Wake effects within and between large wind projects: The challenge of scale, density and neighbours - onshore and offshore

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Abstract

This paper captures some of the latest developments in the field of wake modelling and provides previously unpublished operational evidence from a large project in the USA. Leading and developmental modelling techniques are benchmarked against these new measurements and other operational cases with conclusions drawn on accuracy, uncertainty and the physical mechanisms which underlie the real-life situation and equivalent assumptions in the modelling domain. The performance of the models is presented through the lens of project size (installed capacity) as well as density (spacing) characteristics. This has been carried out both within the envelope allowed by validation measurements and beyond it, to explore potential performance of hypothetical projects of up to 1.6GW of varying packing density. In addition, for the first time a new modelling approach is introduced which aims to capture large scale wake interaction between wind projects. This model is based on empirical evidence from existing projects as well as a review of leading CFD-based methods. Case studies based on the potential interaction between Danish offshore developments (Horns Rev 1&2 and Nysted 1&2) are presented and conclusions drawn on the potential implications for future projects in areas of high development activity such as the German Bight.

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1. Introduction

Confidence in energy yield prediction is a critical success factor when securing debt finance for the construction of any wind project, be it on land or offshore. There are many issues which affect prediction certainty, most notably those associated with the quality and duration of wind measurements as well as the computer modelling implemented to predict wind flow variation and wake effects. Previous validation studies have revealed that wakes are of considerable importance for large projects, where conventional wake modelling has been shown to be deficient in some instances.

Analysis of operational data from large projects has allowed these conventional models to be refined in order to correct identified prediction bias[1]. As a result, these methods may now be applied with some confidence for projects that are of a similar scale to current validation cases (100-200MW). However, considerable uncertainty remains when carrying out calculations for larger projects and clearly this is an issue when considering the scale of developments in certain markets such as the USA, China and Offshore. A related challenge is that associated with the interaction between wakes of neighbouring projects - a factor which can also have a substantial impact on energy production and uncertainty.

This paper examines key issues in the field of wind farm wakes by virtue of three targeted case studies :

- Validation of a leading computer model against operational data from a large onshore wind project in the United States.
- Exploration of the variation of predicted annual wake losses with project scale (megawatts) and inter-turbine spacing.
- Introduction of a new empirically based model for predicting the interaction of neighbouring wind projects.

On the basis of the evidence presented in these case studies, conclusions are drawn on the state-of-the-art modelling techniques with specific recommendations for further study to address the evident knowledge gaps.

2. Wakes - just an offshore problem ?

Operational data from early offshore wind developments have provided an excellent basis for benchmarking the performance of wake models, even where such models are primarily designed and most frequently applied to onshore wind projects. There are two main reasons for this. Firstly, the minimal variation in ambient wind conditions across offshore projects serves to mitigate the conflation of topographic effects and wake losses within the operational records under consideration. This same issue has meant that the vast majority of operational projects onshore are unsuitable for use as validation datasets. This is because it is difficult with any level of confidence to establish the proportion of the variation in power production across the site that is a result of wake losses and the proportion which is a result of ambient variation. Secondly, offshore wind projects tend to be constructed in regularly-spaced arrays, which allow geometrically straightforward case data to be derived.

The first substantial field-study of offshore wake effects came in 2003 through the ENDOW project which was based on measurements at the 5MW Vindeby project[2]. In this instance the performance of leading wake models were benchmarked against single, double and quintuple wake cases. In 2004, results were released from the 160MW Horns Rev offshore wind project[3]. Subsequent careful examination of this dataset and confirmation of the observed trends in other large commercial offshore wind projects, lead to the refinement of industry leading models[1].

However, due to the absence of reliable datasets, free of the influence of topographic effects described above, there has been significant debate in the industry over whether the effects observed at Horns Rev and elsewhere are in some way specific to the offshore environment. There are clearly ambient meteorological conditions which are relatively homogenous in the offshore environment but which vary widely on land - most notable amongst these being turbulence intensity. Both theory and measurements indicate that the recovery of wakes and hence the overall efficiency of a wind farm is reasonably strongly correlated to the ambient turbulence intensity.

In order to investigate this issue further and in partnership with E.ON Climate & Renewables, the authors have undertaken a targeted case study examining the performance of a leading wake model for a flow case involving the interaction of 19 individual wakes in low turbulence conditions.

Wake effects have been measured within a large onshore wind farm along a row of 20 turbines with inter-turbine spacing at around 5 rotor diameters. The row of turbines examined forms part of a much larger wind farm, as shown in Figure 1.

Approximately one year of ten minute turbine Supervisory Control And Data Acquisition (SCADA) system data were made available for the analysis. The ten-minute turbine power production, mean wind speed, mean wind direction and turbine status were used in the study.

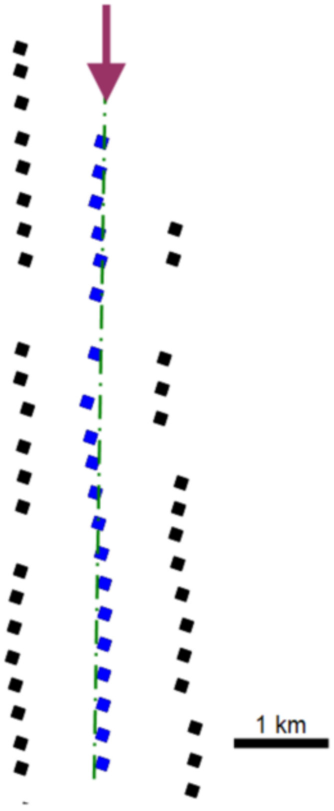


Figure 1: Wind turbine layout for the 19 wake case

To minimise the introduction of bias due to turbine downtime the measured results were derived only from records for which all turbines were available for each ten minute record. These data have been subject to initial quality checks to remove any power performance issues and spurious values.

To allow turbine power output to be compared to modelled results, the power output was normalised to the free-stream power output (i.e. performance with no wake effects). These normalised results are referred to henceforth as relative power. The first turbine in the row were considered to be the most appropriate to define the free-stream power output.

Relative power for each turbine within the row of interest for direction sectors of 5 degree width have been examined for the wind speed range from 5 to 9m/s, over a range of 35 degrees, centred on the approximate centre-line of the row of interest. The selected direction sectors each contain approximately ~100 ten-minute records of data which is considered to be statistically acceptable for analysing wake effects.

The wake effects for the case examined have also been modelled in GH WindFarmer 4.1 utilising the Eddy Viscosity model with the application of the Large Wind Farm (LWF) correction methodology. It is worth noting that this methodology has been developed primarily as a result of trends observed in large offshore projects, as discussed above. Measured and modelled sector-wise relative power results are presented in Figures 2-5.

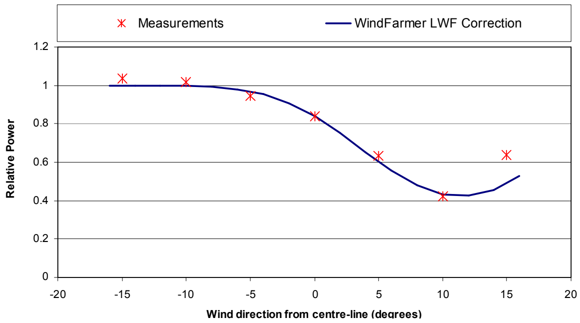


Figure 2: Average relative power - 1 wake (WTG 2)

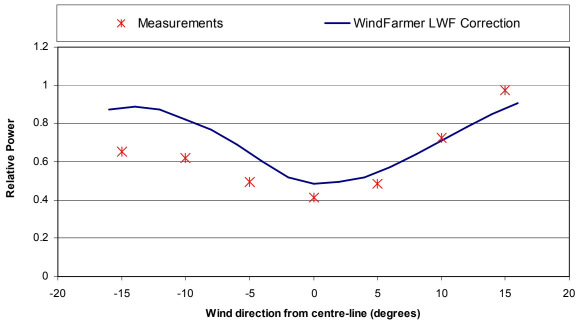


Figure 3: Average relative power - 8 wakes (WTG 9)

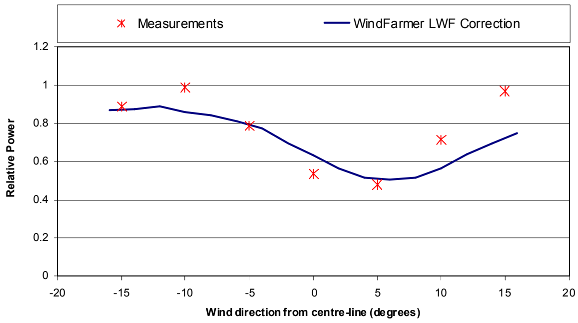


Figure 4: Average relative power - 14 wakes (WTG 15)

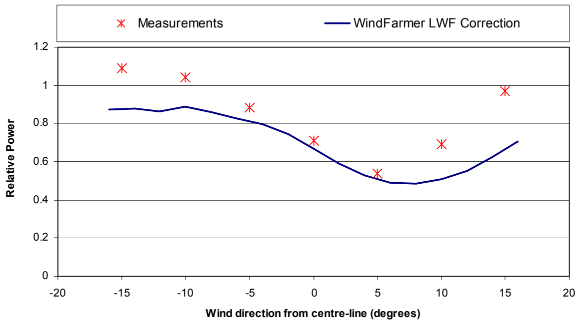


Figure 5: Average relative power - 19 wakes (WTG 20)

In addition, relative power results for the average of the examined sectors are presented turbine by turbine in Figure 6.

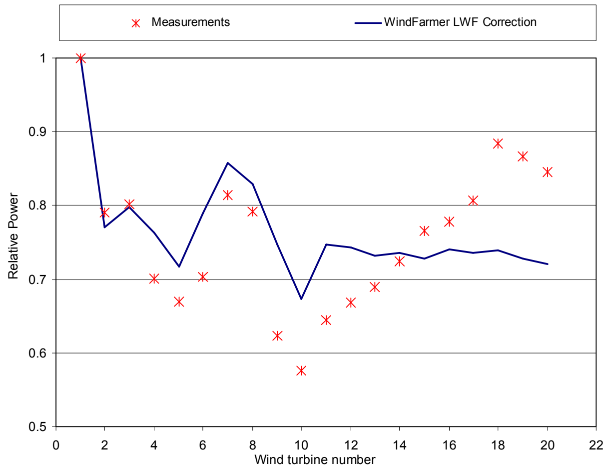


Figure 6: Average relative power across 35 sector

On the basis of these results, the following findings have be drawn:

- The turbines are not aligned in a straight row leading to significant lateral variation in the measured relative power profile which in general is captured well by the wake model.
- As an average across the 35 degree test sector, relative power output reaches a minimum of just below 60% at the 10th turbine, with no further decline through to the 20th turbine.
- The increase in relative power for turbines 18 to 20 may be caused by ambient wind speed variation along the row of turbines. Further work is required to fully understand the wind climate at this wind farm site, which despite being topographically uniform, appears to exhibit some ambient wind speed variation which is likely to have influenced the results of the current study to some extent.

This case study highlights the difficulty of drawing solid conclusions on wakes from onshore wind projects via conventional operational records. The confounding influence of ambient wind speed variations is always likely to add a significant degree of uncertainty to the results of any wakes study based on such data - even for very flat sites such as that examined here.

Despite this, increased confidence in the performance of the wake model validated here has been developed, since it captures both the high resolution directional power trends as well as the overall magnitude of wake losses even very deep within a large onshore project. In this sense, the performance of the Large Wind Farm correction model within GH WindFarmer which was originally developed on the basis of offshore wind project datasets, has shown that it is possible to develop engineering codes which perform well for large projects be they offshore or on dry land.

3. Uncertainty over scale and density

Arguably the two most significant independent variables when considering the magnitude of wake losses within wind farm developments are the overall capacity (or scale) of the development in question and the physical area over which that capacity is deployed (or packing density).

The scale of the development will effectively determine the average 'depth' into the array an individual wind turbine lies and therefore the number of individual wakes to which that turbine is subjected.

The density of the development will effectively determine the average magnitude of velocity deficits induced by the incident wake(s) by virtue of the degree of separation between the wake causing turbine(s) and the turbine of interest.

There are several potential means of defining these two variables. For example, "scale" may be expressed as :

- Total installed capacity (MW)
- Estimated Annual Energy Yield (GWh / annum)
- Total number of wind turbine units

Likewise, "density" may also be expressed in a number of ways, such as:

- Wind turbine units per unit area
- Installed capacity per unit area
- Total rotor swept area per unit area
- Average inter-turbine separation

For the purposes of the case study that follows, the lattermost definition has been adopted in both cases.

Unfortunately, available empirical evidence does not adequately capture the sheer range of likely future wind farm deployments - especially at higher capacities. Data are simply not currently available from suitable operational projects in excess of 500MW for the study of wake effects. However, at the time of writing, the first offshore wind projects of this scale are under construction and on land, clusters of this magnitude are already in operation in the US market. Such utility-scale wind farm developments are becoming an increasingly important feature of the wind energy industry - particularly in the key growth markets of North America, China and Offshore. Even if an isolated suitable test case of the relevant scale were available today, it would likely constitute and therefore be only valid for, a single density.

In the absence of empirical data spanning the relevant ranges of scale and density, a targeted case study has been carried out on the basis of four semi-independent modelling techniques. This has been implemented in order to at least explore the magnitude of wake losses predicted by state-of-the-art modelling across some extreme but relevant ranges of scale and density.

A project consisting of between 16 and 400 wind turbines arranged in a regular square array has been examined. The wind farm density has been varied in terms of inter-turbine spacing expressed in units of rotor diameters (D) between 4D and 12D, as illustrated for the 144 wind turbine case in Figure 7. A typical northern European wind direction distribution (wind rose) has been assumed with an associated mean wind speed of 9.9m/s at an assumed hub height level of 80m above mean sea level. A notional 4MW wind turbine model has been assumed with relevant technical parameters selected so as to be representative of current and near-market technology.

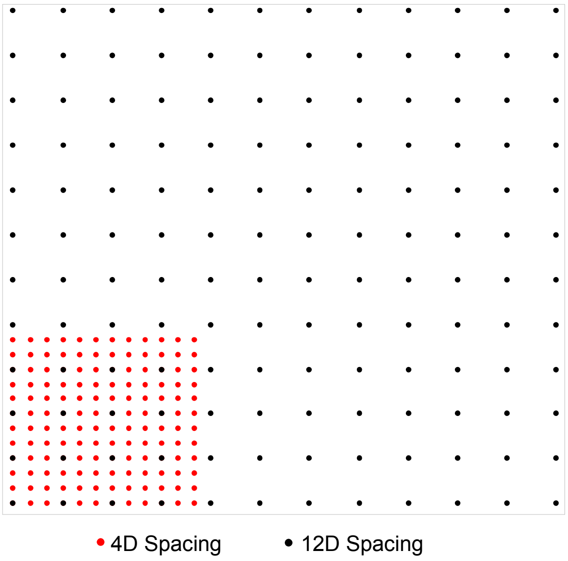


Figure 7: Wind turbine layouts for extreme cases examined

Three of the four wake models adopted for the study are those currently utilised by GL Garrad Hassan for commercial energy production assessments for offshore wind projects, as described below.

Model A constitutes a correction to conventional array efficiency modelling using inner boundary layer (IBL) theory. This correction was developed primarily on the basis of operational data from the Horns Rev Project. The modelling of wake effects using this method involves several steps, which are summarised below:

1. The project is represented by an area of increased roughness in the wind flow model. The roughness (z0) value is derived from a calibration exercise against operational data from the Horns Rev Project.
2. The resulting IBL spatial variation in wind speed over the project site is predicted using the WAsP computational flow model[4].
3. The corrected upstream wind speed at each turbine location is calculated using the IBL adjustment factors calculated by the wind flow model described above.
4. A conventional array efficiency calculation is implemented within this corrected flow field using the Eddy Viscosity wake model[5] as implemented in GH WindFarmer software.

Model B is the Large Wind Farm correction model[1], as used in the 19 wake validation exercise presented in Section 2 of this paper. This model is fully integrated within GH WindFarmer software which also corrects the Eddy Viscosity model based on the development of an inner boundary layer. Instead of modelling an area of increased roughness in the flow model, the disturbance caused by each individual turbine is modelled. This allows the effect for a wider variation of turbine layouts to be considered for the purposes of design and optimisation. Again, the model has been calibrated to measurements from the Horns Rev project.

Model C is an implementation of the simple Park model as proposed by NO Jensen[6] and widely used in the industry for preliminary array efficiency calculations. The model retains the advantage of being extremely flexible due to its sensitivity to the specified wake decay constant. For onshore wind projects a wake decay constant of 0.07 is often used, whilst for offshore projects wake decay constants of between 0.04 and 0.05 have been widely utilised.

A simple extension of this model has been developed whereby the wake decay constant is characterised as a function of project installed capacity. The empirical function used to derive the wake decay constant has been formulated from estimated array efficiencies from small and medium sized offshore wind projects.

The fourth model (**Model D**) is an experimental engineering model currently under development by GL Garrad Hassan; it is based on the classical Eddy Viscosity model designed to better capture the interaction and progression of multiple wakes as they propagate through large wind projects.

Calculations of array efficiency have been implemented for the generic wind farm cases and all four models described above. The array efficiency results are presented as a function of project scale in Figure 8.

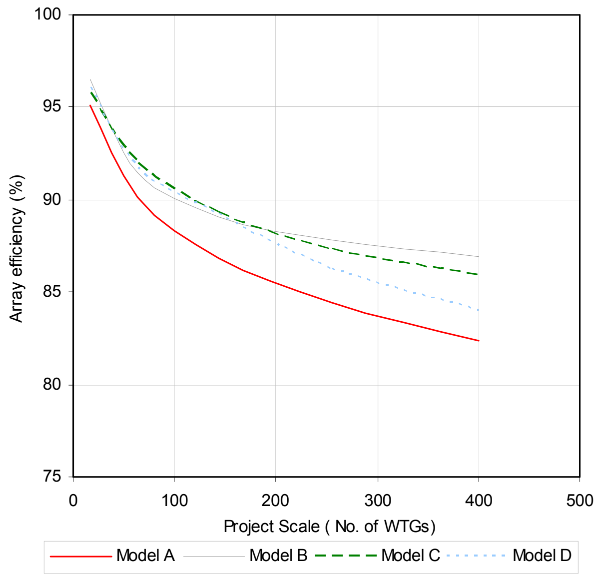


Figure 8: Array efficiency for the four models by project scale

The results presented in Figure 8 are for a density of 8D and show variation from ~97% to ~83% array efficiency when moving between the extremes of scale and the most optimistic and pessimistic modelled prediction.

In broad terms, the projected model trends are reasonably similar with a phase of rapid efficiency drop through to ~100 wind turbine units with a more gentle decline beyond. However, in detail there is some level of variation with respect to both the rate of decline and the shape of that decline, which leads to significant levels of divergence at the upper end of the scale. For the 400 wind turbine case, the range of array efficiency results is ~5%.

The array efficiency results are presented as a function of project density in Figure 9. These results are for a wind farm of 144 units arranged in a 12 x 12 regular array with density expressed in rotor diameters (D).

The results in Figure 9 show that for higher densities (below ~6D spacing) there is a wide degree of divergence between the four models, with array efficiency estimates spanning a 7% range at 4D. For lower densities, agreement between three of the four models (B, C and D) is relatively good with a range of just 1% at 12D spacing. Model A provides outlying results for the lower density cases - which is likely to be a function of the relatively crude characterisations of the wind farm area as a single roughness element with a uniform roughness length value.

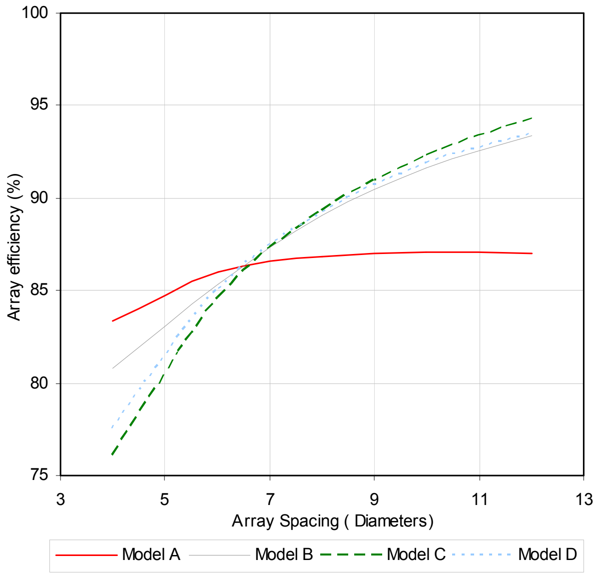


Figure 9: Array efficiency for the four models by density

On the basis of the case study presented above, the following conclusions are drawn:

- There is a significant degree of variation in model predictions of wake effects when considering a wide range of project scale and density.
- This divergence or 'scatter' is evident despite the fact that three of the four models have a significant degree of commonality and therefore not fully independent from a theoretical point of view. Additionally, all four models have been tuned or calibrated to some extent to the same limited operational datasets.
- It is clear from these results that there is a substantial degree of uncertainty associated for wake modelling when stepping outside of the relatively limited envelope of current validation. Therefore, when making commercial predictions of array efficiency for large wind developments, an ensemble averaging approach may be justifiable on the basis of error cancellation.

4. Nuisance neighbours

A targeted literature review has been conducted with the aim of identifying suitable empirical evidence to use as the basis of an indicative assessment of external wake effects. For clarity, external wake effects are defined as those caused by neighbouring wind farms and so the review has focused on this issue rather than consideration of conventional wake effects within an individual wind farm.

In 1989, Nierenberg published the results of a study examining external wake effects in the Altamont Pass, California [7]. This work utilised data recorded at anemometry masts downwind of a 50MW wind project, to a distance of approximately 5km. The results indicated that an energy deficit of 20% may be expected immediately downstream of the 50MW project and at a distance of 5km a 15% deficit can be expected.

These results should be viewed in light of the special meteorological conditions experienced in the Altamont Pass and in particular the atmospheric temperature inversion, which inhibits flow recovery at heights of less than 100m. However, the works does illustrate that under certain circumstances, wake effects from large projects can persist much further downstream than conventional wake models would predict. The results of this work were not used substantively in the analysis which follows.

In 2004, Elsam Engineering published a study on wake effects in and around the 160MW Horns Rev offshore wind farm [3]. The part of the study of relevance provides direction wind speed correlation results between three masts around the wind farm, each affected to a greater or lesser degree by the external wakes created by the project.

The results of this study indicated that for westerly winds, a wind speed deficit of 8% can be expected 2km downstream of the project, recovering to a ~3% deficit 6km downstream (referenced to free stream conditions).

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 Synthetic Aperture Radar (SAR) [8, 9]. 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 assumption being the wind speed is strongly correlated to the wavelength of short-crest localised "wind waves". Data from both satellite and aeroplane mounted SAR instruments were used in the study although due to methodological limitations of the latter, only the satellite mounted SAR results have been utilised for the work presented in this report.

The Risø analysis of the SAR data involved the collation of images covering the area surrounding the Horns Rev and Nysted projects. For each image, wind speeds were estimated along two parallel transects aligned to the mean wind direction at the time the image was recorded. In each section (or cell) of the transect, the wind speed of the 'waked' transect was deducted from the wind speed of the 'freestream' transect so as to estimate the wind deficit caused by the wind farms as a function of downstream distance.

The fact that the wind speed deficit estimates were derived for each image and then aggregated means that the method is not reliant on the absolute accuracy of the SAR wind speed measurements since the results are relative - between the two transects. The results show good agreement with the Elsam study [3] with a velocity deficit of around 8% being evident immediately downstream of the wind farms. However, the recovery is somewhat slower, reaching a deficit of ~3%, 10km downstream (of the wind farm).

The Danish R&D project "*Store mølleparkers skyggevirkning: malinger og dataanalyse*" (Shadow Effects of Large Wind Farms: Measurements, Data Analyses and Modelling) supported the analysis of the Horns Rev and Nysted wind farms by a team of researchers from Risø and DONG (Elsam and E2) between 2004 and 2007 [10].

Key Danish researchers at the forefront of this field contributed to this work and a number of approaches were developed in detail and evaluated against the data from the two wind farms. Wind turbine production data as well as met masts 2km and 6km down-wind from both of the wind farms, has been available within the projects; unfortunately, due to the commercial value of this data, it is unlikely to be released to the general scientific community, which means uncertainties remain regarding interpretation and application of the conclusions.

The results of the Elsam/E2 and Risø work [3, 8, 9, 10] have been used to inform the design of the empirical model, referred to henceforth as the Neighbouring Wake Model (NWM), which is described below.

To maintain model robustness, the focus has been to attempt to model all aspects of this phenomenon in as sophisticated a manner as appears necessary but to ignore all other effects which would be challenging to model or are adequately covered elsewhere. The most important of these exclusions, is that of the wake effects within each wind farm. It is assumed that this should be calculated in the conventional manner (for example, using GH WindFarmer software) and the two wake losses figures added in a linear manner (internal plus external).

Table 1 lists the parameters that are used within the model. Table 2 lists the assumed parameter values used within this study. An example of wake deficit development and recovery is shown in Figure 10, which illustrates three confidence scenarios: central, optimistic and pessimistic.

Parameter	Value	Comments
Deficit at Front of Wind Farm	% of wind speed	Takes account of additional impact of first wind turbine as well as the wind farm boundary
Deficit Development Through Wind Farm	% of wind speed per km travelled within wind farm	Exponential deficit development trend assumed
Maximum Deficit at Exit of Wind Farm	% of wind speed	Limiting value to capture momentum equilibrium
Recovery Distance	Distance for wind speed deficit to recover to 50% of initial value	Exponential recovery trend assumed

Table 1: NWM Parameter Definitions

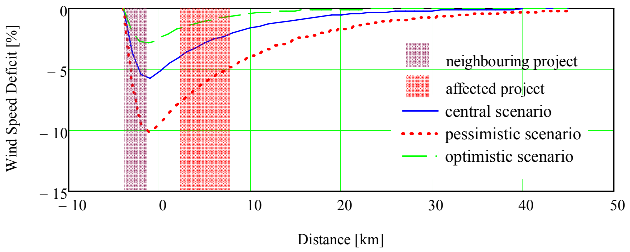


Figure 10: Example of NWM deficit development and recovery

In order to reflect the significant levels of uncertainty associated with the input assumptions of the NWM, the calculation has been repeated three times to provide optimistic, pessimistic and central results. Table 2 presents the assumed range of values for these three scenarios.

- The Optimistic scenario values may be characterised as representing relatively sparse (low density) neighbouring projects.
- The Pessimistic scenario values may be characterised as representing relatively high density neighbouring projects and potentially stall regulatory wind turbine technology.
- The Central scenario values may be characterised as representing moderate density neighbouring projects.

The overall range of results from the three scenarios may also be used to characterise the error bar associated with the overall external wake loss estimate.

Parameter	Optimistic	Central	Pessimistic
Deficit at Front of Wind Farm	BR = 1.0% AR = 0.5%	BR = 2.0% AR = 1.0%	BR = 3.0% AR = 1.5%
Deficit Development Through Wind Farm	BR = 1.0% AR = 0.5%	BR = 2.0% AR = 1.0%	BR = 4.0% AR = 2.0%
Maximum Deficit at Exit of Wind Farm	BR = 20% AR = 20%	BR = 25% AR = 25%	BR = 30% AR = 30%
Recovery Distance	BR = 4% AR = 4%	BR = 6% AR = 6%	BR = 8% AR = 8%

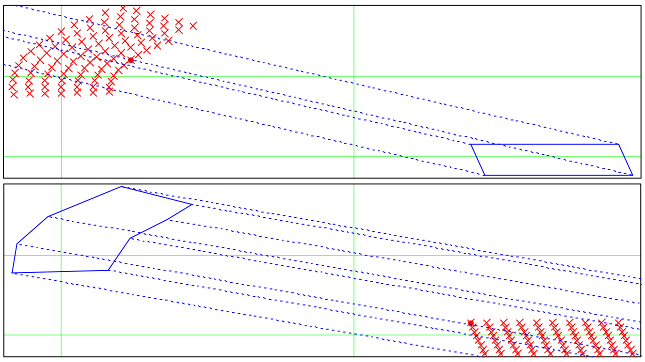
BR = Value utilised Below Rated wind speed
AR = Value utilised Above Rated wind speed

Table 2: NWM Parameters

In order to demonstrate the application of the NWM methodology and to explore the magnitude and sensitivity of the estimated losses, two example calculations have been carried out :

- Horns Rev 1 and 2
- Nysted 1 and 2

For the purposes of these example calculations, input assumptions associated with these projects have been obtained from public domain sources with nominal assumptions with respect to turbine layout and technology made as required. **For these reasons, the results presented below should be considered as an academic case study only, for illustrative purposes.** The relative position of the two project-pairs are presented in Figures 11 and 12.



NB Project information based on public domain information

Figure 11: Relative locations of the Horns Rev 1&2 projects

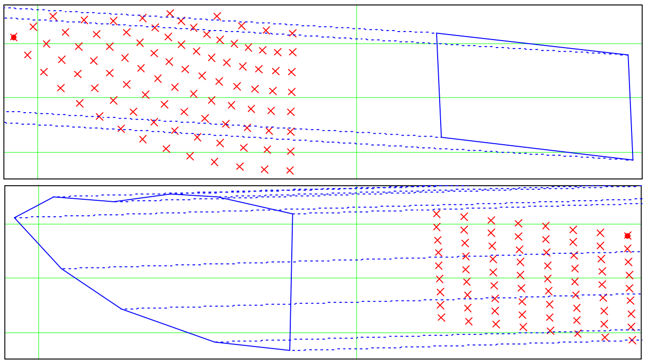


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Figure 12: Relative locations of the Nysted 1&2 projects

Headline results of the calculations are presented in Table 3 below.

Project	**Annual Energy Production Loss**		
	Optimistic	**Central**	**Pessimistic**
Horns Rev 1 Impact on Horns Rev 2	0.0%	0.0%	0.1%
Horns Rev 2 Impact on Horns Rev 1	0.0%	0.1%	0.3%
Nysted 1 Impact on Nysted 2	0.1%	0.4%	0.9%
Nysted 2 Impact on Nysted 1	0.5%	1.3%	2.7%

Table 3: NWM example calculation results

The results of the example NWM calculation for the Horns Rev projects shows that a relatively minor energy production loss is predicted in both directions. This is primarily a function of the significant separation between the two projects (~15km) which allows the flow to substantially recover. The slightly higher loss predicted for the original project (Horns Rev 1) is a result of the relative orientation of the two projects, which given the prevailing wind rose assumed for the analysis, leads to Horns Rev 1 being located on the leeward side of the second project for a relatively greater proportion of time.

For the Nysted case study, the overall magnitude of the predicted losses are substantially greater, due to the relative proximity of the two projects (~5km). This modest separation has the affect of both increasing the intensity of the losses estimated for individual wind direction sectors as well as increasing the number of those sectors which result in a loss. The significantly greater loss predicted for the original project (Nysted 1) is again a function of the relative orientation of the two developments in the context of the prevailing wind direction distribution assumed for the sites.

On the basis of the case study presented above, the following conclusions are drawn:

- The best available empirical and CFD evidence has allowed a basic modelling approach (NWM) to be developed to estimate a range of possible energy production losses associated with the interaction of neighbouring offshore wind projects.
- The NWM approach has been applied to two real-life project pairs in Denmark. Whilst validation results are not available at this time, the predictions of annual energy production loss range from 0% to 2.7% in these cases. This indicates that projects in close proximity may suffer significant, but not excessive losses associated with a neighbouring development.
- The wide range of results from the NWM approach is indicative of the substantial levels of uncertainty associated with the source data and further empirical evidence is required to improve confidence in this and other modelling techniques for estimating inter-project effects.

5. Overall Conclusions

A variety of established and new wind farm wake models have been applied to test cases for which there is operational evidence and for larger theoretical examples. This has included benchmarking of an established computer model against new validation cases from the USA. Sensitivity to project size and turbine density have been investigated and a previously unpublished methodology demonstrated to estimate the impact of neighbouring projects on one another. The following conclusions are drawn on the current extent of industry knowledge and the consequences of this when considering large and neighbouring developments both offshore and on land.

- A good level of agreement has been demonstrated when comparing operational results from a large onshore wind project and one of the leading computer models for this application - which has been developed on the basis of empirical evidence from offshore wind projects. This suggests that it is possible to develop models which perform with good accuracy both offshore and on land.
- Through application of leading offshore wind wake models to a hypothetical case study it has been shown that there is a substantial degree of uncertainty associated when stepping outside of the relatively limited envelope of current validation with respect to both the scale and density of the development in question. For this reason, when making commercial predictions of array efficiency for large wind developments and/or those with unusual packing densities, an "ensemble" averaging approach may be justifiable on the basis of error cancellation effects.
- The limited but valuable body of evidence on the impact of one wind project on another has been condensed into a simple empirical model. This new technique has been demonstrated here against two real life project-pairs to illustrate key design sensitivities (most notably the relative location of the projects and their density) as well as the potential impact magnitude that such effects could have for future projects.

Whilst the wind industry has made good incremental progress over the last few years on the basis of the limited available empirical evidence for research into wake effects, substantial levels of uncertainty remain when stepping outside of the envelope of model validation. This is of paramount importance when considering the nature of planned wind developments in the key growth markets for the wind industry; North America, China and Offshore. On this basis, there is a clear driver for improved confidence in the state-of-the-art modelling and to achieve this, the authors recommend that a major new joint industry project should be progressed in which direct wake measurements, perhaps using remote sensing technology, are recorded deep within and in-between large operational wind projects. Such direct measurements may be supplemented with conventional SCADA records and wind turbine / support structure loads measurements in order to build-up an unsurpassed characterisation of the flow and turbulence field. Such a project has the potential to instigate a step-change in knowledge and understanding in this field. This is needed if the industry is to take advantage of the benefits which may come from reduced wake-related uncertainties in the context of project financing and design.

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