-min average wind speed recorded by the anemometer on the wind turbine nacelle exceeds 25 m/s and the wind turbine remains stopped until the 10-min average wind speed reaches values below 20 m/s, thus leading to a so called wind speed hysteresis of [20 25] m/s. When dealing with wind farms, what is available is the wind speed forecast. This is usually given as the average wind speed over a grid area with a spatial resolution of several km, therefore using the wind turbine hysteresis is not feasible. From the analysis done, it came out that a hysteresis of [18 22.5] m/s, i.e. 10% lower than the wind turbine one, would be suitable when dealing with wind farms.

Even with this wind speed hysteresis, the ability of the forecast systems to predict when a wind farm will go from full production to zero is not very good. In general, the forecast seems to overestimate the EWP, with only 25% of the forecast EWPs having a correspondence in the model wind speed data. Furthermore, 60% of the EWP that could be identified in the model data were not predicted by the forecasts. The same conclusions arise from the EWPs that occurred during the project period. Again, the wind speed forecasts are not able to predict that the wind farm will stop producing due to EWP.

When looking at the wind power production, the conclusions are similar. In both modelled and measured EWPs, the forecast wind power failed to predict the wind farm stopping. This could be, to some extent, due to the fact that the power curves used in Energinet.dk to transform wind speed in wind power are calibrated for wind speeds in the range of 5-10 m/s (the wind power optimisation range). In general, the extreme wind speed part of the power curve has not received much attention, partially because today, losing the power produced by an offshore wind farm, i.e. in the range of 200 MW, does not represent an important threat to secure operation of the power system. Further, the results of the analysis confirm that today, when dealing with EWPs, the wind power forecast error is at 1 p.u., as considered in the KPI.D4.1 in [11].

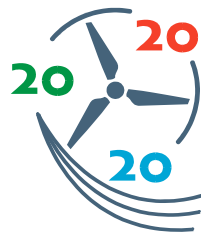
Today, wind speed forecasting systems do not have a good performance in predicting EWPs. This means that conducting controlled wind turbine shut down based on wind speed forecasts is rather unreliable and could lead to large and maybe unnecessary lost wind energy.

On the other hand, an improved storm control algorithm means that the wind turbine will not abruptly shut down going from full production to zero (see Figure 3), hence resulting in an error of 1 p.u. (from full production to zero production) but it will, probably, continue operating – at reduced power – for higher wind speeds, hence resulting in a wind power forecast error smaller than 1 p.u.

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EC-GA n° 249812
Project full title: Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions

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