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# Reliability indexes for offshore wind power production under extreme wind conditions

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## Abstract

Reliability of offshore wind production under extreme wind conditions was investigated in this report. The wind power variability from several offshore wind farms in Western Denmark were simulated using the Correlated Wind model developed at Risø. A total of 25 annual wind power time series for six large offshore wind farms were used in the analysis. Two storm control strategies were used. The analysis involved several aspects inspired from reliability studies. The reliability aspects investigated are storm events occurrences and durations, storm control strategy impact on the capacity factor (lost production), the loss of production, ramp rates and reserve requirements.

## Introduction

In order to meet the very ambitious plans of developing clean and sustainable energy, like the 20% renewable in EU by 2020 [1], some countries plan to install significant capacity of offshore wind farms. Denmark, for example, plans for 50% wind in 2025 [2] and the vast majority of the new installations will be large offshore wind farms. Offshore wind farms are more exposed to extreme wind conditions, as weather phenomena are more extreme at sea.

This makes the subject of offshore wind power production reliability an increasingly important research subject. There are several factors the reliability of wind farms depends on: wind turbine, the internal collecting grid of the wind farm, the transformer, the grid connection, the power grid, etc. However, critical situations are when the whole wind farm trips [3]. One reason for a wind farm tripping is extreme wind conditions.

This report presents the results of investigating the reliability of offshore wind farm production under extreme wind conditions. The analysis is done at wind farm level and at power system area level. At the wind farm level, the analysis aims at quantifying the impact that storm control strategies have on the availability of the wind farm during storms. At power system area level, on top of the storm control strategy, the spatial distribution of the offshore wind farms is investigated. For that, two scenarios are considered.

The simulations are done using the Correlated Wind (CorWind) simulation software. It simulates wind power variability for a large number of wind turbines over large areas.

Section 2 presents the software used to simulate the wind power variability from the large offshore wind farms in Western Denmark. The two storm control strategies used in the simulations are presented in Section 3, while the scenarios considered are given in Section 4. The simulation and analysis results of offshore wind power reliability are presented in Section 5. Finally, the report ends with some concluding remarks.

## CorWind simulation software

The analyses presented in this report are based on simulations with the CorWind power time series simulation model, developed at Risø DTU [4]. CorWind can simulate wind power time series over a large area such as a power system region and in time scales where the wind turbines can be represented by simple steady state power curves, i.e. typically greater than a few seconds.

CorWind can be used e.g. for comparison of the impact of the site selection of future wind farms on the system reserves requirements.

CorWind is an extension of the linear and purely stochastic PARKSIMU model [5], which simulates stochastic wind speed time series for individual wind turbines in a wind farm, with fluctuations of each time series according to specified power spectral densities and with correlations between the different wind turbine time series according to specified coherence functions. The coherence functions depend on frequency and space, ensuring that the correlation between two wind speed time series will decrease with increasing distance between the points. Moreover, the slow wind speed fluctuations are more correlated than the fast fluctuations. Finally, the stochastic PARKSIMU model includes the phase shift between correlated waves in downstream points, ensuring that correlated wind speed variations will be delayed in time as they travel through the wind farm. These model properties ensure that the summed power from multiple wind turbines will have realistic fluctuations, which has been validated using measured time series of simultaneous wind speeds and power from individual wind turbines in two large wind farms in Denmark [6].

The CorWind extension of PARKSIMU is intended to allow simulations over a large areas and long time periods. The linear approach applied in PARKSIMU assumes constant mean wind speeds and constant mean wind directions during a simulation period, which limits the geographical area as well as the simulation period significantly – typically to the area of a single wind farm and to max 2 hours periods. CorWind uses reanalysis data from a climate model to provide the mean wind flow over a large region, and then adds a stochastic contribution using an adapted version of the PARKSIMU approach that allows the mean flow to vary in time and space.

For the present studies, the climate model data is provided by the Regional Model (REMO), developed at Max-Planck Institute (MPI) [7]. A set of data covering historical data for all Europe in 25 years, i.e. 1979 – 2003 with a resolution of 50km × 50km in space and 1 hour in time is available. For each of the 50km × 50km points of the REMO model, the given wind speed represents an average over the area.

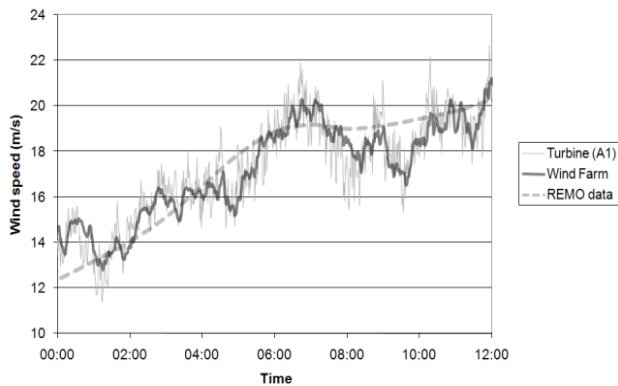


Figure 1 Twelve hours of simulated wind speeds for Horns Rev wind farm, showing the wind speed for a single wind turbine (here denoted A1), the average wind farm wind speed and the REMO data

Figure 1 shows an example of a 12 hour wind speed simulation performed by CorWind. The wind speeds are simulated for all 80 wind turbines in the wind farm, and the figure shows the wind speed of a single wind turbine (here denoted A1), the average wind speed in the wind farm, and the REMO data. It is seen that the REMO data is very smooth and thus only gives the variation in the mean flow. In order to include realistic fluctuations at all time scales, CorWind adds a stochastic contribution with the missing variability.

Comparing the wind turbine and wind farm average wind speeds in Figure 1, it is also seen that the fast wind turbine fluctuations are smoothed much more than the slow fluctuations,

which is because the wind speeds are simulated with a realistic correlation taking into account that slow fluctuations are more correlated than fast fluctuations.

### Storm Control of Wind Turbines

The typical power curve of a modern wind turbine is presented in Figure 2. The wind turbine will shut down when the average wind speed reaches a certain value denoted  $V_4$  in the figure. The typical shutdown wind speed is 25 m/s. 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.

There are other ways of dealing with the wind turbine operation during very high wind speeds, like the so-called Enercon Storm Control System [8]. This control strategy prevents sudden shut downs of the wind turbine. This is done using a modified power curve, shown in Figure 3. In this case, the wind turbine does not automatically shut down at a certain wind speed but it starts reducing the power at a wind speed,  $V_{storm}$  in Figure 3, smaller than the shut down wind speed. If the wind speed increases further, the wind turbine keeps reducing the power until it reaches zero and thus stops. The wind speed at which the wind turbine would be fully stopped is higher than the typical shut down wind speed (25 m/s). Using this storm control strategy, the wind turbine avoids sudden shut downs and start ups at high wind speeds.

In this work, storm control strategies similar to the ones presented above were used. However, the present version of CorWind assumes a unique power curve, and therefore hysteresis is not

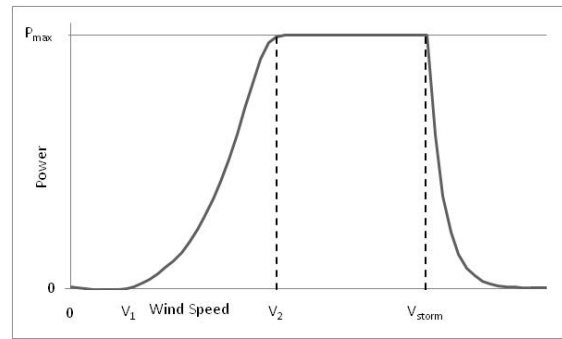
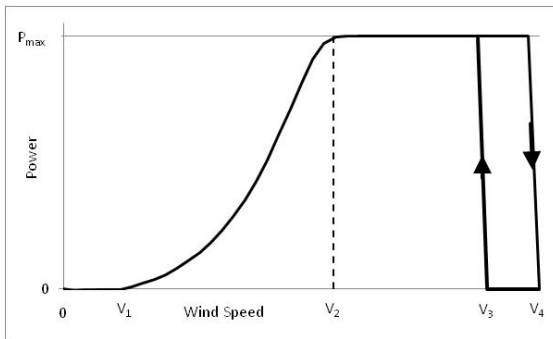


Figure 3 Enercon-type power curve

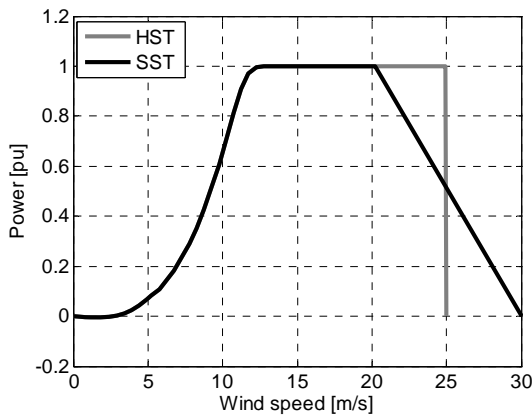


Figure 4 Power curves used in the simulations

included. Thus, the control strategy that shuts down the wind turbine when the 1-min average wind speed reaches 25 m/s starts-up again when the same average wind speed gets lower than 25 m/s. This strategy is similar to the one shown in Figure 3 with  $V_4 = V_3 = 25$  m/s. This strategy will be further addressed to as “Hard Storm Transition” (HST) control. The second storm control strategy, inspired from the Enercon storm control, implies that the produced power decreases when the 1-min average wind speed exceeds 20 m/s and stops completely when 30 m/s are reached. This control strategy will be further addressed as “Soft Storm Transition” (SST) control. The power curves associated with those storm

control strategies are presented in Figure 4.

### Simulation setup

Future wind farms installed in Denmark will be dominantly off shore. Several possible locations have been identified by the Danish Energy Authority [9]. In order to assess the impact of the geographical spreading of the wind farms over the power systems reserve requirements, a simulation case has been specified.

The six wind farms that are simulated are shown in Figure 6. The first wind farm is the existing wind farm in Horns Rev. The second wind farm is the Horns Rev 2, which is expected to be commissioned by the end of 2009. The last 4 wind farms are among the positions in [9].

Data for Horns Rev and for Horns Rev 2 is given in details, including the positions sizes and positions of the individual wind turbines. The wind turbine size and relative positions have some influence on the simulation result, but the main most important parameter is the total power and the geographical position of the wind farm (Figure 5). Another assumption is the annual mean wind speed, which is applied to calibrate the MPI weather model date. These mean wind speeds are estimates based on the report on future Danish offshore sites [9].

The main wind farm data applied in the simulation is summarised in Table 1. Actual position and wind turbine ratings are used for the two existing Horns Rev wind farms, while it is assumed that each new wind farms consists of 40 × 5.0 MW wind turbines arranged in an array with 8 rotor diameters between rows and 6 rotor diameters between the turbines in each row.

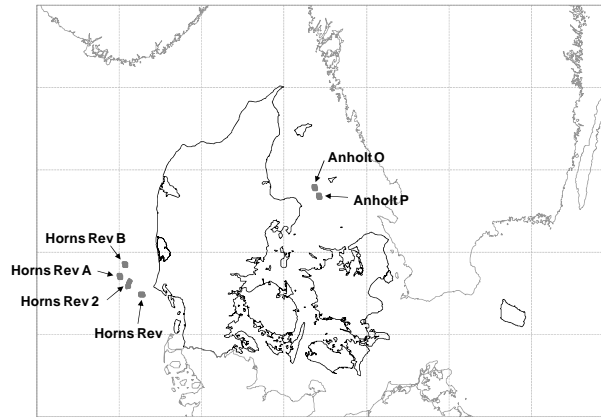


Figure 5 Simulated wind farms

Table 1 Data for the 6 simulated wind farms

Name	Symbol	Wind turbine power	Total power	Annual mean wind speed
<b>Horns Rev</b>	HR1	80 × 2.0 MW	160 MW	9.6 m/s <sup>)</sup>
<b>Horns Rev 2</b>	HR2	91 × 2.3 MW	209 MW	10.4 m/s <sup>)</sup>
<b>Horns Rev A</b>	HRA	40 × 5.0 MW	200 MW	10.6 m/s <sup>)</sup>
<b>Horns Rev B</b>	HRB	40 × 5.0 MW	200 MW	10.5 m/s <sup>)</sup>
<b>Anholt O</b>	DAO	40 × 5.0 MW	200 MW	9.0 m/s <sup>)</sup>
<b>Anholt P</b>	DAP	40 × 5.0 MW	200 MW	9.0 m/s <sup>)</sup>

<sup>)</sup>the annual mean wind speeds are estimates based on [9].

All wind farms are simulated for 5 years of Reanalysis data, 1999 – 2003. The time step of the simulation is selected to 1 minute. The stochastic part is simulated with a period time of 1 day. This is a compromise between computer simulation time and simulation accuracy. Longer period times are possible, but it would require longer computer simulation time, and yet not add variability because the stochastic part includes variability faster than one day. To ensure that the stochastic randomness is still properly represented, each year was simulated with 5 different random seeds for the stochastic part. Thus, a total of 25 years, i.e. 5 years × 5 seeds, of simulation time series are used for the analysis.

The idea is now to analyse the reliability of the individual wind farms during extreme winds events (storms) as well as to compare two scenarios:

- the concentrated scenario: Horns Rev and Horns Rev 2 are supplemented with 2 new wind farms Horns Rev A and Horns Rev B.
- The spread scenario: Horns Rev and Horns Rev 2 are supplemented with 2 new wind farms Anholt O and Anholt P.

The concentrated scenario is clearly beneficial from the point of view of annual energy production, because the annual mean wind speed is significantly higher in the Horns Rev area than in the Anholt area. However, from the point of view of wind power fluctuations, the concentrated scenario will provide faster and larger variations and therefore will probably require larger power reserves, especially during periods with extreme wind speeds.

## Simulation results

For each simulated year, the saved results consist in one-minute time series of the average wind speed over each wind farm and the total power produced by that wind farm. The analysis was done in terms series of wind power production reliability indexes inspired from the standard power system reliability analysis techniques and in terms of operational impact of wind power on the power system.

The attention is focused on the operation of wind farms under extreme wind conditions. Therefore, the first step was to quantify the frequency and duration of periods with extreme wind conditions. For this purpose, Extreme Wind Periods (EWP) were defined as the periods of time starting when the wind speed exceeds 25 m/s and lasting until the wind speed decreases below 20 m/s. This definition is similar to the standard wind turbine storm shut down control with hysteresis as in Figure 3. Since the focus is on large wind farms, the average wind speed over the wind farm is the one that defines the start and stop of the EWP. By this definition, the EWP are solely defined by the wind speed and therefore independent of the storm control strategy used.

When the aim is to quantify the impact of the extreme winds on the power produced by the wind farms, the focus is on the down ramping. For this purpose, the periods where the down ramping of power is caused by storm control are first identified, so that down ramping due to storms can be distinguished from down ramping due to decrease in wind speeds at lower wind speeds. These periods are called the Storm Control Event (SCE) periods. Since SST control is becoming active at 20 m/s and HST at 25 m/s, SCE period is considered to start when the average wind farm wind speed crosses 20 m/s. In order to maintain some hysteresis, an SCE period then stops when the wind speed gets lower than 15 m/s, which is in due time before the power starts ramping down due to decreased wind speeds. Obviously this SCE definition leads to having a higher number and longer duration of SCEs than EWPs. However, the idea with the SCE periods is to quantify the power ramping in those periods, and not to quantify the frequency and duration of the SCE periods.

At power system area level, the results are analyzed and compared for two scenarios, presented in §4. In this case, EWP starts when all the wind speeds (four wind farms in each scenario) cross 25 m/s and it stops when all of them are getting lower than 20 m/s. Basically, it is a “all on – all off” strategy. SCE for power system area level is similarly defined, with 20 and 15 m/s the border values.

### A. Frequency and duration of occurrence

This section analyses the frequency and duration (F&D) of EWP's as reliability indexes to quantify the impact of storms on the power system reliability of wind farms. This approach is equivalent to reliability assessment of failures of other power system components including power plants as e.g. applied by Negra [10]. The frequencies and durations of EWP's are calculated for both individual wind farms and for power system area level.

The individual wind farm number of occurrences, for each year and each seed, are shown in Figure 7. The number of occurrence is influenced by both the year, thus the REMO data, and by the seed, thus the higher (> 1 per day) frequencies.

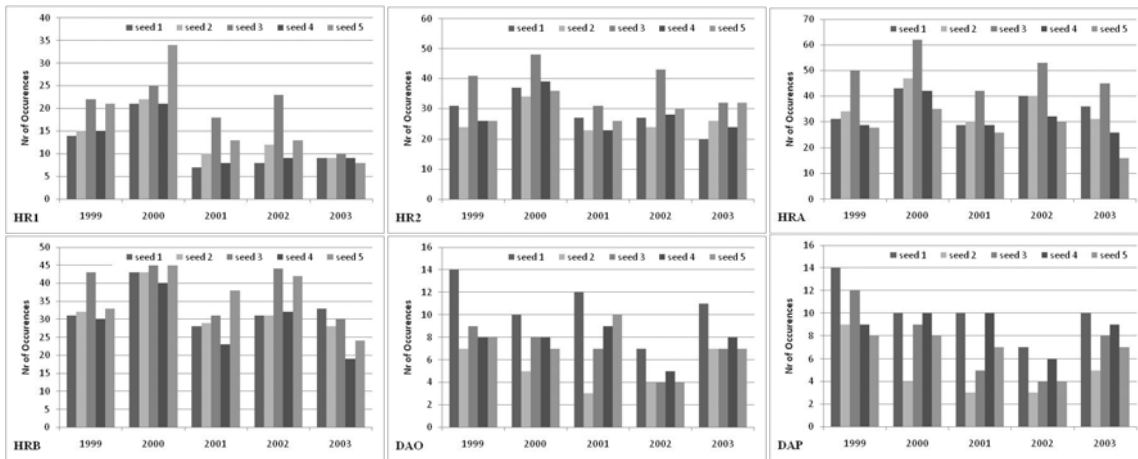


Figure 6 Number of occurrences; individual wind farms

The following observations are immediately made from Figure 6:

- The numbers of occurrences in the simulations are generally higher than expected, although no analysis of measured data has confirmed this. The number of occurrences in the simulations is very dependent on the upscaling of the REMO data given at 10 m height to wind turbines hub heights, which is presently done by a constant scaling factor as explained in the discussion part of the paper. To improve this and to ensure sufficient confidence in the results, it will be necessary to analyse the distribution of wind speeds at the offshore locations.
- The different locations with different annual mean wind speeds have a significant influence on the number of occurrences in the simulations. HRA and HRB with the highest mean wind speeds out in the open North Sea have the highest number of occurrences, while DAO and DAP with the lowest mean wind speed in the inner sea of Kattegat have the lowest number of occurrences. In between is HR1 and HR2, with HR1 as the wind farm at Horns Rev with least number of occurrences and the smallest annual mean wind speed.
- The historical year has some influence on the result. This is especially clear for year 2000 at the Horns Rev wind farms in the North Sea, where the numbers of occurrences are high due to a year with several storms. Apparently the storms in 2000 were not strong enough to influence significantly the number of occurrences on DAO and DAP in the inner sea.

The distribution of the storm occurrences binned by their duration, for each wind farm, is shown in Figure 7. A one hour bin was used.

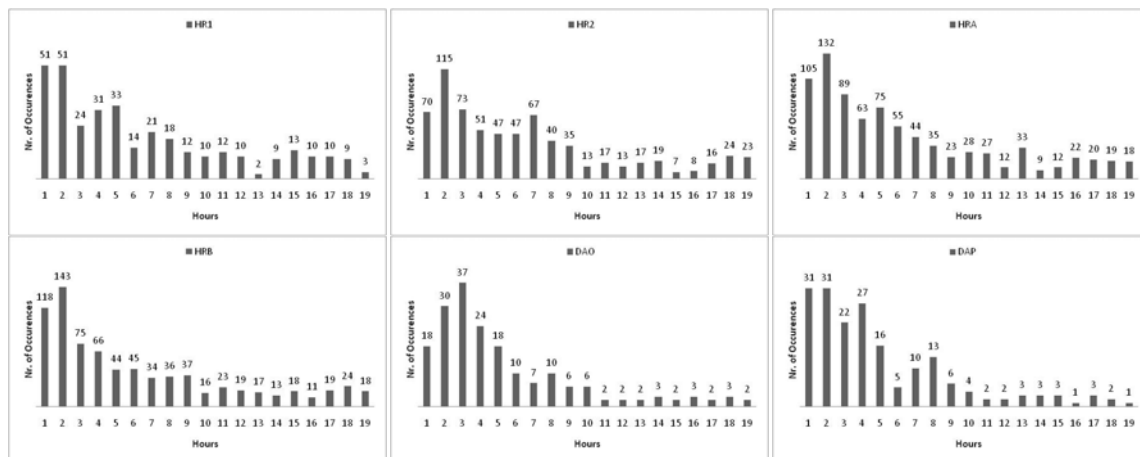


Figure 7 Storm events occurrences for each wind farm; 1-hour bins

The distribution of the 1-hour bin storm occurrences varies from wind farm to wind farm. Storm events with duration between one and two hours are the most common for each wind farm, except for DAO wind farm, for which the most common storm duration seems to be between two and three hours.

At power system level, the resulted storm events occurrences, for each scenario and for each year and seed, are presented in Figure 8.

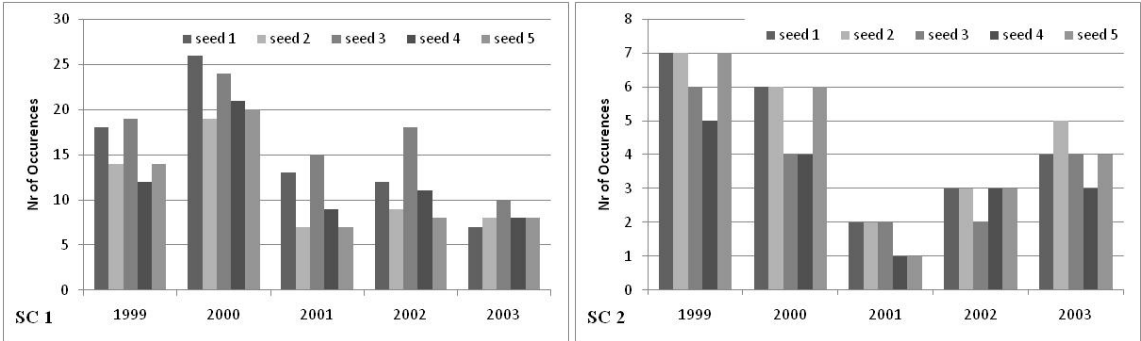


Figure 8 Storm events occurrences for each scenario

Table 2 Storm events; Average values per scenario

Scenario		Sc 1	Sc 2
Storm duration in hours	min	81	18
	max	294	36
	average	166	52

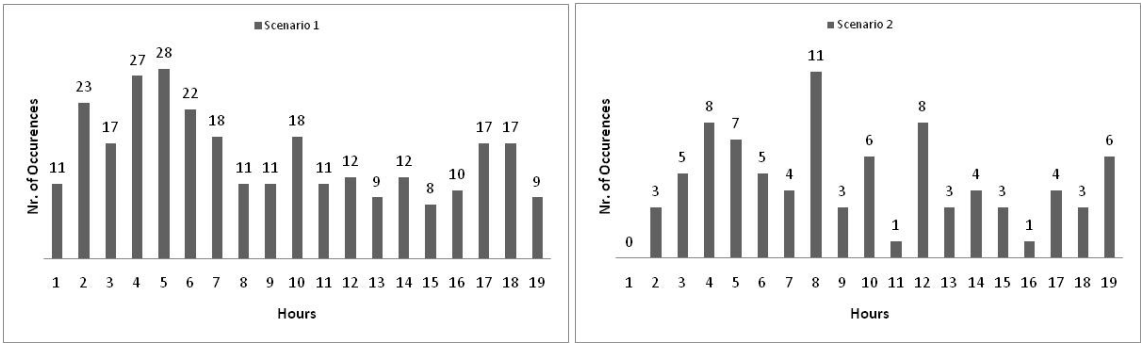


Figure 9 Storm number of occurrences for each scenario; 1-hour bins

The average values, resulted from the 25 one-year wind speeds time series, for each scenario, are given in Table 2. The results indicate that the total duration of the high wind speed events, over a power system region, can be significantly reduced – more than 60% - by properly selecting the location of the wind farms. Thus, from an average duration of 166 hours of storm events in the first scenario, the mean annual duration is reduced to 52 hours in the distributed scenario.



The distribution of the storm events occurrences, with 1-hour bin, is shown in Figure 9. The differences between the two scenarios are not very significant, the distribution being similar with regard to duration, but with significantly different number of occurrences.

### B. Lost Energy

This index shows how much production is lost, annually, due to storm events. Depending on the storm control used, the wind turbines will either produce at rated value and then shut down (zero production) or progressively produce less (ramping down) as the wind speed increases. The lost energy is expressed in terms of capacity factor (CF). The capacity factor is defined as the ratio between the energy produced by the wind turbine and the maximum power that the wind turbine could produce, over a period of time  $C_F = E_a / N_h \cdot Cap$  where  $N_h$  is the period of time, in hours; typically one year is used;  $Cap$  is the installed capacity and  $E_a$  is the energy produced by the wind farm.

Since the same wind speed time series were used in both simulations, the difference in the capacity factor of the individual wind farms will only depend on the storm control strategy used.

The impact of the storm control strategy on the wind farm capacity factor is given in Table 3. The average annual lost production differs for the considered wind farms. The storm control strategy can lead to a lost production equivalent with 10 to 35 full load hours.

Table 3 Average lost production for each wind farm

Name	HR1	HR2	HRA	HRB	DAO	DAP
Capacity factor difference %	0,25	0,37	0,39	0,38	0,13	0,12
Equivalent full load hours	21,65	32,80	34,26	33,04	11,02	10,81

### C. Ramp rates

The definition of ramp rates applied in this work is quite similar to the definition of load following applied by Parson et. al. [14]. The same definition of ramp rates was used in [15]. The intention is to

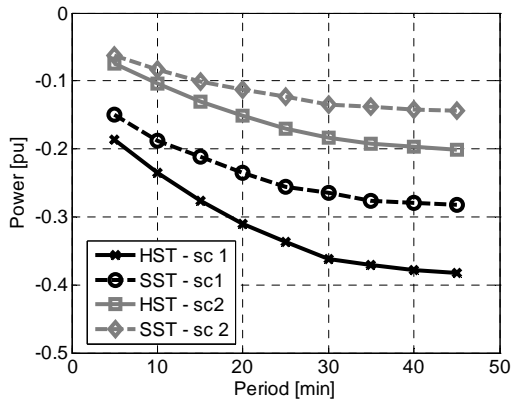


Figure 10 1% fractile versus time windows

quantify the changes in mean values from one period  $T_{per}$  to another, which specifies the ramp rate requirement that the wind farm power fluctuation causes to other power plants. Ramp rates are calculated only during SCEs.

The instantaneous time series of power can be either measured or simulated. Then the mean value of the power is calculated at the end of each period, although it is illustrated for all time steps in Figure 20. The ramp rate is simply the change in mean value from one period to the next, i.e.  $P_{ramp}(n) = P_{mean}(n+1) - P_{mean}(n)$ . Note that this definition specifies the ramping of the wind farm power. Thus, negative ramp rate means decreasing wind power, which requires positive ramping of other power plants.

The ramp rates were calculated for the two scenarios and for different time periods, from 5 to 45 minutes, in steps of 5 minutes and for both storm control strategies. The 1% fractile, the one giving the extreme value of the decreasing wind power, for different time windows is presented in Figure 25.

The ramp rates seem to depend more on the geographical location of the wind farms than on the storm control strategy used. The ramp rates for the second scenario are more than half compared to first scenario, while the control strategy manages to reduce the ramp rates by app. 30%

#### D. Reserves requirements

The definition of ramp rates applied in this work is quite similar to the definition of load following applied by Parson et. al [14]. The same definition of ramp rates was used in [15]. The intention is to

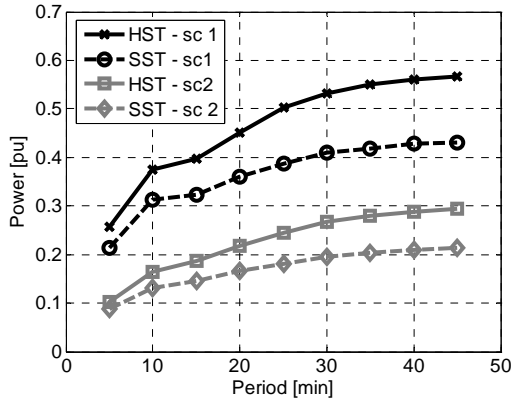


Figure 11 Reserves versus time windows

quantify the difference between the instantaneous power and the mean value which are dealt with as ramping. Reserves are calculated only during SCEs. Since the reserves must be allocated in advance, the positive reserve requirement is defined as the difference between the initial mean value and the minimum value in the next period. Formally, the reserve requirements are defined as  $P_{\text{ramp}}(n) = P_{\text{mean}}(n) - P_{\text{min}}(n+1)$ . Note that with this definition, positive reserves means decreasing wind power that requires positive reserves from other power plants.

The 1% fractile, the value on the extreme of the duration curve, is shown in Figure 31 versus the time windows.

The reduction of the reserves achieved by the proper siting of a wind farm is bigger than the one provided by the storm control, as the values of the 1% fractile (Table 19) show. The reduction achieved by the distributed scenario is more than half for all time windows considered, while the storm control reduces with maximum 30% the reserves requirements. Of course, a combination of both proper siting and adequate control strategy will lead to very significant reductions of the reserves requirements, in the range of 60-70%.

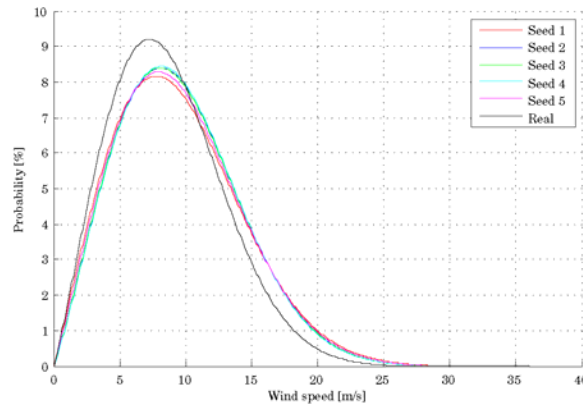


Figure 10 Comparison between simulations and real data with Weibull fitting

## Discussion

As mentioned earlier, the REMO data are given at a height of 10 m. Therefore, the values need to be scaled to the hub height of modern wind turbines. In the present version of CorWind, a

simple scaling by a constant is applied, and this constant is calibrated so that the specified annual mean wind speed at the specific wind turbine is obtained. This is a very simple approach, which can be questioned, especially when the focus is on the storm wind speeds with relatively low probability. This can be seen in Figure 10, where the distribution of simulated with the same five seeds used above and measured ones are plotted. The data are 10-min averages from a met mast installed at Horns Rev 1. The results indicate that the constant factor scaling leads to under simulate lower wind speeds, i.e. 5 – 10 m/s and over simulate extreme wind speeds, i.e. over 20 m/s.

## Conclusions

There are very ambitious plans for installing large offshore wind farms. This makes the offshore wind power production reliability an increasingly important research subject. This paper investigates the offshore wind power production under extreme winds reliability. Several indexes are defined.

Control strategies play a crucial role in increasing the reliability of offshore wind farms power production under extreme wind conditions.

Availability of wind power production at power region level can be improved by proper wind farm location selection.

## Acknowledgement

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