

IMPACT OF NEIGHBOURING WIND FARM WAKES ON ENERGY YIELD OF OFFSHORE WIND FARMS

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Summary

Accurate assessment of the expected energy yield of a prospective wind farm is critical to allow the project to proceed. It is well known that wind turbine wakes develop differently in the wind conditions found at large offshore sites compared with the typical small and medium size onshore wind farms from which detailed wake models have been developed. Due to the limited number of large wind farms built to date, in particular in close proximity to each other, operational data is scarce. New approaches are needed to model the phenomenon observed. We present results from an empirical method that has been developed using parameters calibrated against available offshore measurements.

The model is presented in this paper, and the results provided from applying it to a development in the North Sea. This cluster of projects has been created to represent both UK Round 3 zones, as well as German offshore wind development; the model is however applicable to any combination of wind projects.

1. Introduction

The offshore wind energy industry has now moved beyond the stage of being dominated by small-scale demonstration projects; larger, commercial-scale projects are starting to become the norm. Many Northern European countries have designated offshore wind energy zones within their waters, and a number of governments have led tenders for sizeable projects. The combination of this increased level of activity with spatial limitations on project siting has led to a high number of project applications in close proximity to one another.

This new era of the offshore wind industry heralds a hitherto-unaddressed issue: that of the interaction between large upwind projects and the wind climate as experienced by their downwind neighbours. Wake effects have been studied extensively in the case of single turbines, and regarding energy production within larger turbine arrays; however there has been less research into inter-project wakes. The lack of measured data makes study of the phenomena difficult, while the prior sparseness of offshore wind projects has not motivated commercial research into the topic.

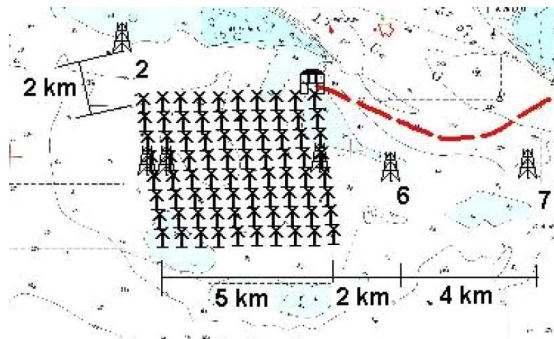


Fig. 1 Horns Rev Masts [3]

2. Background

In 2004, Elsam Engineering published a study on wake effects in and around the 160MW Horns Rev offshore wind farm [3]. Of greatest interest to the subject here is the comparison of measured wind speeds between the met masts, these masts lying between 2km and 6km distant from the wind farm, figure 1.

In 2005, Risø National Laboratory published results of a study into the wake effects around the Horns Rev and Nysted projects based on data gathered by satellite- and aircraft-mounted Synthetic Aperture Radar (SAR) [1]. This technology is based on the capture of radar images of the sea surface with wind speed estimates derived from the backscatter contained in the images - the physical basis being that the wavelength of capillary waves is driven by the wind speed at the surface (i.e. the effect of a breeze blowing over smooth water and roughening up the surface).

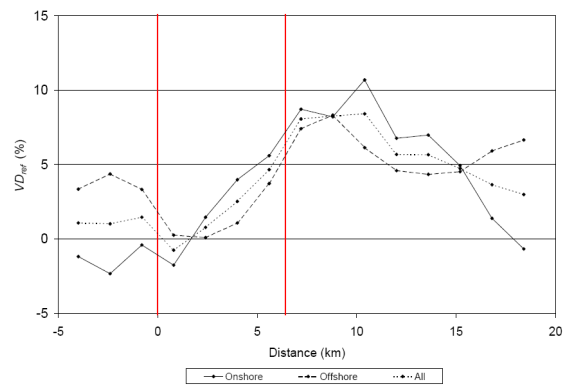


Fig. 2 Results from the Risø Study

As part of their study, Risø analysed a limited number of SAR images covering the area around Horns Rev and Nysted. Figure 2 shows the average of the profiles as the wind speed deficit develops and then recovers.. While giving

qualitative results, there is a high quantitative uncertainty associated with the usage of SAR data.

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 ~3%, 10km downstream (of the end of the wind farm). It is notable that the offshore wind dataset exhibits a much slower recovery - perhaps due to a greater level of atmospheric stability.

The Danish R&D project [2] undertaken by a team of researchers from Risø and DONG analysed the performance of the Horns Rev and Nysted wind farms in greater detail. The project had access to both turbine production data as well as wind measurement data from the 2km and 6km downwind 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 illustrates the most significant parameter: the flow recovery in the wake. A wide range of flow recovery situations is observed.

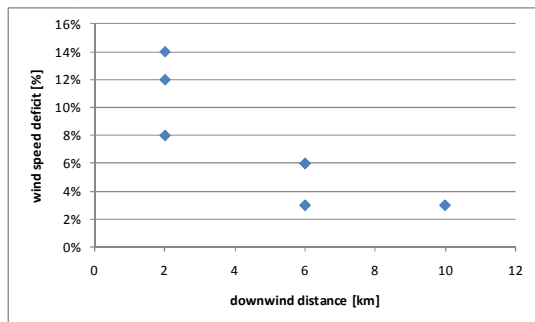


Fig. 3 Wind speed deficit recovery downwind of the project

3. Methodology

The key parameters required to define the model are as follows:

- Deficit at front of windfarm (% of wind speed) – Takes account of additional impact of the first wind turbine as well as the wind farm boundary (i.e. A single row wind farm in theory has a depth of 0 km)
- Deficit Development Through Wind Farm (% of wind speed per km within wind farm)
- Maximum Deficit at Exit of Wind Farm (% of wind speed) – limiting value; assumes wind farm and atmosphere have reached an equilibrium; wind speed deficit is assumed to develop in an exponential manner
- Recovery Distance (Distance for wind speed deficit to recover to 50% of initial value) – Assumes wind speed recovers in an exponential manner

In the interests of creating a robust model that can encompass a wide range of situations, including varying turbine sizes and project layout densities, the model includes three scenarios: optimistic, central, and pessimistic. These scenarios are based to a large extent on the Horns Rev and Nysted projects (the “reference projects”); for a full analysis of any projects under consideration, comparison should be made with the characteristics of these reference projects. From analysis of the literature, values were derived for the parameters defined above, see Table 1. An example of the wake development is shown in Figure 4.

	Below / Above Rated	Optimistic	Central	Pessimistic
Wind Speed Deficit at Front of Wind Farm ¹ [%]	BR	1	2	3
	AR	0.5	1	1.5
Development of Wind Speed Deficit Through Wind Farm [% per km]	BR	1	2	4
	AR	0.5	1	2
Maximum Wind Speed Deficit at Exit of Wind Farm [%]	BR	20	25	30
	AR			
Deficit-halving Recovery Distance [km]	BR	4	6	8
	AR			

¹ Due to first wind turbine, to compensate for the implicit assumption that it takes up negligible distance and for potential additional influences

Table 1: Recommended Values for Inter Wind Farm Wake Model Parameters

Different parameter values are used for below and above rated wind speeds, since thrust reduces significantly. Although this has a strong empirical and scientific basis, the impact is minimal, since energy production above rated wind speed is constant.

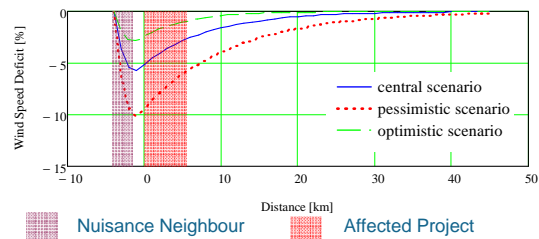


Fig. 4 Example of Wake Development and Recovery Modelling

The model has been implemented in Mathcad. The inputs are as follows:

- Target project turbine coordinates
- Wind speed and direction (wind rose) at target project
- Target project turbine power curve
- Boundary coordinates of neighbouring projects

The program then examines each turbine at the target project in turn, and calculates through each direction sector (default 1 degree angle) the incident mean wind speed according to the wind rose, accounting for any neighbouring projects encountered in the path. Hence the energy production of each turbine can be found, over all compass directions, and so the production of the entire project summed; the energy lost due to the influence of neighbouring projects can then be calculated as a proportion of the potential production in the absence of neighbours.

Additionally to the Mathcad model, the exponential recovery function is in the process of being implemented in WindFarmer 4.2 (to be released 2011) in combination with the large wind farm model [5].

There is no experimental knowledge as yet of how wakes between large neighbouring wind farms will interact with each other. The commissioning of Horns Rev II will hopefully provide the first opportunity to investigate this scenario in the real world, however it must be noted that the distance between Horns Rev and Horns Rev II is significantly greater than that between the type of projects this tool has been designed for, hence applicability will be limited.

4. Case study

A representative cluster of wind farms was created, consisting of 9 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 many German applications. The wind rose from Fino1 was hence assumed to be representative of conditions in the North Sea, see Figure 5.

Development was modelled as taking place in a phased approach, with the first six projects using generic 5 MW turbines, and the last 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.

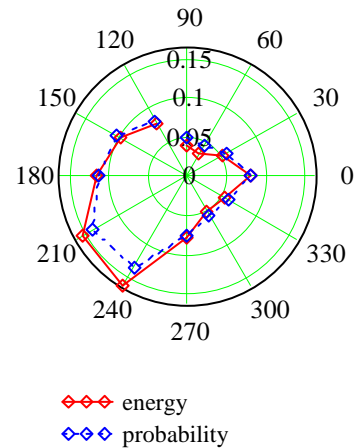


Fig. 5 Wind rose for case study

In order to test the effects of project spacing, three runs were completed, with gaps between the projects of 4km, 6km and 10km. Turbine and project layouts were assumed to be square; in reality, turbine layouts are often optimised with respect to internal wake effects, however this is not the focus of the model under investigation. Project layouts with respect to each other do not appear to have yet been optimised for external wake effects, although this may yet be seen in some UK Round 3 zones.

Figure 6 illustrates the 4km spacing case – note the three Northerly projects have fewer turbines, as they utilise the 8MW unit. Figure 6 shows the wind rose utilised in the analysis. Table 2 highlights selected results.

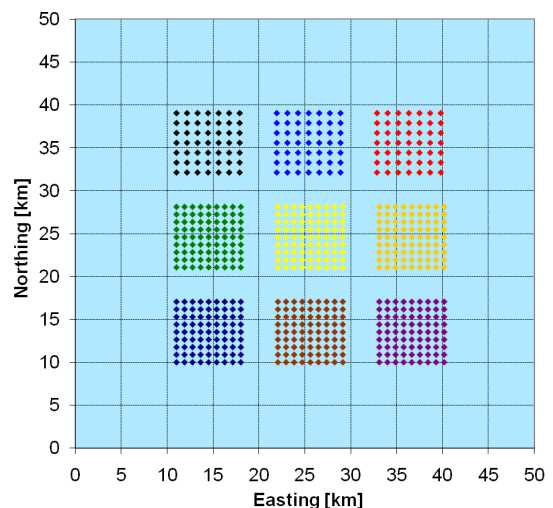


Fig. 6 Layout of the cluster of projects

Spacing	Target project	Neighbours	Loss (optimistic)	Loss (central)	Loss (pessimistic)
4km	SW	Mid	0.1	0.2	0.4
4km	SW	All	0.5	1.6	3.4
4km	Mid	SW	0.1	0.4	1.0
4km	Mid	All	1.3	3.9	8.8
4km	NE	Mid	0.1	0.4	1.0
4km	NE	All	0.9	2.6	5.5
6km	SW	Mid	0.0	0.1	0.3
6km	SW	All	0.3	1.0	2.3
6km	Mid	SW	0.1	0.2	0.6
6km	Mid	All	0.7	2.4	5.9
6km	NE	Mid	0.1	0.3	0.6
6km	NE	All	0.5	1.6	3.6
10km	SW	Mid	0.0	0.0	0.1
10km	SW	All	0.1	0.4	1.1
10km	Mid	SW	0.0	0.1	0.3
10km	Mid	All	0.3	1.1	2.9
10km	NE	Mid	0.0	0.1	0.3
10km	NE	All	0.2	0.7	1.7

Table 2 Energy losses as a percentage reduction (projects identified by compass direction; see map in figure 5)

It is immediately apparent that increasing the spacing between projects by only a few kilometers markedly reduces the energy losses. Due to the exponential recovery profile assumed, this effect is largest when distances are smallest. It is also noteworthy that despite the prevailing wind direction being from the South-West, the effect of neighbouring projects on all sides causes a significant reduction in energy yield. The middle project experiences a loss approximately 50% higher than the average. Results in the WindFarmer implementation are in this case study in line with the pessimistic model assumptions.

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 turbine choice does not have a very significant effect on projects with similar spatial dimensions.

5. Conclusions

A model has been presented, based on empirical evidence from two operational offshore wind projects, namely Horns Rev I and Nysted I. This model has been applied to a representative cluster of projects in the North Sea, in order to investigate the potential energy yield losses due to neighbouring project wakes. The results were

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.

This model constitutes a robust, practical approach to modeling inter-farm wakes, taking relatively very little processing time to analyse even a large number of projects (analyzing the effect of a dozen neighbours on a target project might take 1-3 minutes depending on computer specification).

The model has been created based on measured data from operational offshore wind projects; nonetheless, there has been little opportunity for validation with further empirical data. There are a number of uncertainties associated with the quality of the data and the methodology employed in this analysis. These include uncertainties regarding SAR data for wind speeds; the inherent assumption that conditions at the reference projects are representative of those at other projects under analysis; general uncertainty regarding the behaviour of offshore wakes, and the interaction of wakes from different projects.

Further refinement to the model will come with the analysis of operational data from offshore projects experiencing neighbouring project wakes.

4. Acknowledgements

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5. References

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- [5] Schlez, W, Neubert, A „New Developments in Large Wind Farm Modelling” Proceedings of the European Wind Energy Conference, 2009