Wake measurements from the Horns Rev wind farm
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Summary
Horns Rev is a large offshore wind farm exposed to low turbulence flow. It has a layout and a location which makes it excellent for general studies of wake effects. Three met masts are installed around the wind farm area to study the recovery of the wake flow behind the wind farm and support the development of new scientific and engineering models for calculation of external wake effects from large offshore wind farms.

All wind farm operation data is stored by a SCADA system. The SCADA system collects data from more than 200 sensors every 10 minutes. This data is used for the analysis of internal wake effects.

Wind speed and turbulence has been analysed for three lines of turbines - two aligned and one diagonal line of turbines. The analysis shows that there is a large reduction in wind speed from the first turbine to the second in a row, but that the wind speed does not change much from the second to the tenth row.

The wind data from the wake masts show that there is still a clear influence of the wind farm 6 km downstream on both mean wind speed and turbulence. The wake masts also indicate that the boundary layer has still not stabilized at pure offshore conditions even though the fetch is more than 15 km.

Key words: offshore, wind farm, turbulence, wake

This is a paper on wake measurements from the Horns Rev wind farm. We are of the impression that a presentation of these measurements is of great interest to the scientific community.

From a scientific point of view, the Horns Rev wind farm is very interesting for the following reasons:

• It is an offshore wind farm being exposed to low turbulence flow that has an absolute minimum disturbance from the underlying surface
• It has a very regular shape and layout that is perfectly suited for general studies
• It is fairly large, enabling studies of large wind farm objects
• It will be exposed to wind from all possible wind directions

The wind farm
The wind farm layout is a 10 times 8 matrix forming a slightly oblique rectangle. The distance between the turbines is 560 meters in both directions, corresponding to 7 rotor diameters.

The turbines are numbered so that the westernmost column is numbered from 01 to 08 with 01 being the turbine in the northwest corner, and the easternmost column being numbered 91 through 98. This may lead to the wrongful assumption that there are actually 98 turbines, but as several numbers are unused, the number of turbines is still only 80.
Referring to UTM zone ED32, the co-ordinates of the corner turbines in the rhombus are:

<table>
<thead>
<tr>
<th></th>
<th>X co-ordinate</th>
<th>Y co-ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>423974</td>
<td>6151447</td>
</tr>
<tr>
<td>08</td>
<td>424386</td>
<td>6147543</td>
</tr>
<tr>
<td>91</td>
<td>429014</td>
<td>6151447</td>
</tr>
<tr>
<td>98</td>
<td>429431</td>
<td>6147543</td>
</tr>
</tbody>
</table>

The wind farm is located in the North Sea, approximately 30 km west of Esbjerg. The distance to the nearest point on shore (Blåvands Huk) is approximately 13 km.

Around the wind farm three met masts are installed.

<table>
<thead>
<tr>
<th>Mast</th>
<th>X co-ordinate</th>
<th>Y co-ordinate</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2</td>
<td>423412</td>
<td>6153342</td>
</tr>
<tr>
<td>M6</td>
<td>431253</td>
<td>6149502</td>
</tr>
<tr>
<td>M7</td>
<td>435253</td>
<td>6149502</td>
</tr>
</tbody>
</table>

Plotting of these co-ordinates will show that M2 is located 2 km north-northwest of the northwest corner turbine (01). M6 and M7 are located 2 and 6 km east of the wind farm respectively on a line that passes right through the middle of the fourth and fifth row.

**The wind turbines**

The wind turbines are all of the Vestas V80 type shown in the picture below. Please do not pay too much attention to the fact that the turbines are not operating and do not agree on the wind direction. This picture was taken just after the construction, and at that time the turbines were not allowed to go into normal operation yet.

In the summer of 2003 two more masts (called M6 and M7) were installed. The purpose of these masts is to study the recovery of the wake flow behind the wind farm for westerly winds, and support the development of new scientific and engineering models for calculation of external wake effects from large offshore wind farms.
The dimensions of the turbines are shown in the sketch below.

For the wake measurement, the most interesting turbine data are the diameter, the hub height and the thrust coefficient. When using the Vestas V80 turbine in wake modelling tools, the values for power and thrust coefficient listed below can be applied.

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Electric Power (kW)</th>
<th>Thrust coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>66.6</td>
<td>0.818</td>
</tr>
<tr>
<td>5</td>
<td>154</td>
<td>0.806</td>
</tr>
<tr>
<td>6</td>
<td>282</td>
<td>0.804</td>
</tr>
<tr>
<td>7</td>
<td>460</td>
<td>0.805</td>
</tr>
<tr>
<td>8</td>
<td>696</td>
<td>0.806</td>
</tr>
<tr>
<td>9</td>
<td>996</td>
<td>0.807</td>
</tr>
<tr>
<td>10</td>
<td>1341</td>
<td>0.793</td>
</tr>
<tr>
<td>11</td>
<td>1661</td>
<td>0.739</td>
</tr>
<tr>
<td>12</td>
<td>1866</td>
<td>0.709</td>
</tr>
<tr>
<td>13</td>
<td>1958</td>
<td>0.409</td>
</tr>
<tr>
<td>14</td>
<td>1988</td>
<td>0.314</td>
</tr>
<tr>
<td>15</td>
<td>1997</td>
<td>0.249</td>
</tr>
<tr>
<td>16</td>
<td>1999</td>
<td>0.202</td>
</tr>
<tr>
<td>17</td>
<td>2000</td>
<td>0.167</td>
</tr>
<tr>
<td>18</td>
<td>2000</td>
<td>0.14</td>
</tr>
<tr>
<td>19</td>
<td>2000</td>
<td>0.119</td>
</tr>
<tr>
<td>20</td>
<td>2000</td>
<td>0.102</td>
</tr>
<tr>
<td>21</td>
<td>2000</td>
<td>0.088</td>
</tr>
<tr>
<td>22</td>
<td>2000</td>
<td>0.077</td>
</tr>
<tr>
<td>23</td>
<td>2000</td>
<td>0.067</td>
</tr>
<tr>
<td>24</td>
<td>2000</td>
<td>0.06</td>
</tr>
<tr>
<td>25</td>
<td>2000</td>
<td>0.053</td>
</tr>
</tbody>
</table>

For the wake measurement, the most interesting turbine data are the diameter, the hub height and the thrust coefficient. When using the Vestas V80 turbine in wake modelling tools, the values for power and thrust coefficient listed below can be applied.

For the purpose of scientific work on wake effect, however, this is a major disturbance of the otherwise nice and flat thrust coefficient curve. Operating the main controller will make it practically unpredictable, and the data from those periods will have to be sorted out.

Internal wake effects observed
All data about the wind farm operation is collected and stored by a Surveillance, Control and Data Acquisition system (SCADA). It operates on an ethernet connection between the wind farm and a database server in Esbjerg.

On this server values from more than 200 different sensors are stored every 10 minutes. This adds up to a large amount of data. The database has at least 300 Gb disk space and is continuously expanded.

These data are used for the analysis of internal wake effects.

For the purpose of scientific work on wake effect, however, this is a major disturbance of the otherwise nice and flat thrust coefficient curve. Operating the main controller will make it practically unpredictable, and the data from those periods will have to be sorted out.
just as important as it is for the economy of the installation. As the availability at Horns Rev - due to transformer and generator problems - has not yet reached the required level, this has been an issue given special attention in the data presented here as well. Some types of analysis, such as the array efficiency of the entire wind farm simply does not make sense at the present stage, since too little data is available with all turbines in operation at the same time. But other interesting phenomena can still be observed.

The types of analysis selected for this paper are:

- Analysis of shelter in individual rows
- Analysis of spread of wake effects
- Analysis of local speed up

Even with the transformer and generator problems it is still possible to get a good idea of the reduction of wind speed along a single line of turbines. Four different lines have been selected for analysis:

<table>
<thead>
<tr>
<th>Line</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line 1</td>
<td>172.0</td>
</tr>
<tr>
<td>Line 2</td>
<td>269.0</td>
</tr>
<tr>
<td>Line 3</td>
<td>269.0</td>
</tr>
<tr>
<td>Line 4</td>
<td>220.4</td>
</tr>
</tbody>
</table>

Line 1 is a line on the eastern boundary of the wind farm.

Line 2 is an east-west going line approximately in the middle of the wind farm.

Line 3 is a line on the southern boundary of the wind farm.

Line 4 is a diagonal line from the southwest towards the northeast. This line differs from the three others in the distance between the turbines being larger, and the perpendicular distance to neighboring turbines being smaller.

The wind directions used for the analysis have been taken from the recordings at M2 (northwest of the wind farm). This tends to produce slightly unstable results for line 1, which is probably partly due to the distance and partly due to disturbances in the general flow from the wind farm. Therefore results from line 1 are not shown here.

The wind directions to be used for the individual lines are shown in the table below. The small deviation from pure west is due to the fact that the turbine rows are aligned with the UTM co-ordinate system, which at that location has a deviation from true north of 1 degree.

The data presented in the above plot is wind speed measured on the nacelle anemometers. These anemometers are calibrated to account for the disturbance by the nacelle and rotor, and comparisons with the individual power curves indicate that they are fairly accurate.

The graph is for wind speeds between 6 and 7 m/s on the westernmost turbine, and shows the reduction in a very narrow wind direction sector. As the graph shows, the general tendency is a large reduction from the first to the second turbine, but it also shows that the sheltering effect further downstream seems to stabilize at a constant level.

The largest scatter is seen on the second turbine (1), where a single observation indicates that situations with speed-up in the second row of turbine can be found in special conditions.

The fact that there are no dots for turbines 4 and 8 indicate that no information was available in the SCADA database. During that period this normally means that the turbine has no power due to a faulty transformer, but it could also just be a communication failure between the turbine and the SCADA system.

Line 3

The next plot shows the same situation on line 3. It shows very much the tendency with regard to the average wind speed reduction being large at the second and fairly constant for the rest of the row. The scatter, however, is significantly larger.
The larger scatter is probably caused by the fact that the turbines are more exposed to free inflow during the turbulent variations of the wind directions.

**Line 4**

Also in line 4 (the diagonal line) the tendency is the same. The most significant difference here is that the spread of the observations is significantly smaller than in both line 2 and 3. This indicates that from this wind direction the wakes actually merge with wakes from the neighbouring rows, forming a more uniform flow for the turbines.

If we compare the wind speed reduction in line 2 (which is aligned) and line 4 (the diagonal) they show more or less the same reduction. The wind speed is slightly lower in line 2 than in line 4, but not as much as we normally see in wake calculation models.

**Turbulence intensity**

The turbulence intensity along the lines has been investigated as well.

This is slightly trickier, since turbulence intensity is not calibrated on the nacelle anemometers. It is our general impression that the turbulence levels measured on the nacelle anemometers are smaller than those measured on the masts, and the masts are believed to be the more accurate.

Nevertheless, we find the plots rather interesting.

This graph shows the turbulence along line 2. It shows that generally there is an increase from the first to the second turbine, but further downstream the level is fairly constant. One interesting observation is that the spread of the recordings is fairly large, and the lower spots indicate that even in the 10th row, you can observe situations where the turbulence is not increased at all compared to the first turbine.

In line 4, the general tendency is the same. The turbulence level increases from the first to the second turbine, and is fairly constant for the turbines further downstream. It is noteworthy that the spread of the data is significantly smaller than in line 2 and that it does not show neither deep drops nor high peaks. Again this could be a consequence of merging wakes producing a more uniform flow pattern.
**Directional dependence**

To investigate the directional dependence of the wake effects, two turbines have been selected for further analysis.

The first turbine is no 35, which is located in the middle of the wind farm.

In this analysis we have taken the liberty of neglecting any effects of reduced availability of the wind farm. The only requirement in the data selection has been that turbine 08 at the southwest corner and turbine 35, being the object of analyses, were both in operation. The results shown should be viewed with that in mind. The absolute magnitude of the wind speed reduction cannot be trusted completely, but most likely the directional dependence will give a true picture.

As indicated by the arrows on the layout chart above, the wind directions selected were from 150 to 300 degrees.

Both the aligned and the diagonal rows are seen clearly on turbine 35, and there appears to be practically no reduction in wind speed for intermediate wind directions.

If wind turbine power output is observed instead of the wind speed of the nacelle anemometer, the largest reduction is still seen when the flow is aligned with the rows, but a small reduction is also seen for the intermediate wind directions.

The larger wake effect for intermediate wind directions seen on the power signal is probably partly due to the power output being significantly more sensitive than the wind speed, and partly because some parts of the rotor can easily be exposed to shelter from an upwind turbine even though the anemometer in the centre of the rotor is not.

The second turbine selected for directional dependence analysis is turbine 71.

On this turbine, the individual lines are hardly seen. Wakes seem to have merged, forming a flow field that has no directional dependence.
The most significant effect is from direction 270 and 300 where it is clear that both turbines are exposed to free wind, and wind speeds recorded are identical.

The tendency of the power output is the same, showing practically no special reduction for wind directions aligned with the turbine rows.

**External wake effects**

External wake effects can be studied using the results from the three met masts located around the wind farm.

The met masts have slightly different heights, but this is does not seem to have any significant influence on the observations made.

<table>
<thead>
<tr>
<th>Hub height/top level</th>
<th>Turbines</th>
<th>Mast 2</th>
<th>Mast 6</th>
<th>Mast 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70</td>
<td>62</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

For the analysis of the external wake effects, only wind speeds between 3 and 10 m/s have been selected.

As for the analysis of the directional dependence on wake effects, no sorting has been performed to get a well-defined availability, so this should be kept in mind for these results as well. The results are not suitable for detailed model calibrations yet, but they show some general tendencies.

In this first graph, we have plotted the relation between the wind speed at masts M6 and M7. This means that for the westerly wind directions this graph shows the recovery of the wind speed from 2 to 6 km downstream.
It is noteworthy that the effect of the masts being installed between the turbine lines is seen so clearly for wind directions aligned with the turbine rows.

For wind directions between 20 and 50 degrees the influence of land is clearly seen on M7. For these wind directions, the flow towards M7 passes over the land at Blåvands Huk where M6 has a significantly larger fetch.

For wind directions between 50 and 120 degrees still a small influence of land is seen, indicating that the boundary layer flow has not yet changed completely to stable offshore conditions at this distance from shore.

In this second graph we have added the relation between the wind speed at M6 and M2. This graph gives a clear picture of the wake effect on mast 2 for southeasterly winds, and confirms the reduced sheltering effect from wind directions aligned with the turbine rows.

Unfortunately, the plot also shows irregularities that cannot be explained at the present stage. For wind directions between northwest and east there seems to be good agreement between wind speed measurements on the two masts. But wind directions between south and northwest are not as expected.

For the directions 205 and 215 both M6 and M2 should be exposed to free inflow with no disturbances within a distance of hundred km. Nevertheless there is a difference in wind speed of 5%, which is about 5 times more than expected due to the vertical wind gradient. Also for the westerly directions it was to be expected that the reduction would be larger than what is actually measured when compared to M7.

By adding the relation between M7 and M2 to the plot (below) the irregularities become even more obvious. These measurements indicate that for westerly winds, the wind farm should lead to an increase in wind speed at a distance of 6 km downstream. We hope that a more careful study of possible disturbances from aviation obstruction lights and lightning protection will provide a reasonable explanation for that.

The assumption so far is that for wind directions between south and northwest there is a deviation in wind speed readings between the old mast (M2) and the new masts (M6 and M7) in the order of 4%. Whether it is M2 that is too low or M6 and M7 that are too high is presently unknown.

The turbulence intensity behind the wind farm has been investigated as well.

This plot shows the turbulence intensity recorded at M2, M6 and M7. Increased turbulence is seen on M2 for southeasterly winds.

When looking at turbulence data only from M2, the effect of the wind farm is almost hidden by the fact that the southeasterly winds have the lowest level of turbulence in the undisturbed conditions.

For easterly wind there is a clear (though very small) tendency showing that turbulence is higher on M7 than on M6 which could be a result of M7 being closer to land.
It appears that to obtain low turbulence offshore there is an optimum fetch where the disturbance from land has disappeared, and the waves have not yet been raised to a level that significantly influences the turbulence. For northeasterly winds where the fetch is smallest, there is still a clear effect of land on both mean wind speed and turbulence. For southeasterly winds where the fetch is 50 to 100 km, the turbulence level is the lowest, and for northerly winds with waves coming all the way from the north of Scotland the turbulence level is high compared to the average.

For westerly winds the increase in turbulence on M6 and the recovery or relaxation of the flow towards M7 is very clear. The measurements clearly show that increased turbulence has not disappeared 6 km downstream of a large offshore wind farm.

It is noteworthy that the tunnelling effect of wind flow passing undisturbed between rows 4 and 5 is mainly a mean wind speed phenomenon. It is not seen on the turbulence plots at all.

**Future R&D plans for the Horns Rev wind farm**

In relation to wake effects, two future projects should be mentioned:

- Wake effects of large offshore wind farms
- Load measurements on turbine 14

Wake effects of large offshore wind farms is a Danish project involving Risoe National Laboratory, E2, with data from the Nysted offshore wind farm, and Elsam, with the Horns Rev data.

The project is funded by the Danish PSO system (Funds provided and administered by Eltra and Elkraft), and is scheduled to run from September 2004 to September 2006.

The main goal of the project is to develop new scientific and engineering models for calculation of wake effects of large offshore wind farms.

The load measurements on turbine 14 are a project presently involving only Vestas and Elsam. Activities were started during the summer of 2004, and measurements are expected to run for 9-12 months from December 2004.

The main goal of that project is to measure both the loads on nacelle and blades when operating in wake and free flow and to investigate loads transferred from the monopile to the seabed.

This project involves no public funding, and the measurement results are as such the property of Vestas and Elsam exclusively. Nevertheless the project expects to be able to provide useful data to public R&D projects on loads and wake effects for wind turbines in large offshore wind farms. This requires, however, that public funding is granted to the scientific community for such work, and so far this has proven to be surprisingly difficult.

**Further access to Horns Rev data**

People from the scientific community often approach Elsam to get access to measurement data from the Horns Rev wind farm.

Our general policy on these matters is that we do whatever we can to help. However, in order to minimize the risk of spreading data that could directly or indirectly constitute information of commercial interest to Elsam or in any way reduce the competitive power of Elsam, we do not provide raw data for arbitrary analysis work.

Besides protecting the commercial interests of Elsam, we also believe that we can provide a better service by supplying processed data rather than raw data – simply because data processing requires a profound knowledge of details and irregularities in the wind farm operation (like the wind farm main controller).

This paper provides good examples of the kind of information that can be extracted from the SCADA system and the met masts. We believe that it will also provide most of the information needed to model the Horns Rev wind farm in wake calculation models.

If anybody wishes to model the Horns Rev wind farm and perform wake calculations, they are hereby invited to send us the results of their calculations. Then we will in return do our best to extract data that can confirm or reject the results of the model.

If you would like to learn more about the wake measurement analysis performed, you are very welcome to send an email to the lead author of this paper.