Wake effects at Horns Rev and their influence on energy production

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1. Abstract

In recent years a number of programs have been carried out with the purpose of investigating wake effects at Horns Rev offshore wind farm. The latest Danish project "Large wind farms shadow: measurements and data analyses" aims to map the downstream effect of large wind farms, and includes monitoring the in-park wake effects. The wind farm considered, Horns Rev, has an installed capacity of 160 MW. Approximately one years data are available after the final completion of the Horns Rev turbines, this paper presents the first analysis based on a large amount of data from the Horns Rev wind farm in operation.

The data for the current paper are acquired partly from the meteorological masts positioned north west and east of Horns Rev and from the SCADA database, which contains all observed data from the turbines at both wind farms.

This paper presents analysis of the power output in a row of operating turbines and the dependency on wind direction relative to the row direction. The aim is to describe the magnitude of the wake effects and give an indication of the importance of wind direction. For the majority of the selected cases the turbines were operating at wind speeds with high rotor thrust. Comparison of the results for different spacing at Horns Rev (along rows and columns and for diagonal spacing) will provide insight to the mechanism of wake development and expansion.

Part of the project involves development of a model based on the analytical solutions of wake development described by Frandsen et al. (2004). This model is currently being operationalised Horns Rev and results from the modelling will be compared with the data analysis. The objective is to illustrate whether the merging of wakes within large wind farms can be described by simple linear models or whether the inclusion of the two-way interaction between the wind turbines and the boundary-layer is a necessary prerequisite for accurate models of wakes to be used in future wind farm design.

2. Introduction

To increase the understanding of the wake effects from large wind farms a number of projects are currently being carried out with the purpose of describing and quantifying wakes. Especially the economical aspect has been an important driver in this project, since an improved ability to predict wake losses may improve the feasibility of large wind farms significantly.
Horns Rev wind farm is particularly interesting for future offshore projects since it is to some degree similar to a number of proposed wind farms: It is a large matrix spaced with 7 rotor diameters and it has a long land fetch of approximately 14km.
The wind farm consists of 80 Vestas V80 turbines with 2MW generator and 70m hub height. It is laid out in a matrix with 8 rows (east-west) and 10 columns (north-south).

Since the wake effect modelling is still in its early stages the current project is limited to focus on wakes in situations where the wind is aligned with the rows of the wind farm as shown in figure 2.1.

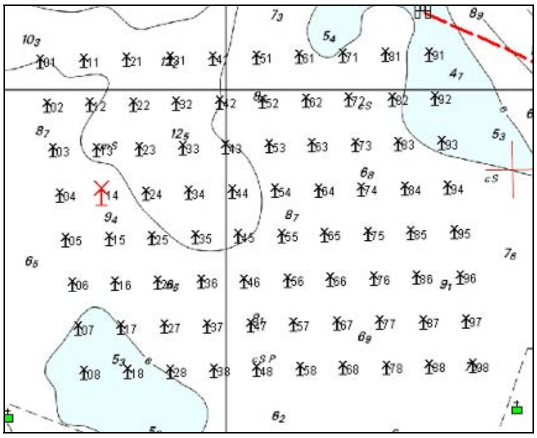
Figure 2.1 Wind farm layout

Although other papers (for example Jensen, Leo et al. [1]) have presented similar analyses of the Horns Rev data the present work is the first covering a large amount of valid data, which allows a higher degree of statistical independency.

The available data tends to decrease significantly as the necessary criteria are applied. An example of such criteria may be: narrow wind speed and wind direction intervals and all turbines in a row are in operation. It is obvious that very specific analyses require a very large set of data to provide reasonable results.

3. Data

The data is taken partly from the SCADA database, which is continuously updated with turbine performance parameters and partly from the met. masts close to the wind farm. The met. masts are positioned as shown in figure 3.1 with M2 northwest of the wind farm and M6 and M7 east of the wind farm. M6 and M7 were initially erected to facilitate measurements of the wake effects behind the wind farm (in the predominant western wind direction), whereas M2 should be in free stream at nearly all times.

Due to downtime of the measuring system at M2 it has been necessary to use a large amount of data from the M6 mast although it is often in wake from the wind farm. However, since it concerns mainly the wind vane it is assumed that the error committed is acceptable, as the wind farm is not expected to impose a general change of wind direction downstream.

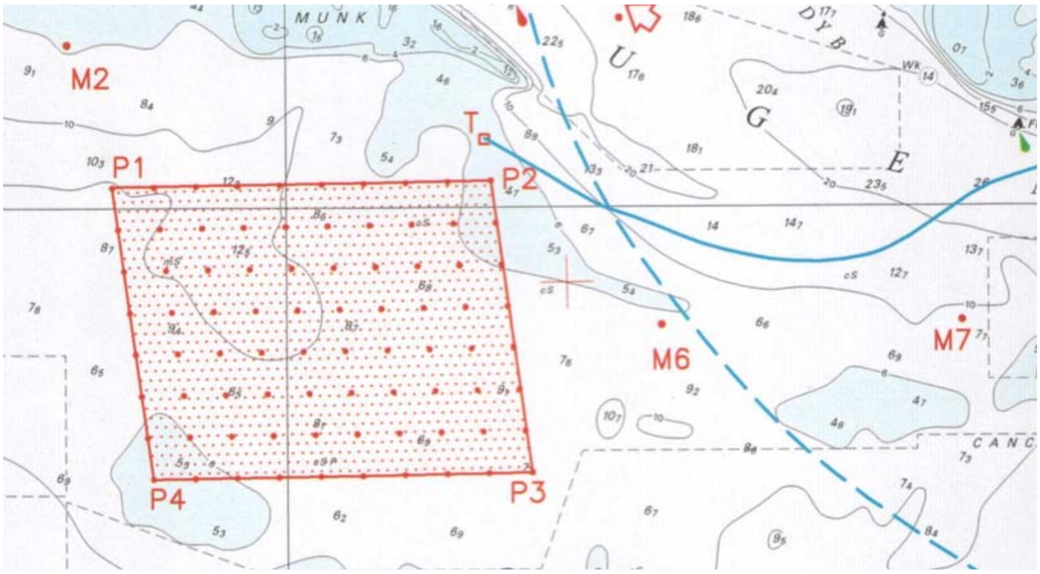

Figure 3.1 Wind farm and met. mast positions

All data are acquired as 10-min means and information from the mast and the SCADA system is combined in one file containing all data for the analyses. The period with valid data ranges from 1-1-2005 to 31-12-2005 and has a recovery rate of approximately100%.

To ensure that a large amount of data is available for the analyses only the border rows and columns are excluded i.e. for west wind situations the first and eighth rows are left out.

4. Wake modelling

The analytical model derived by Frandsen et al. (2006) [3] links the small scale and large scale features of the flow in wind farms. The model currently handles regular array-geometry with straight rows of wind turbines and equidistant spacing between units in each row and equidistant spacing between rows. Firstly, the case with the flow direction being parallel to rows in a rectangular geometry is considered by defining three flow regimes. From the upwind end of the wind farm, the model encompasses three regimes as illustrated in Figure 4.1: In the first regime, the wind turbines are exposed to multiple-wake flow and an analytical link between the expansion of the multiple-wake and the asymptotic flow speed deficit are derived. The second regime materializes when the (multiple) wakes from neighbouring rows merge and the wakes can only expand vertically upward. This regime corresponds (but is not identical) to the flow after a simple roughness change of terrain. The third regime is when the wind farm is “infinitely” large and flow is in balance with the boundary layer.

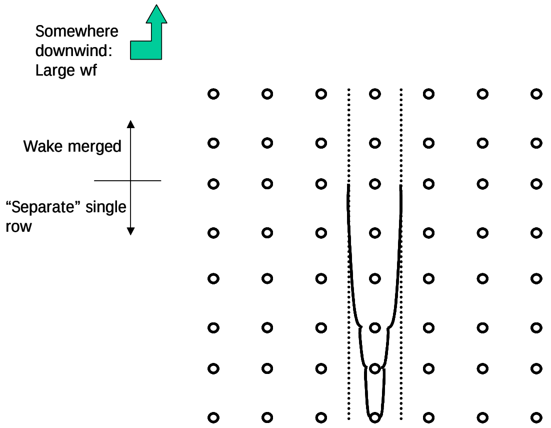

Figure 4.1. Illustration of the regimes of the analytical model. The flow is parallel to the rows of wind turbines.

In brief the expansion of the wake behind a wind turbine is given by the general solution:

$$D_x = \left(\beta^{n/2} + \alpha \cdot s\right)^{1/n} D_0, \qquad s = x / D_0$$

where the solution for *n* has been suggested as 3 by e.g. Schlichting (1968).

α is the decay constant which is related to the thrust coefficient C_T and β is the initial wake expansion, also being calculated from the thrust coefficient:

$$\beta = \frac{0.5 \cdot (1 + \sqrt{1 - CT})}{\sqrt{1 - CT})}$$

Figure 4.2 shows results for the single/multiple wake model which does not account for turbine wake interactions with the ground. By adjusting parameters in the model it is possible to get a good fit to the observed data. Notably, the exponent parameter was chosen as *n*=1, which choice provides the excellent fit for the first few units. At the end of the row, the model recovers too well, which is expected: with the chosen way of modelling the asymptotic value of *n* for increasing wind turbine number must be ½ to ensure a non-vanishing wind speed deficit.

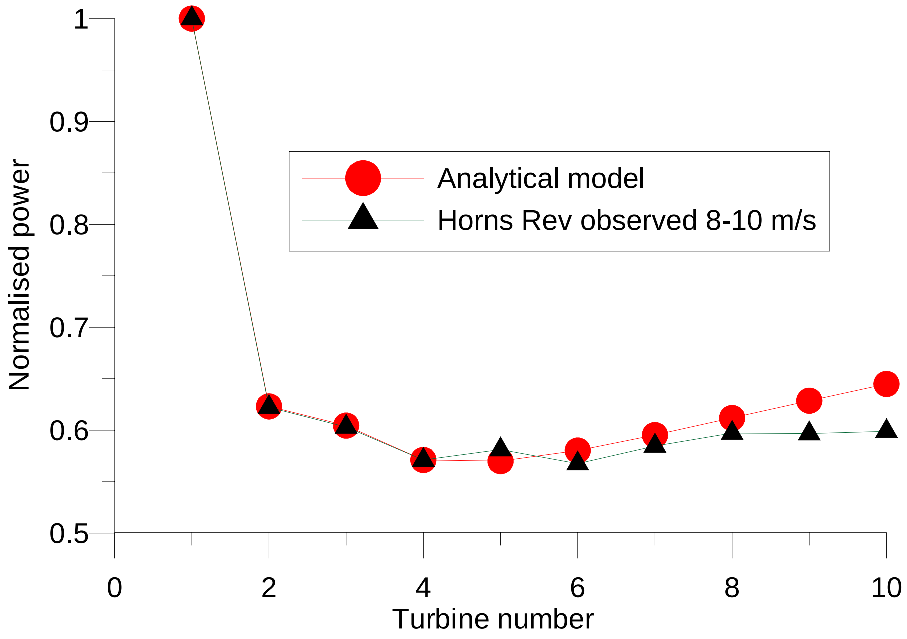

Figure 4.2 . Comparison of single wake model with observations for Horns Rev.

5. Results

Seeking applicable data in a data set like the current one faces a dilemma: use a large amount of information to allow statistical independency by having wide wind direction sectors for each case or narrow down the sectors to see the exact wake effects for each direction.
In the section below the difference between these approaches and their results are shown.

5.1 Wind along the row with wide direction sector

The rows 2 through 7 are analysed using a 30 degree wide sector ranging from 255° to 285°. The wind speed interval is chosen to be between 7 and 10m/s as this is where the power is relatively high (although not full load) and the thrust coefficient has not dropped significantly as at high wind speeds.
There are several ways to define the wind speed: Either using the wind speed from one of the masts or calculating the wind speed from the power of one of the front line turbines. Basically one should expect that the most reliable solution would be to calculate wind speed from the output power as this would reflect the wind speed in the wind farm rather than some kilometres away. However, results show that the standard deviation of the results becomes much larger using this approach rather than taking the wind speed from the M2 mast. Therefore in the following the wind speed is taken from M2 and wind direction from M6 (due to the already mentioned downtime of the measuring system).

The observed wake effect is plotted for this situation represented by the relative power drop of each turbine in the row. It is obvious that the largest relative power drop is observed from turbine 1 to turbine 2, whereas the power drop from turbine 2 to turbine 10 is smaller than between the first 2 turbines. The plots are separated in 1m/s intervals.

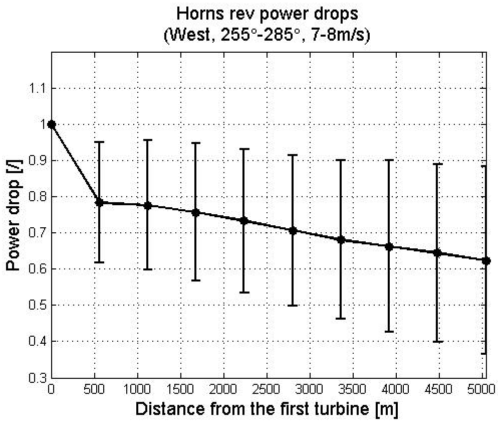

Figure 5.1 Relative power drop 7-8m/s

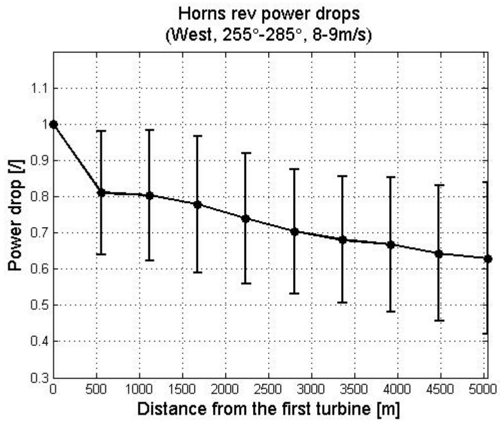

Figure 5.2 Relative power drop 8-9m/s

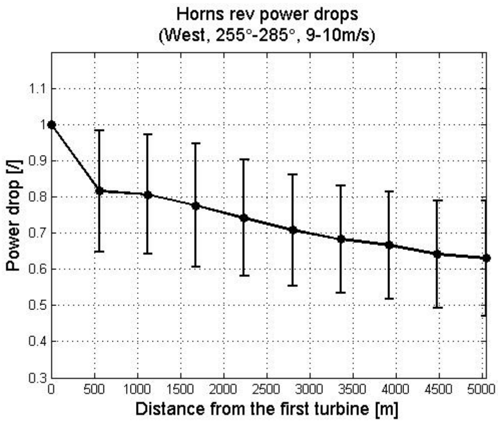

Figure 5.3 Relative power drop 9-10m/s

Besides observing the mean value down the line of turbines it is quite interesting that the standard deviation of the results (represented as a vertical line at each mean value point) is very large for all cases. This indicates that the results cover very different situations.

There are several possible reasons for the large deviations and these should be checked individually (turbulence, wind shear and wind direction dependency). One of the more likely reasons is that the results cover more than one phenomenon or physical condition of the wake; therefore this is looked more into in the following section.

5.2 Wind along the row with narrow direction sector

To try and separate the different situations the wind direction sector is narrowed down to +/- 2°. The remaining conditions are similar to the ones in section 5.1. This means that the data extracted for this analysis are included in the former investigation.

The plots are shown below:

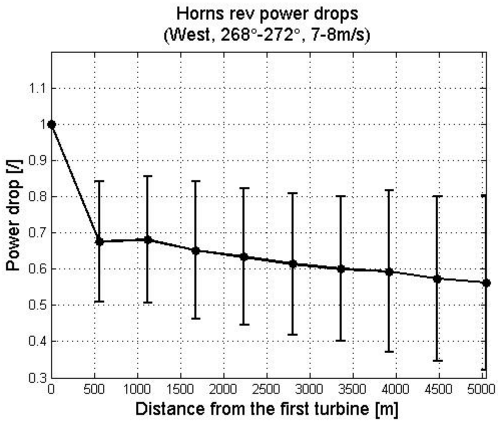

Figure 5.4 Relative power drop 7-8m/s

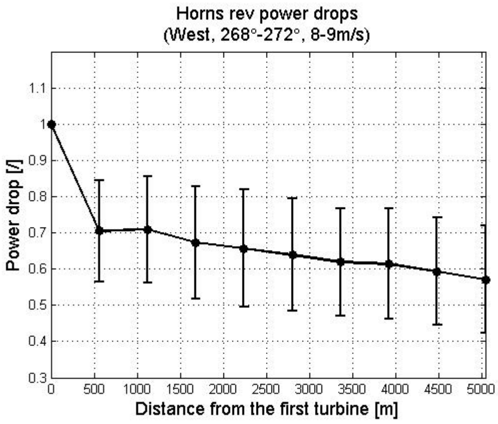

Figure 5.5 Relative power drop 8-9m/s

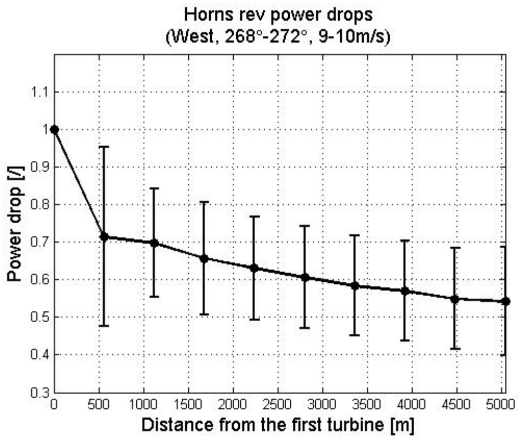

Figure 5.6 Relative power drop 9-10m/s

The results show that there is a significant change in the wake effect when the wind is limited to being parallel to the row direction (or very close to it). The power drop from turbine 1 to turbine 2 has increased from an average value of approximately 0.2 to about 0.3. This indicates that the very large power drops between the first two turbines described in earlier papers (for example Jensen, Leo et al.) only occurs in a very narrow sector around the row direction. At other wind directions the power drop is significantly smaller from turbine 1 to turbine 2.
For the remaining turbines the pattern is almost the same for the two analyses: the power drop from turbine 2 to turbine 10 is between 0.15 and 0.2, which occurs in an almost straight line.
The natural conclusion to this difference between wake effects for flow parallel to the row and wind direction being slightly off the row direction is that a wake model must be able to give significantly different results for even small changes in wind direction.
Unfortunately the standard deviations of the results are still very large and they have not decreased by narrowing the wind direction sector, so it is possible that another factor is causing the different situations and that sorting the data according to this factor might give lower deviations.

In earlier work, situations have been shown where the power output from the turbines increases down the line (for the last 4-5 turbines). Of course these situations are still present, however the mean results show that the general tendency is a large power drop from turbine 1 to turbine 2 and a steadily decreasing power output along the line of turbines. When creating a new wake model it has to be decided whether it should be able to predict all situations or simply have the ability to present the mean results correctly. This of course is question of the purpose of the model – does it aim at scientific or industrial use?

5.3 Wind along a diagonal

The diagonal in the wind farm allows an investigation of wake effects at a larger distance between the turbines. For Horns Rev the distance between turbines in the south-west to north-east diagonal is 9.3D (740m). To compare results with the data in the section 5.2 the must be a maximum number of turbines in the diagonals. Given the layout it is possible to find 3 lines with 8 turbines. Compared to the former section the present has less data since only 3 lines can be assessed (for western wind direction 6 lines are available).

The analysis has been performed with similar input data as in section 5.2 i.e. the wind direction interval is +/- 2° and mean wind direction is 222°.

The plots are shown below:

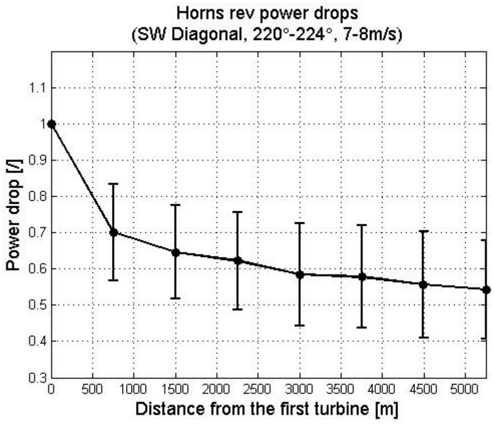

Figure 5.7 Relative power drop 7-8m/s

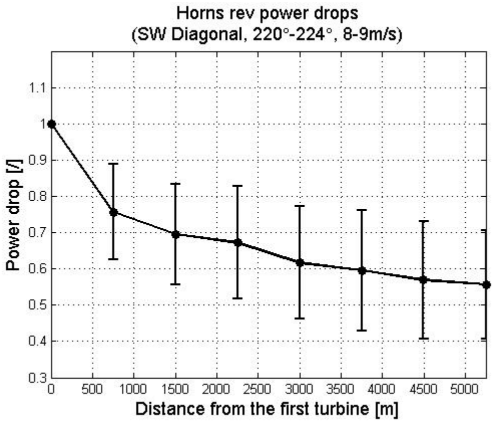

Figure 5.8 Relative power drop 8-9m/s

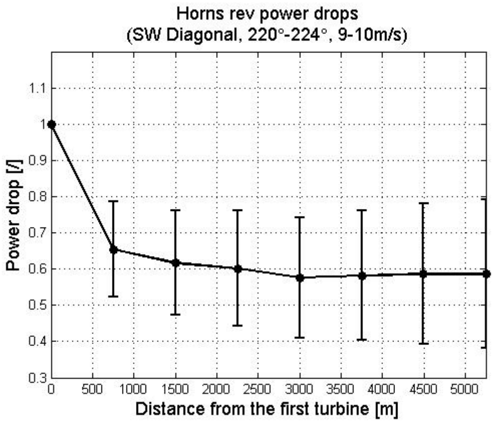

Figure 5.9 Relative power drop 9-10m/s

It is quite obvious that the data basis is smaller for this analyses compared to the former. Especially for the 8-9m/s case there are very few data resulting in a large standard deviation.

Despite the inaccuracies in data mean values it is assumed that the data set may be used for investigating general tendencies.

To compare the results data is plotted for each of the analysed wind speed intervals.

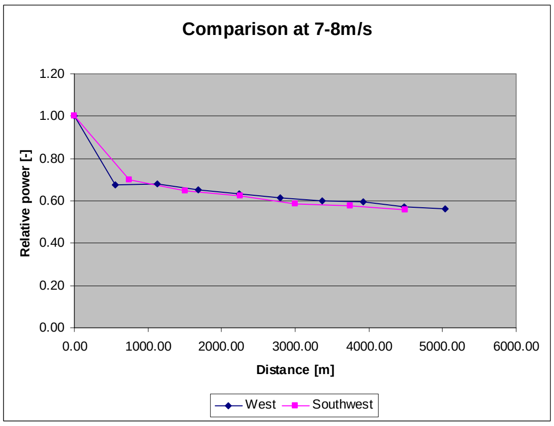

Figure 5.10 Power drop comparison 7-8m/s

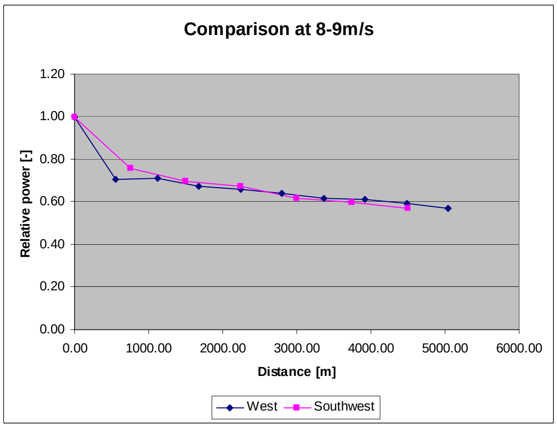

Figure 5.11 Power drop comparison 8-9m/s

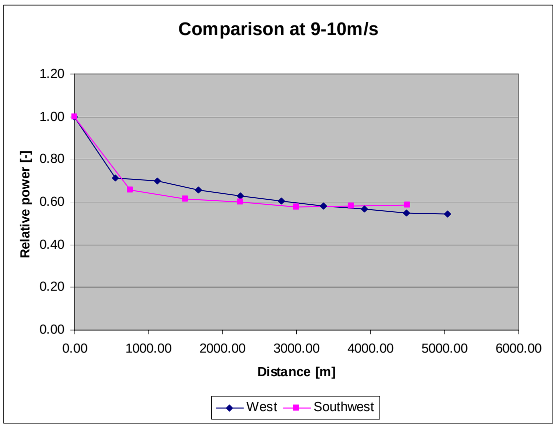

Figure 5.12 Power drop comparison 9-10m/s

The initial conclusion here is that the differences are relatively low and the power drop from turbine 1 to turbine 2 is very significant for both cases. Generally the power drop between the first two turbines is largest at 7D spacing (for the lower wind cases), and for the next 3 turbines the power drops of almost equally. After this there seems to be an obvious difference between the 7D and the 9.3D case at 9-10 m/s: For the 9.3D case the power output levels out from turbine 5 and is almost constant for the remaining turbines in the row. This indicates that the size of the “infinitely” large park depends on the distance between turbines in the wind farm. It also shows that the infinitely large wind farm is achieved at a fairly limited number of rows in the wind farm.

5.4 Directional dependency

If differences are experienced in the data for shifting wind directions it must be analysed what causes this effect. For example a short land fetch may cause changes to wind shear and turbulence compared to when the land fetch is practically infinite. In this section the results of section 5.2 are compared with similar results with wind from coming from east.

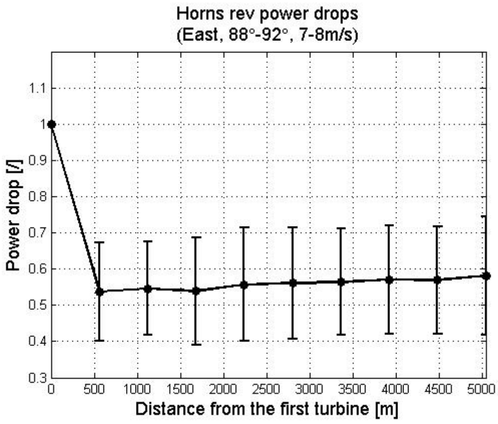

Figure 5.13 Relative power drop 7-8m/s

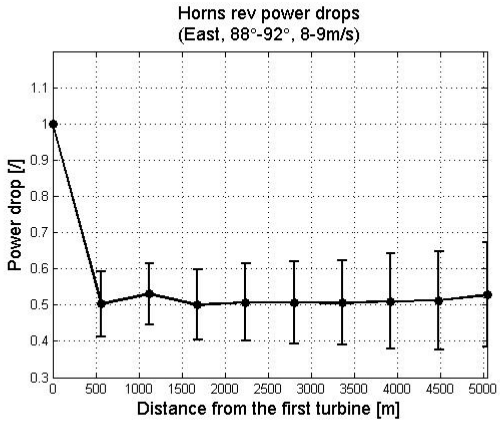

Figure 5.14 Relative power drop 8-9m/s

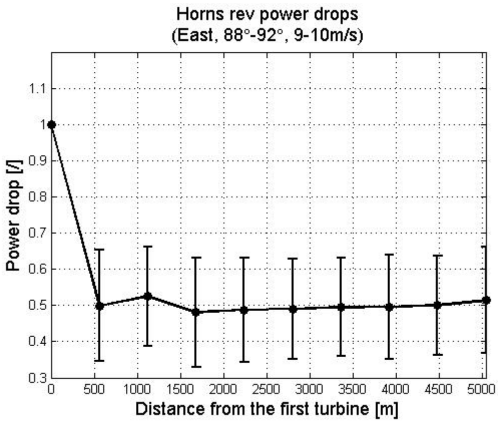

Figure 5.15 Relative power drop 9-10m/s

The most obvious differences between these results and the ones in section 5.2 are the very large power drop from turbine to turbine 2 and the slightly increasing power towards the end of the line. There are several possible explanations to this and the most probable ones are described below:

The land fetch of 15km to the east may cause different wind conditions such as wind shear and turbulence, which has a different effect on the power output.

Another very possible explanation is that the difference is caused by the difficulty of describing the wind direction for the entire wind farm by one single measurement, which is positioned very far from the western turbines. It has already been established that the power drop is not as significant for wind directions slightly off the line direction as it is when the wind is straight down the line. When using a wind direction measurement far from the first lines of turbines it is quite possible that the wind direction at the turbines is not always straight down the line as predicted by the wind vane at the met mast 5km away. This would give some cases with lower power drop between turbines 1 and 2 and eventually cause a larger mean value of the mentioned power drop. This case with first rows of turbines being far from the met mast occurs when wind is coming from the west (see section 5.2).

When wind is coming from the east the first rows of turbines are relatively close to the met mast and the chance that they experience the same wind direction as the mast is quite large. This means that the power drop from turbine 1 to turbine 2 will be occurring when wind is coming straight down the line for the majority of the cases. The result is that the power drop for this direction is likely to be larger (on average) than what was found for the west wind case. In figures 5.13 through 5.15 this is exactly what is found compared to the figures of section 5.2.

Another indication that this explanation is plausible is that the average power seems to be increasing towards the end of the line. If the turbines furthest away from the met mast are sometimes experiencing another wind direction they will not be in direct wake and therefore the power output from these turbines will be larger than the ones upwind. The effect is the exact same as seen in west winds.

Alternatively there might be horizontal gradients in the wind speed increasing as flow moves offshore (i.e. from east), which are slightly counteracting wake losses.

One last factor that seems to have an effect on the wake loss is the atmospheric stability. Recently an investigation of the wake loss pattern has been compared to the simultaneous temperature difference between air at 62m and water at sea level. As this difference is assumed to give a good indication of the stability the analyses concludes that this factor does influence the wake effects. Furthermore the mean stability varies from one wind direction to another, which means that different directions will have different wake conditions and thereby the same results cannot be expected for the eastern and western winds.

6. Conclusion

The conclusions to the work done for this paper relate to the results and to the proposed model for wake calculations.
As in earlier work large power drops were experienced for wind directions where wind is parallel to the wind turbine rows, however compared to the governing conviction a power drop from 100% to 50% between the first two turbines must be considered extremely large.
The analyses also showed that the direction and where it is measured is very important for the results. It is difficult to use one wind direction for the entire wind farm especially for the turbines far from the mast. This implies that there is no such thing as steady state for a physical system of this size and it must be expected that the wind will always vary from one point in the wind farm to another causing the data points to be scattered. One has to accept that working with wind farm data is a statistical process that implies a significant spread in the data basis.

It is shown that the very significant power drop occurs in a very narrow sector around the line direction and once wind is not straight down the line the power drop decreases fast with direction.

A good agreement was found between data from the east-west rows (in west wind) and the southwest diagonal (in south-west wind) although it seems there is a tendency for the power drop to become almost constant towards the end of the wind farm for the diagonal case. This implies a balance between the wind farm and the boundary layer above it.

There are strong indications that atmospheric stability has an influence on the wake phenomena and that the stability is strongly dependant on the wind direction, although the wind farm is placed far offshore.

Generally the model is able to predict the mean power drop from turbine 1 to turbine 2 in the row (when wind is parallel to the wind turbine row) after finding suitable model parameters. Towards the end of the wind farm the model is slightly over predicting production, as the energy recovery seems to be too large.

7. Acknowledgement

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8. References

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