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Impact of Large Neighbouring Wind Farms on Energy Yield of Offshore Wind Farms

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Summary

For the success of a wind energy project, it is essential that the expected energy yield is accurately predicted, requiring the detailed assessment of both the wind resource and the interactions between the wind turbines. For large offshore projects, it is well known that the turbine wakes develop differently compared with the typical small and medium size onshore wind farms.

In this paper, we use newly established methods, based on a boundary layer perturbation to predict the array effects of large wind farms. There is particular focus on predicting the interactions between neighbouring wind farms, through the incorporation in the model of a new wind speed recovery function. Available offshore measurements have been used in the development of the methods, and the models generalised, designed for application to any wind farm project design and location.

Results of the model are then presented for a cluster of large wind farms, created to mimic North Sea developments such as the UK Round 3 Zones and other major projects in northern Europe. Separation distances from 4 to 10 km between adjacent wind farms are explored and are found to strongly influence the additional array effects from neighbours.

1. Introduction

The offshore wind energy industry in Northern Europe is now engaged in the design and construction of large projects often comprising hundreds of turbines. Offshore wind energy zones have been designated within the waters of many Northern European countries, such as the UK Round 3 Zones with capacities up to 9 GW, and the multiple zones in the German Bight. This increased level of activity combined with spatial limitations on project siting has led to a large number of projects being planned in close proximity to one another. In a few locations, neighbouring projects are already in operation or under construction, for example at Horns Rev and Nysted (also known as Rødsand).

For accurate energy yield predictions, it is essential to predict accurately the array effects within such large offshore wind farms. It is also necessary to include the effects that large upwind projects have on the wind climate that is experienced by their downwind neighbours. Wake effects have been studied extensively for single turbines and for energy production in small and medium sized arrays, and there is an increasing body of research on the particular array losses found in large offshore wind farms. However there has been less research into wake effects between several large arrays of turbines. On one hand, the scarcity of detailed measured data has made study of the phenomena difficult; however on the other hand the commercial significance for research into such models is steadily increasing.

In this paper, the component methods for a large wind farm model are described, and the more recent updates to modelling wind speed recovery between wind farms are explained in more detail. A case study is presented that explores the sensitivity of energy yield to the separation between adjacent large wind farms.

2. Background

In 2004, a study on wake effects in and around the 160 MW Horns Rev I offshore wind farm was published by Elsam Engineering [1]. Of greatest interest to the subject here is the comparison of measured wind speeds between the meteorological masts, these masts lying between 2 km and 6 km distant from the wind farm, as shown in Figure 1.

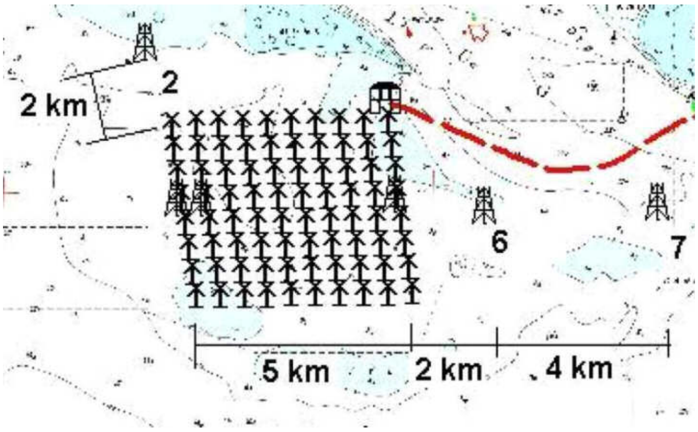

Figure 1: Horns Rev Masts [1]

In 2005, Risø National Laboratory published results of a study into the wake effects around the first Horns Rev and Nysted projects based on data gathered by satellite- and aircraft-mounted Synthetic Aperture Radar (SAR) [2]. With this technology, estimated wind speeds are derived from images of the backscattered radar on the physical basis that the wavelength of capillary waves is driven by the wind speed at the surface.

As part of their study, Risø analysed a limited number of SAR images covering the areas around the two wind farms. Figure 2 shows the average of the profiles as the wind speed deficit develops and then recovers. The separate plots for "onshore" and "offshore" indicate winds blowing towards or away from nearby land. While giving qualitative results, note that there is a high quantitative uncertainty associated with SAR data.

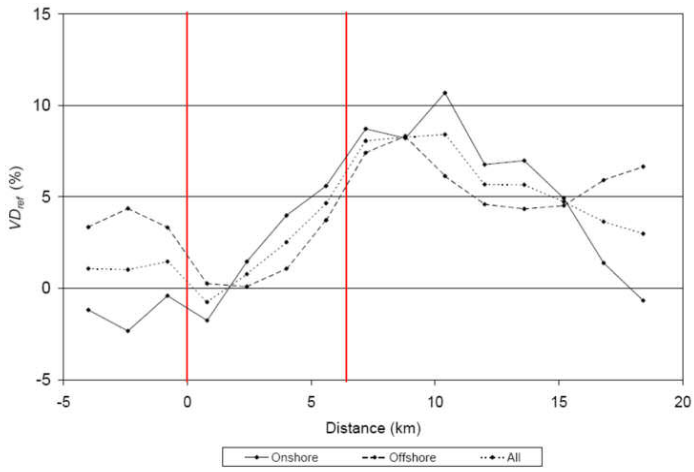

Figure 2: Results from the Risø study using SAR [2]

The results show broad agreement with the Elsam study with a velocity deficit of around 8% being evident immediately downstream of the wind farms. The recovery is somewhat slower however, reaching a deficit of around 3% at 10 km downstream (of the end of the wind farm). It is notable that the offshore wind dataset exhibits a much slower recovery, possibly due to a greater level of atmospheric stability.

The Danish R&D project [3] undertaken by a team of researchers from Risø and DONG analysed the performance of the first Horns Rev and Nysted wind farms in greater detail. The project had access to both turbine production data and wind measurement data from the 2 km and 6 km down-wind met masts; unfortunately, due to the commercial value of this data, it has not been released in its entirety to the general scientific community, though processed subsets have been distributed to selected partners, including the European UpWind R&D project [4].

Figure 3 shows the change in wind speed deficit downstream of the wind farm edge, illustrating the recovery occurring and also the considerable range of values observed.

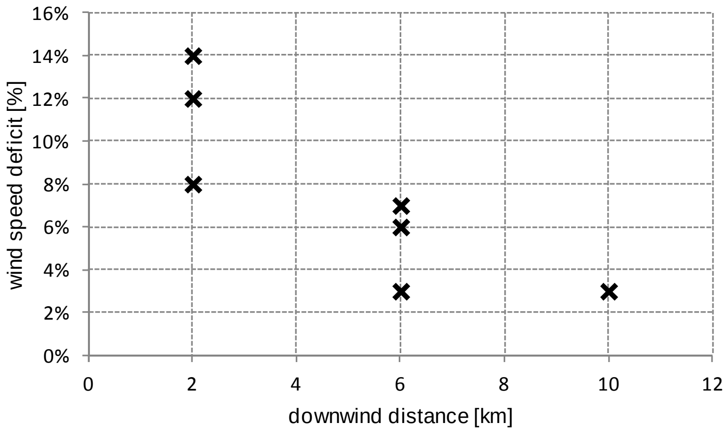

Figure 3: Wind speed deficit recovery downwind of the wind farm

3. Large wind farm model

The standard modelling of wind speeds in wind farms is a two step process. In the first step the ambient wind flow is established without the presence of a wind farm. In the second step, wind turbines are placed within this wind flow and the wakes calculated. It is traditionally assumed that the wind flow can be treated as independent of the wind farm.

However, in the case of large wind farms in low roughness surroundings when additional array losses are found, the situation can be treated as the wind farm causing a disturbance to the atmospheric flow, thereby altering the wind resource itself. This effect has sometimes been likened to a large wind farm behaving like a forest and modifying the atmospheric boundary layer.

Thus the large wind farm modelling method has been developed, by the inclusion of an additional step:

- Use the wind flow model that best describes the ambient wind flow statistics over the potential wind farm site. Typically, but not necessarily, data from a site mast would be used to initiate the model. By applying the wind flow model, wind resource variation over the site will be considered.

- Place the turbines in the wind flow and calculate the large wind farm adjustment to the ambient flow due to the presence of the turbines, using a boundary layer method that includes a displacement height term. The adjustment is only made if certain criteria are met that introduce a dependency of the adjustment on turbine density. These criteria are determined by the model interrogating the field of turbines upstream and to the side of each target turbine, for each wind direction.

- Use a standard wake model together with the corrected ambient wind speeds to analyse the wake deficits between turbines. Wake models that take turbulence intensity directly into account will give more accurate predictions.

Using this combination of methods provides the detail of the wake modelling to be retained whilst allowing full energy analysis of large numbers of turbines to be carried out in a short time scale. For example an energy yield calculation for 100 turbines, 360 direction steps and 50 wind speed steps (18 000 flow cases) can take less than 10 minutes, thus allowing the exploration of many options of layouts and turbine types.

Figure 4 presents results for the Horns Rev I wind farm, comparing operational data with modelled energy yield predictions, with and without the large wind farm correction applied. The results are for wind speeds of 8 m/s when wake effects are most prominent, and for a 30° sector centred around 270°, which is one of the main orien tations of the turbine rows.

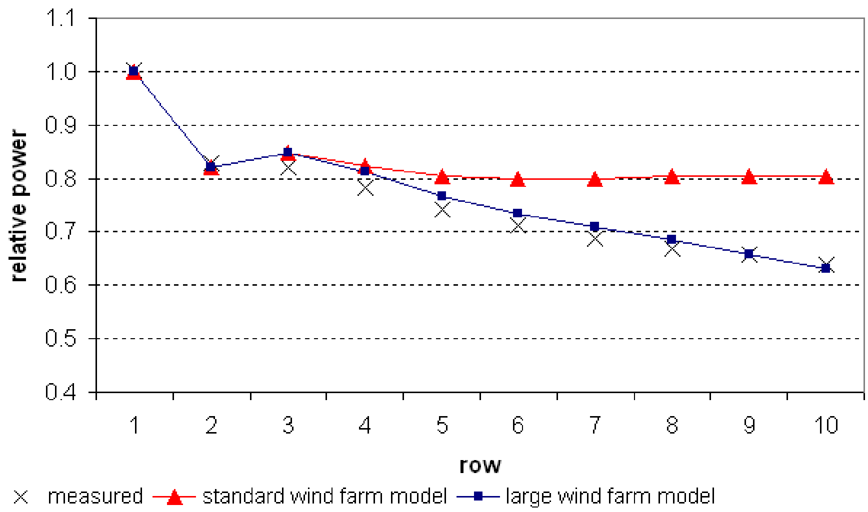

Figure 4: Comparison of operational data at Horns Rev I with models, with and without large wind farm adjustment. Wind speed 8 m/s; directions 255-285° [4]

As can be seen the standard wake model results in overprediction of the energy yield of turbines located deep in the wind farm array. When the large wind farm model is applied (blue line), good agreement is shown. Further details of the model for the large wind farm adjustment together with comparisons with more operational data are given for offshore wind farms in [5] and onshore wind farms in [6].

4. Large wind farm recovery function

In the original model, a basic recovery function was included to take into account the restoration of the ambient wind resource downstream of the wind farm. This recovery model is based on the assumption that the wind farm deficit for an infinitely large wind farm is going to reach equilibrium eventually. Recently, with the release of version 4.2 of WindFarmer [7], the model for the downstream recovery has been refined and this modification is described below.

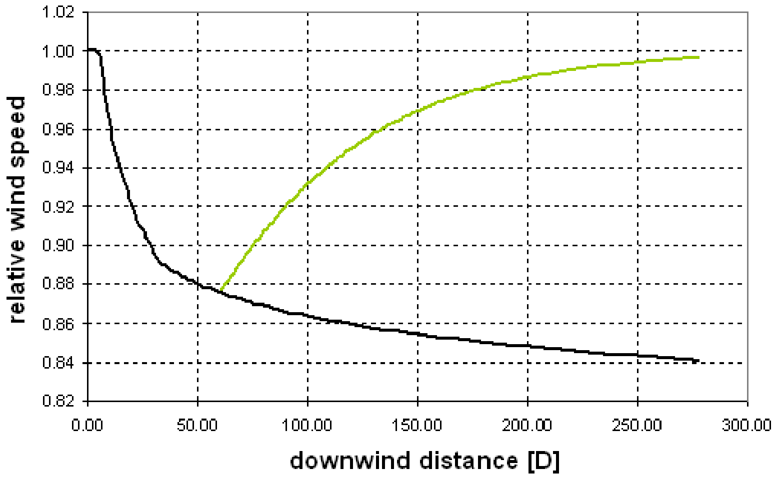

Figure 5: Large wind farm adjustment of the ambient wind speed downwind of a single turbine at hub height Green line = recovery function

The correction factor for the ambient wind speed in the latest model is shown in Figure 5 as a function of the downwind distance behind each single turbine in the wind farm, together causing the large wind farm effect. The black line shows the adjusted ambient wind speed dropping with distance according to the boundary layer model. The green line shows the recovery of the boundary layer which takes over after a certain distance, described using an empirical exponential expression:

$$u_r = u_1\left(1-\left(1-\frac{u}{u_1}\right)*0.5^{\frac{x-x_{start}}{x_{50\%}}}\right)$$

where

u_1	ambient wind speed not affected by the turbines
u	ambient wind speed calculated with the large wind farm correction without recovery
x	downwind distance measured from the turbine location
x_{start}	start distance for the recovery function
$x_{50\%}$	distance where the large wind farm correction has reduced to 50%, measured from x_{start}

5. Calibration of recovery model

The wind speed deficits measured downwind of the Horns Rev I and Nysted I wind farms as published in [3] have been used to find a universal set of the variable parameters x_{start} and $x_{50\%}$. The results for the best fit of the measured data indicate that the parameters x_{start} and $x_{50\%}$ should be selected as 60 and 40 rotor diameters, respectively. Once other measurements become available, these values may need to be modified.

The results using the proposed best parameter set are shown in Figure 6 for Horns Rev and Figure 7 for Nysted. The modelled results are shown for a direction sector of 30° width, centred at 270° for Horns Rev and 278° for Nysted, which ar e major orientations of the turbine rows. In each case, the free wind speed is 8 m/s. Each plot shows the large wind farm model used together with either the PARK or Eddy Viscosity wake model.

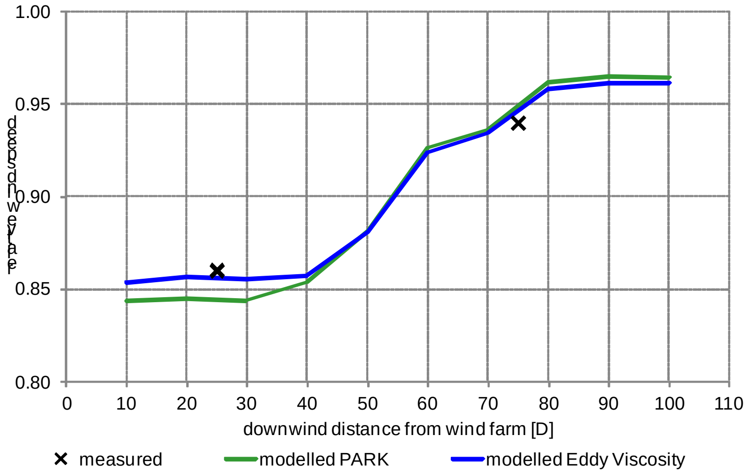

Figure 6: Modelled and measured wind speed downstream of Horns Rev I wind farm

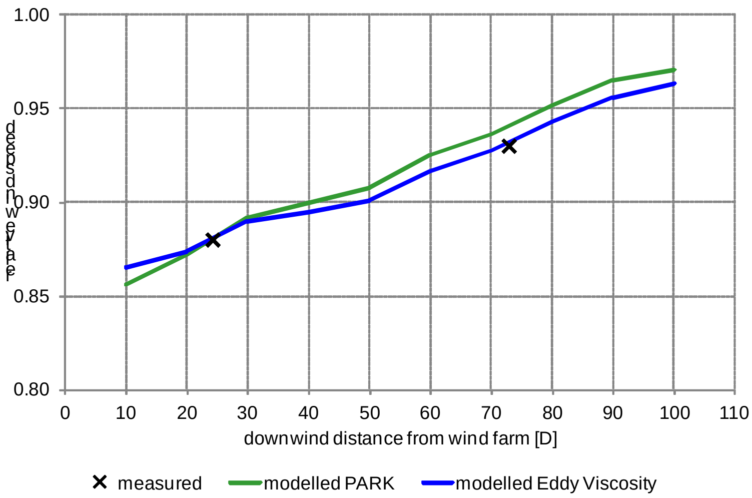

Figure 7: Modelled and measured wind speed downstream of Nysted I wind farm

As yet, performance data from large neighbouring operational offshore wind farms have not become available which would allow examination how the wind farms interact with each other in practice. Hopefully, some of the new wind farms coming on line will provide the opportunity to investigate this scenario.

6. Case study

To explore the implications for the multiple wind farms currently being planned, a representative hypothetical development was created, consisting of nine projects of around 400 MW each. The total zone of 3.6 GW is roughly equivalent to the scale of UK Round 3 developments, while the 400 MW project size is comparable with the first phase of many German projects. The wind rose from Fino1 (Figure 8) was used and assumed to be representative of conditions in the North Sea.

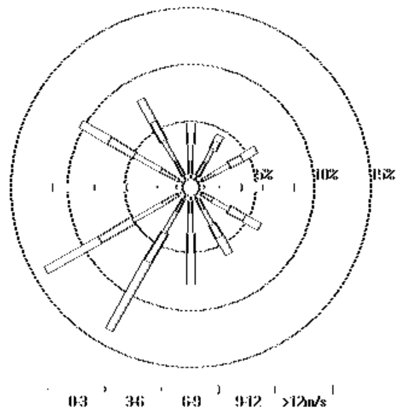

Figure 8: Wind rose used in case study

Development was modelled as taking place in a phased approach, with the first six projects using generic 5 MW turbines, and the later three projects using 8 MW turbines. The characteristics of these turbines (rotor diameter, hub height, power curve) were calculated by scaling existing commercial offshore turbines, and applying first principles to obtain a power production curve. Turbine spacing within the projects was assumed to be 7 rotor diameters for all cases.

In order to test the effects of spacing between projects, three layouts were analysed, having gaps between the projects of 4 km, 6 km and 10 km. Turbine and project layouts were assumed to be square. In reality, turbine layouts are often optimised with respect to internal wake effects though this is not the focus of the investigation being reported here.

Figure 9 illustrates the 4 km spacing case. Note that the three northerly projects have fewer turbines as they utilise the 8 MW unit.

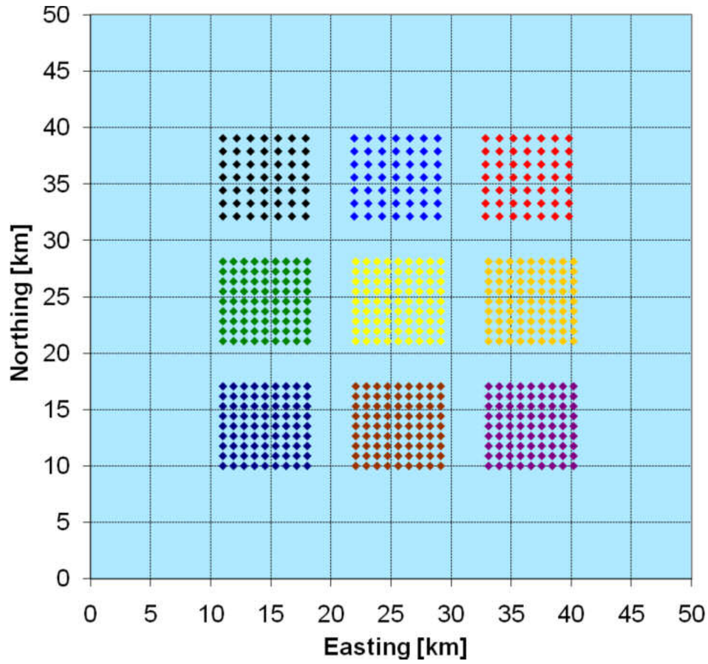

Figure 9: Layout of the cluster of projects

Spacing between projects	Target project	Neighbours	Loss due to neighbours [%]
4km	SW	Mid	**0.5**
4km	SW	All	**2.4**
4km	Mid	SW	**1.3**
4km	Mid	All	**7.9**
4km	NE	Mid	**1.4**
4km	NE	All	**5.0**
6km	SW	Mid	**0.2**
6km	SW	All	**1.6**
6km	Mid	SW	**0.6**
6km	Mid	All	**5.1**
6km	NE	Mid	**0.7**
6km	NE	All	**3.6**
10km	SW	Mid	**0.1**
10km	SW	All	**0.9**
10km	Mid	SW	**0.2**
10km	Mid	All	**2.7**
10km	NE	Mid	**0.3**
10km	NE	All	**1.7**

Table 1: Energy losses as a percentage reduction due to neighbouring wind farms. Projects are identified by compass direction. See Figure 9.

Table 1 highlights selected results. The extra losses caused by neighbouring projects relative to the net energy yield of the target project are shown.

It is immediately apparent that energy losses are markedly reduced when the spacing between projects is increased by only a few kilometres, and due to the exponential recovery profile assumed, this effect is largest at closer distances. It is also noteworthy that despite the prevailing wind direction being from the South-West, the effect of neighbouring projects on every side causes a significant reduction in energy yield.

The Middle project experiences the highest losses. The extra losses when completely surrounded by adjacent projects are 7.9 % with a 4 km gap, dropping to 2.7 % when the gap is increased to 10 km. In comparison, the array losses for the Middle project alone, including the large wind farm adjustment but in the absence of neighbours, is 10 %.

Comparing the losses experienced by the North-East project due to the Middle project, and the losses at the Middle project due to the South-West project, it is apparent that they are in all cases very similar. This implies that for the given recovery model, turbine choice does not have a very significant effect on projects with similar spatial dimensions.

7. Conclusions

A model for array losses within and between large wind farms has been presented, based on data from operational offshore wind projects at Horns Rev I and Nysted I. The method features adjustments to the ambient wind resource that are triggered according to the turbine density experienced by a target turbine for each wind direction. The magnitude of the adjustment is dependent on wind turbine density in a wind farm and based on a boundary layer concept. The method also incorporates a new function to model the gradual recovery of the wakes that extend behind such large wind farms.

This new recovery function is calibrated to known experimental data points and has been applied in this parameter study to a hypothetical cluster of large projects, representative of North Sea developments, to investigate the potential losses in energy yield arising from the influence of neighbouring projects. The results are broadly intuitive, with losses greatest at the surrounded middle project and decreasing with increasing spacing between the projects. Turbine choice did not appear to have a significant effect on energy yield loss.

Further refinement to the model will come as more operational data become available, and in particular data from offshore projects experiencing effects from neighbours. Nevertheless this model constitutes a state of the art, robust and practical approach to modelling both array effects within and between large wind farms, taking relatively very little processing time for the energy yield analysis of even for the dimensions of the largest projects that are currently being designed.

Acknowledgments

The skills of Kevin Dodson in implementing the models are gratefully acknowledged.

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