DNV·GL

VALIDATION REPORT

WINDFARMER

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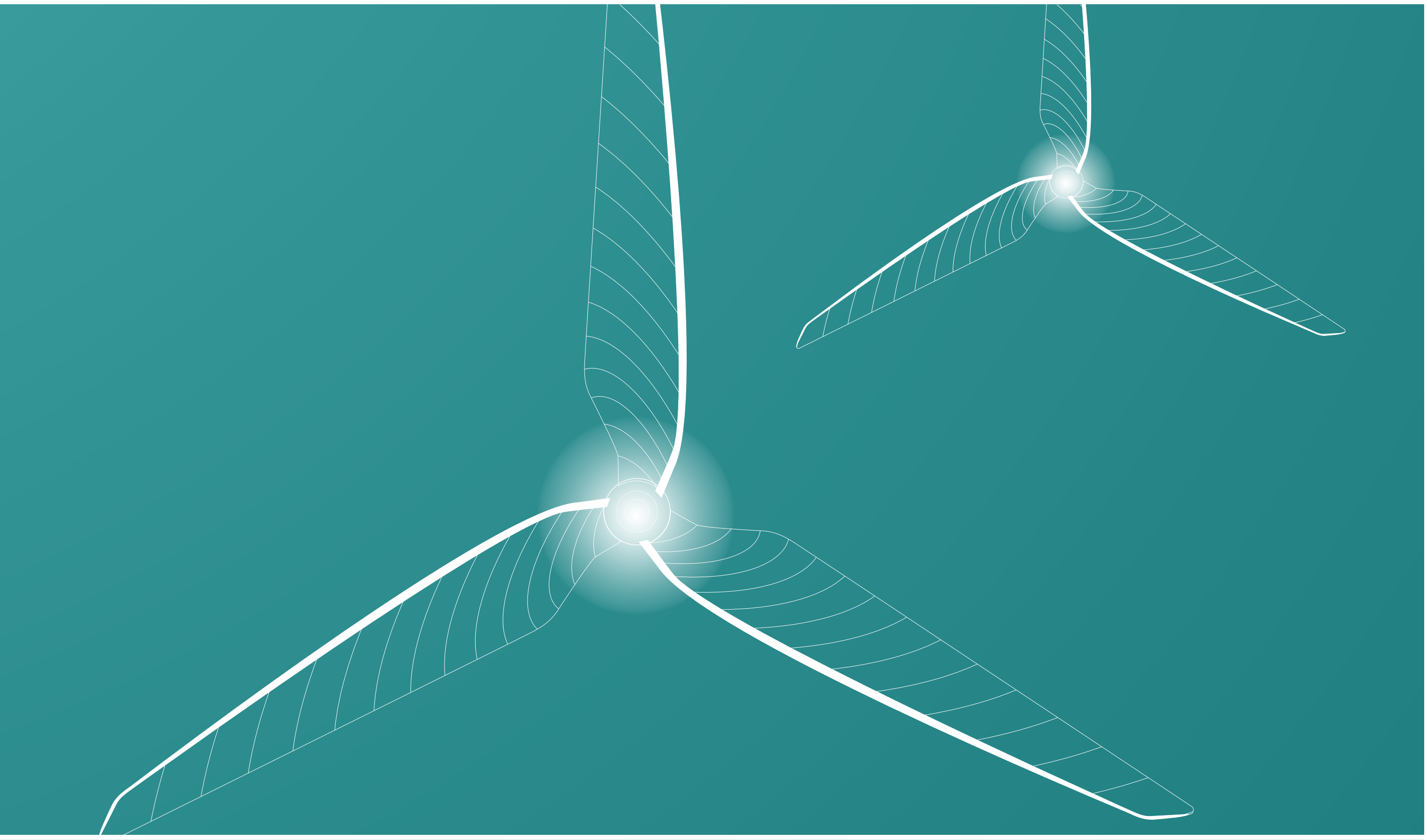

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Garrad Hassan & Partners Ltd., St Vincent's Works, Silverthorne Lane, Bristol, BS2 0QD
England

www.dnvgl.com
windfarmer@dnvgl.com

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1 INTRODUCTION

WindFarmer has been used for many years to assess, design and optimise the layout of wind farms. WindFarmer is used to plan projects ranging from a single turbine to very large arrays with hundreds and even thousands of wind turbines. Most of the worldwide largest wind farms have been designed by WindFarmer clients.

Over the years WindFarmer has demonstrated its accuracy and performance many times over in detailed research projects as well as in commercial applications. This report compiles some key results of the verifications carried out, with the aim to give the user a reference document, spanning decades of model development and validation.

Detailed background information on the models is available from the WindFarmer Theory Manual. This document details validation cases for wake models, the calculation of shadow flicker and ZVI/photomontages. If you have any queries regarding the contents of this report, please do not hesitate to contact the WindFarmer Support Team.

2 WAKE MODELS

For a given site and wind regime, the wake between wind turbines is the key design parameter for finding a geometric arrangement of wind turbines that delivers maximum performance. The turbine wake model as the most important aspect in the process thus forms the core of any wind farm design software package. For this reason, extensive testing, development and validation of the wake models have been carried out.

WindFarmer allows the user to choose between two different wake models. These models are referred to as Eddy Viscosity and Modified PARK wake model. Further details about these wake models are available in the WindFarmer Theory Manual.

2.1 Wake structure

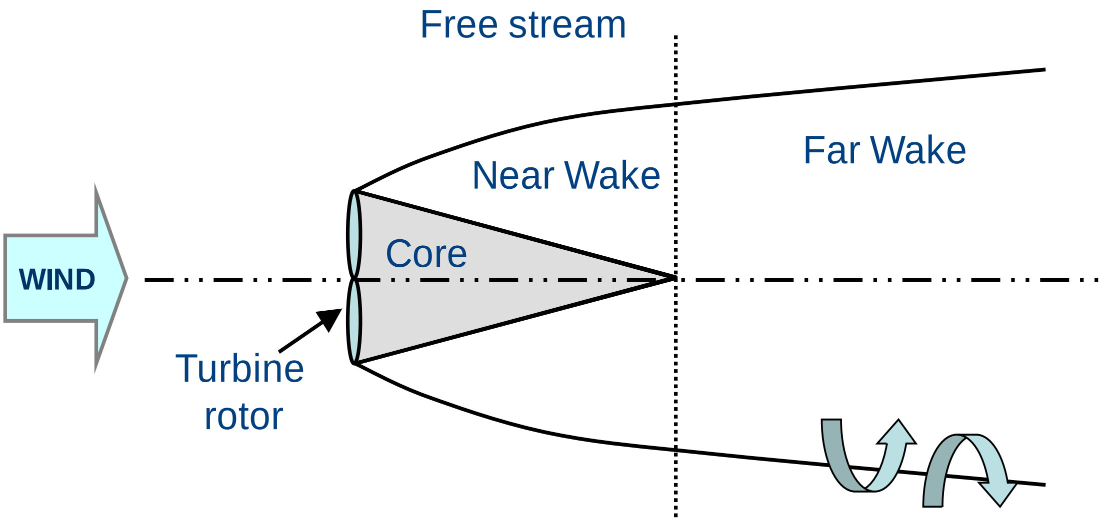

Figure 1: The wake of a wind turbine is divided into Near Wake and Far Wake. Turbulent mixing erodes the core in the Near Wake and the wake develops freely in the Far wake.

2.2 Wake cross section

In 1989 Garrad Hassan carried out a detailed analysis of turbine wakes at the Marchwood Engineering Laboratories (MEL) atmospheric boundary layer wind tunnel [1], which was at the time the largest atmospheric wind tunnel in the UK. The analysis used 1/160th scale horizontal axis wind turbines, which had realistic performance properties, and sophisticated data logging components. This analysis process generated comprehensive data on the mean and turbulent flow downstream of single, and multiple turbines. The model site was flat with an artificial uniform surface full-scale roughness length of 0.075 m.

The rotor diameter of the 1/160th-scale models was 0.27 m, which corresponds to a full-scale rotor diameter of 43.2 m. A hub height of 50 m was given, because this is typical for such a size of turbine. The most important parameter to accurately scale is the turbine thrust characteristics. The model turbines were operated at three ratios of tip speed to wind speed. The equivalent rotor speeds for the three model tip speed ratios are given in Table 1, assuming a free wind speed of 5.3 m/s. We are focusing in the following at tip speed ratios 4 and 5.1 because of their relevance for modern wind turbines. For each tip speed ratio there is also a corresponding thrust – wind speed relationship, as given in Table 2.

Tip speed ratio	Rotor Speed [rpm]
2.9	6.78
4.0	9.37
5.1	11.95

Table 1: tip speed ratios and rotor speeds

Figure 2 "Marchwood" measurements made by GL Garrad Hassan in the early 1990's used large atmospheric boundary layer wind tunnel and fully operational wind turbines.

TSR of 4.0		TSR of 5.1	
Wind speed [m/s]	**Ct**	**Wind speed [m/s]**	**Ct**
4	0.86	5	0.86
5	0.82	6	0.84
6	0.72	7	0.78
7	0.63	8	0.69
8	0.57	9	0.63
	0.52	10	0.58

Table 2: thrust curves for the turbine models

The wind tunnel analysis used equipment such as hot-wire anemometers and a pitôt-static tube to measure the wind flow. In the WindFarmer model domain these detectors are represented by wind turbines with a zero thrust characteristic, and a very small rotor diameter. These measurement turbines were positioned in the wake, allowing point wind speeds to be obtained through the Flow and Performance Matrix in WindFarmer.

Figure 3 and Figure 4 present the crosswind profiles of mean velocity at hub height for downwind distances of 7.5 and 10 rotor diameters and the two tip speed ratios considered for the Eddy Viscosity and PARK models respectively. The WindFarmer results are for a free wind speed of 5.0 m/s. The ambient turbulence intensity is 8.5%. This corresponds to a wake decay parameter of 0.0425 in the PARK model, when a flat, smooth and uniform terrain and neutral stability are assumed.

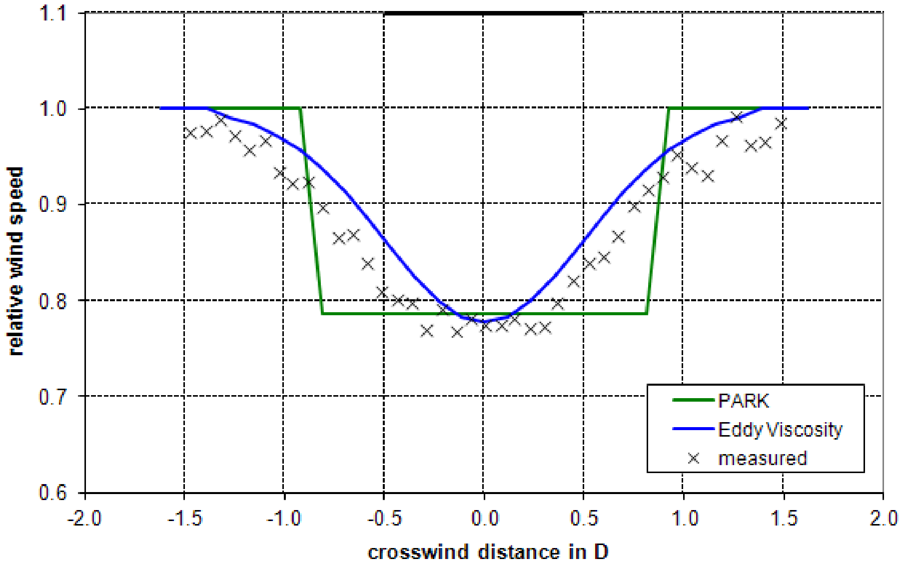

Figure 3: wind speed at 7.5 rotor diameters downwind for the 4.0 tip speed ratio

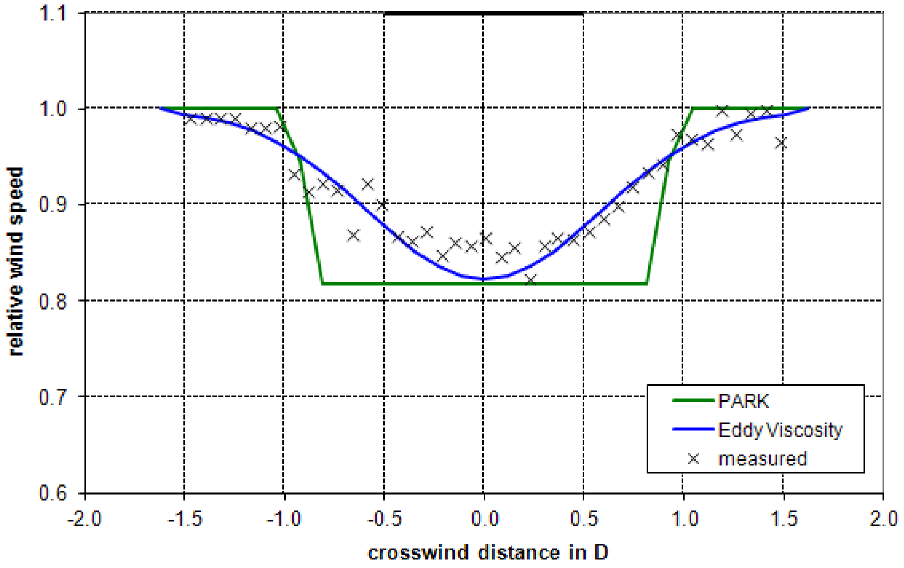

Figure 4: wind speed at 10 rotor diameters downwind for the 5.3 tip speed ratio

The Eddy Viscosity model predicts the general shapes of the wake profiles very well, in particular considering the uncertainty associated with the measurement. The profile of the wake is poorly approximated by the PARK model.

The wind speeds behind a single turbine are show in Figure 5 and Figure 6 for the PARK and the Eddy Viscosity model, respectively. The results are for a thrust coefficient of 0.86. The ambient turbulence intensity is 8.5%. A wake decay parameter of 0.0425 has been used in the PARK model to obtain comparable results.

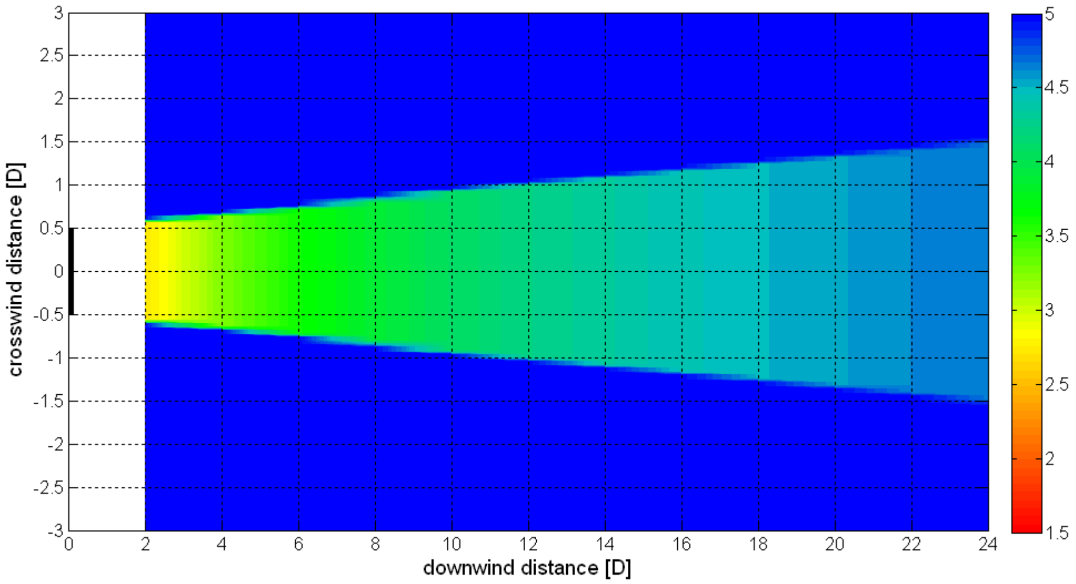

Figure 5: wind speed behind a single turbine modelled with the PARK model

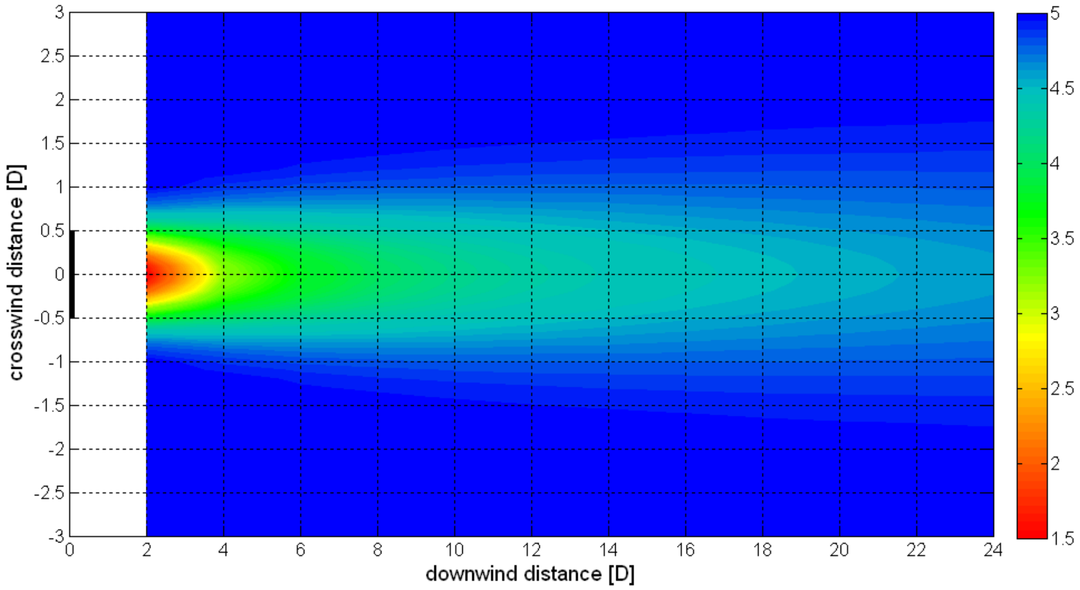

Figure 6: wind speed behind a single turbine modelled with the Eddy Viscosity model

Key differences between the PARK and Eddy Viscosity models (wake expansion, wind speed profile and recovery) are clearly visible from Figure 5 and Figure 6.

2.3 Single upstream turbine wake modelling

As part of the UPWIND project GL Garrad Hassan has been looking at the validation of WindFarmer wake models at a research wind farm at Wieringermeer. The site is located on flat terrain with low roughness and as research wind farm equipped with state of the art, well maintained and high quality measurement facilities. The quality of the field data makes it very useful for studying wake cases in detail.

The research wind farm at Wieringermeer in flat terrain, consists of 5 wind turbines aligned in a single row facing 275 degrees. The pitch-controlled turbines have 2.3 MW rated power. The hub height and rotor diameter is 80 m. A nearby mast was used to determine the wind speed and direction of the free flow, production data was available from the turbines. The turbine spacing in this direction is 3.8 rotor diameters. Results presented here, are shown as power at the 2nd turbine in the row relative to the power at the 1st turbine. In Figure 7, the data and model results are shown for a free wind speed of 7 m/s. For a more detailed description of the site, see [2].

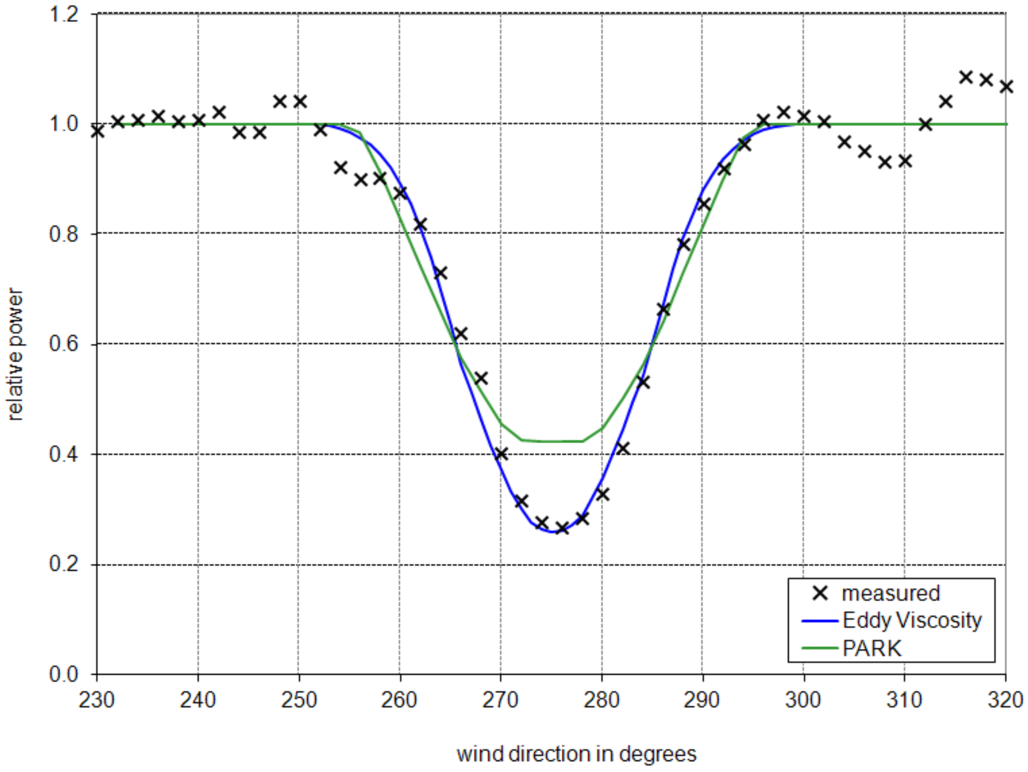

Figure 7: relative power at turbine 2 for a free wind speed of 7 m/s

The power variation with wind direction is due to the rotor of the 2nd turbine being only partially in the wake of the 1st turbine. Modified PARK and Eddy Viscosity models agree very well with the data. The centre line deficit is slightly under-predicted with the modified PARK model.

3 WIND FARM MODELLING

3.1 Nørrekær Enge II

The Nørrekær Enge II wind farm was situated on the south bank of Limfjord in the northern part of Jutland, Denmark.

The surrounding terrain is generally flat. There are, however, terrain features to the south, west and north of the site. To the south the terrain is slightly irregular with the largest irregularity a 50m hill. To the west of the wind farm there are a number of farm buildings and to the north of the site the Limfjord is situated at a distance of some 200m. Work by Risø [3] indicates that the proximity of the Limfjord does, in fact have an effect on the wind flow over the site making the site less homogenous than was originally expected. In general, the wind speed increases in northern direction within the wind farm area.

The wind farm has a total of 12.6 MW installed capacity consisting of 42 stall regulated Nordtank turbines of 300 kW rated power. The wind turbines are situated in two regular grids of 7 by 3 rows at inter machine spacing of 6 rotor diameters along one grid line and 7 to 8 rotor diameters along the other. The separation between the two blocks of wind turbines is approximately 28 rotor diameters. The layout of the wind farm is shown in Figure 8.

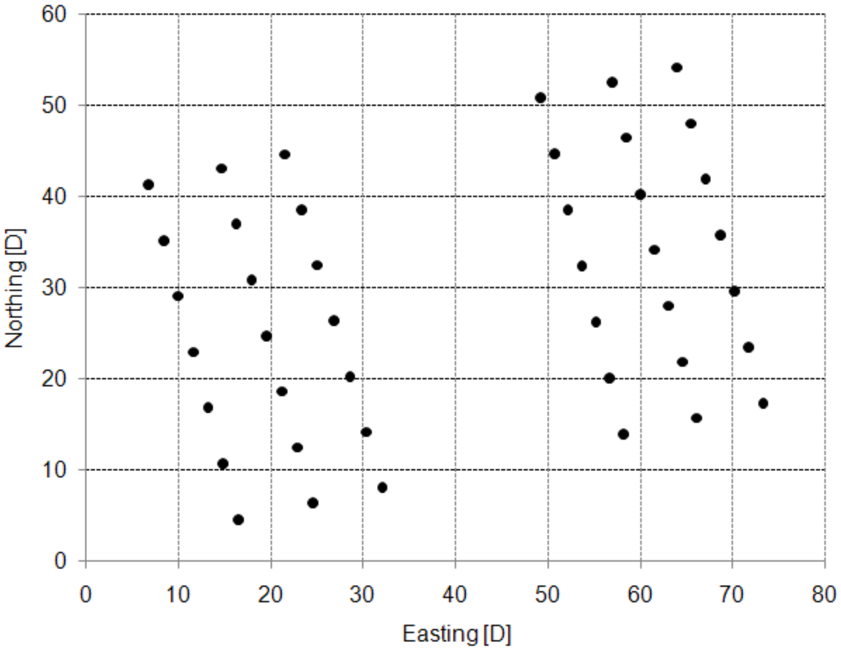

Figure 8: Nørrekær Enge II layout

The data comprised of turbine power from all the turbines in the wind farm, averaged over a number of ten-minute periods, where the wind was blowing along the lines of turbines. The measured data was grouped into direction bins with a width of 2.5 degrees.

For the data from a wind direction of 166 degrees, mean wind speed and power data were grouped by wind speed. A set of thirteen data points was used to calculate the average power production of each turbine. Each data point had the same mean wind speed of around 8 m/s and the same standard deviation of the means, indicating similar wind conditions, and therefore a suitable data set to calculate the average power production for each turbine.

For the direction of 258 degrees, no wind speed information was available. The power from the turbines in the front row of the wind farm was used to estimate the ambient mean wind speed. This was calculated to be 9.07 m/s. The power curve used for both the above conditions is the measured power curve.

The measured and predicted variation of mean power down the lines of the wind farm is presented in Figure 9 and Figure 10 for the 166 and 258 degrees directions, respectively. The figures present measured data from all the turbines at each downstream position. It can be seen that there is considerable scatter between the measured data within each row. In particular in the power production of the turbines positioned at the front of the rows, where no wake effects are present.

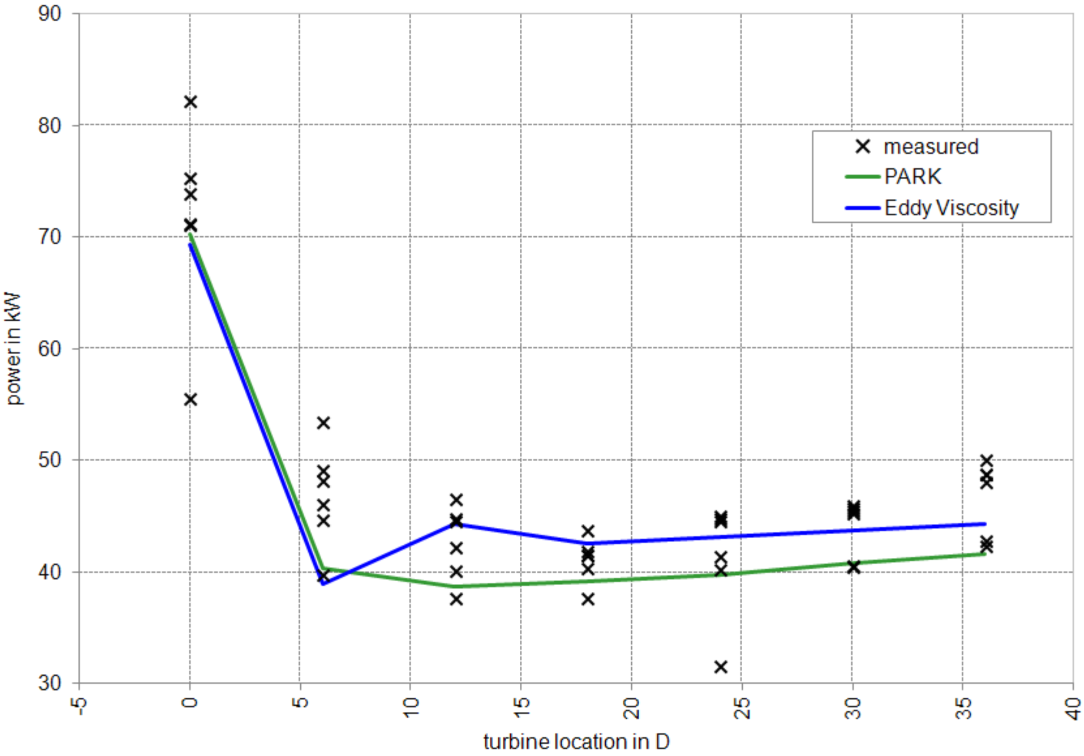

Figure 9: Power output for 166 degrees wind direction and a wind speed of 8 m/s

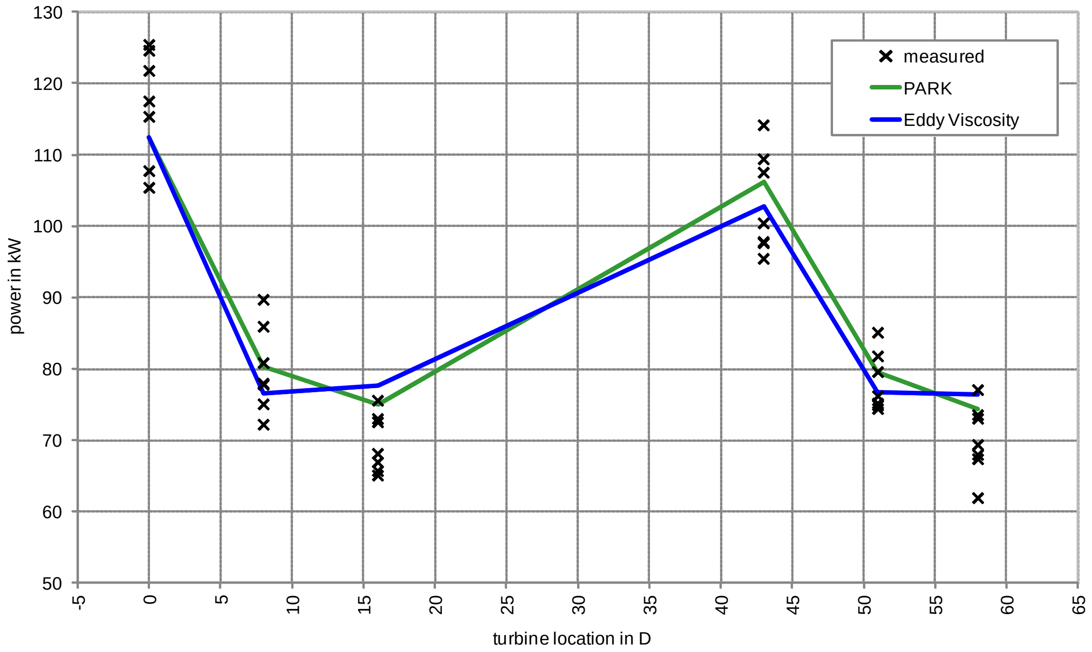

Figure 10: Power output for 258 degrees wind direction and a wind speed of 9 m/s

The agreement between the predictions and measurements is generally good. For the 166 degrees direction, there appears to be a tendency to over-predict the power at the third and fourth turbine positions with the Eddy Viscosity model. For the 258 degrees direction, the power is over-predicted at the third turbine position for both models.

The constant or even increased power for the 3rd turbine in the row, compared to the 2nd turbine is typical for the Eddy Viscosity model. Here, the increased turbulence at turbine 2 (caused by the first turbine) leads to a quicker wake recovery of its wake and so turbine 3 can have similar incident wind speeds as turbine 2. This effect depends on the turbine distances and the turbine thrust curve.

3.2 Vindeby

The Vindeby offshore wind farm is located to the north of the island of Lolland at a minimum distance of 2 km from the coast. The site is impacted by the land surface to the south but this is mainly flat (< 20 m) and agricultural with a roughness of approximately 0.05 m. It consists of 11 Bonus turbines with 38 m hub height and a rotor diameter of 35 m. The distance between the turbines is 300m along and between the rows. A more detailed description of the wind farm and the wake measurements is given in [4]. Figure 11 shows the layout of the site including the masts.

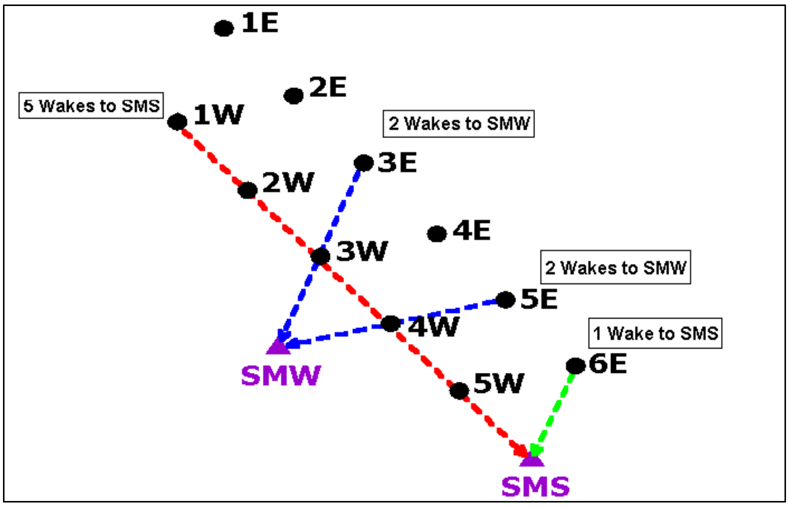

Figure 11: Layout of the wind turbines and masts at Vindeby. Image taken from [4]

Data for cases with a single wake, double wakes and quintuple wakes measured at the two masts were available. Data presented here are for the quintuple wake case at an ambient turbulence intensity of 8 % and free wind speeds of 5, 7.5 and 10 m/s. The vertical wind speed profile at mast “SMS” is relative to a land mast that is not wake affected. The free profile at the land mast is given, relative to the land mast wind speed at hub height. The data and the results from the Eddy Viscosity model are shown in Figure 12.

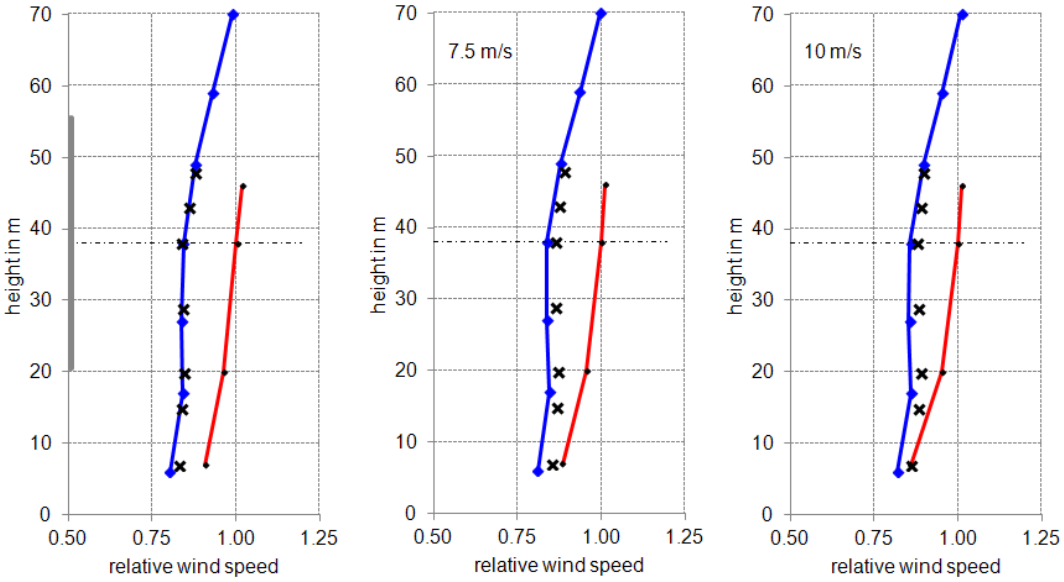

Figure 12: measured and modelled wake profile for the quintuple wake case.

The results from the Eddy Viscosity model agree very well with the measurements.

4 SPECIAL WAKE CASES

Single turbine wake models predict the vast majority of wind farms and wake situations accurately. As we have seen above WindFarmer wake models do an excellent job in such standard cases. This chapter is looking specifically at how WindFarmer performs for cases that are beyond the operational envelope that is usually associated with single turbine wake models. In particular we are looking at two cases:

- Close spacing: The PARK model for example is designed for use at downstream distances greater than 4 rotor diameter. Wake superposition is in all models based on empirical assumptions that are not necessarily valid at close spacing.

- Independent development: All turbine wake models developed since around 1980 assume that the ambient wind flow is not impacted by the presence of turbines. WindFarmer wake modelling allows the user to go beyond the usual.

Figure 13: Typical scenario of a wind farm with close cross wind spacing.

4.1 Closely spaced wind farms

The wake in the near wake, directly behind the rotor, is particularly complex and can only be modelled at great computational expense. Given that turbines are not usually placed at less than two rotor diameters downstream of upstream turbines it is prudent to exclude the near wake region from the models and initiate the models further downstream.

There are wind farms that comprise multiple rows of very closely spaced turbines. Such wind farms are typically in locations with either uni- or bi-directional wind regimes. Under such circumstances, wind farms are often designed with very closely spaced rows across the main wind direction. Inter-turbine distances from 1.1 to 2.5 times the rotor diameter (D) are typical. Along-wind inter-row distances are typically 6 to 9 D. An example layout for such a wind farm is shown in Figure 14.

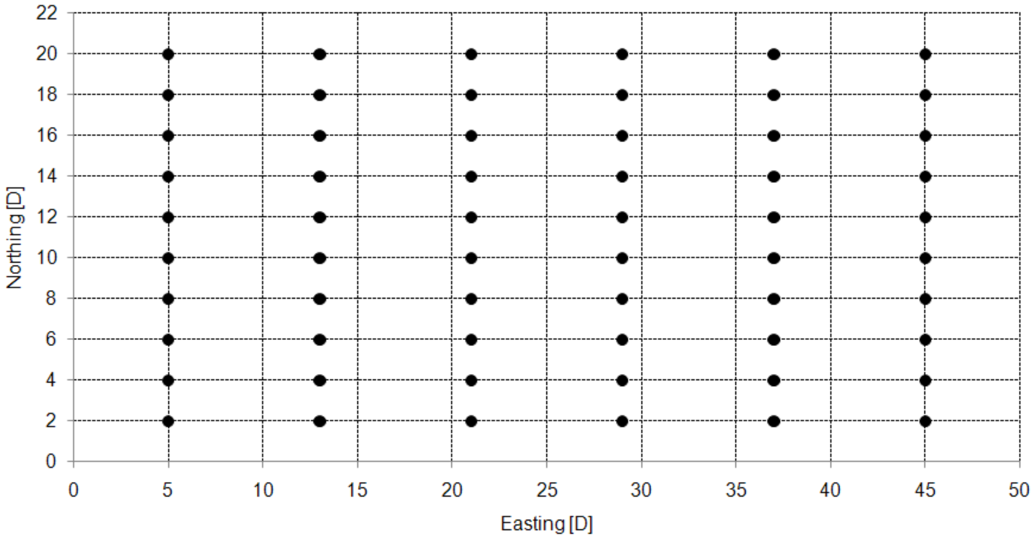

Figure 14: typical layout of a closely spaced wind farm. The main wind direction is West and/or East

Operational data from several closely spaced wind farms have been analysed. Periods have been excluded during which the wind direction changed considerably. The wind direction was considered to be perpendicular to the row. The bin widths for the direction and wind speed were 5 to 10 degrees and 1 m/s respectively.

Data presented here are from several closely spaced wind farms and are compared with the classical Eddy Viscosity model and a modification for closely spaced wind farms. For more validation data see [5]. The free wind speed is 10 m/s, measured at mast located upstream of the wind farms. Note that the wind resource does change within the wind farms so that the wind speed at the single turbines in the same row is different. The power is relative to a turbine in the first row. The results for single turbines in the 3rd and 4th row in a wind farm are shown in Figure 15.

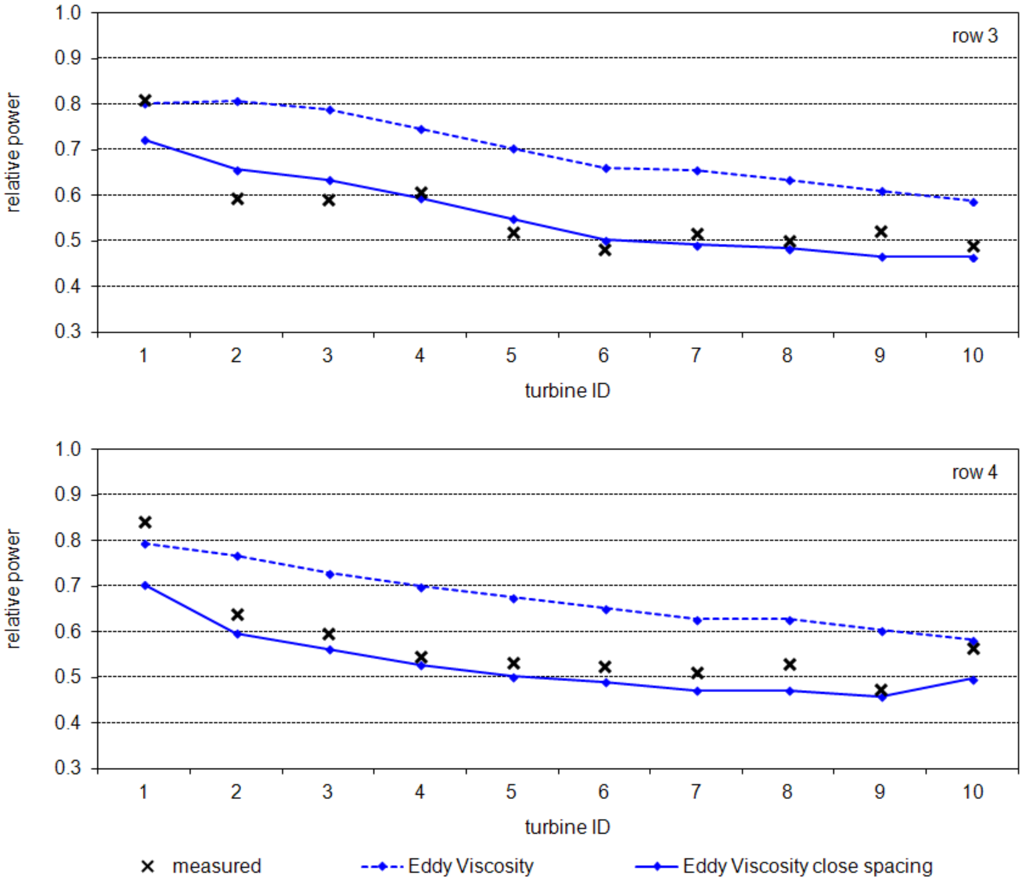

Figure 15: relative power for turbines in the 3rd and 4th row in a closely spaced wind farm

The modification for closely spaced wind farms gives results that much better agree with the measured data. So for closely spaced wind farms it is recommended to use the modified model.

4.2 Deep array effect in very large wind farms

Wake models have, since around 1980, been designed almost exclusively to model the wake of single turbines. For small and medium size wind farms the models work pretty well, as shown in the previous sections. With increasing size of the wind farms, the interaction between the turbines and the atmospheric boundary layer must be taken into account. This interaction is considered in the correction for large wind farms (LWF) that can be used with conjunction with both the Modified PARK and the Eddy Viscosity wake model.

Due to the limited number of validation data, more validation has to be carried out when more data become available.

Figure 16: Horns Rev I wind farm

To model deep array effects, a correction of the wake model was introduced to match the measured data from the offshore wind farm Horns Rev. Later, the model was verified using data from the Nysted offshore wind farm. The wind farm layouts for both wind farms are shown in Figure 17.

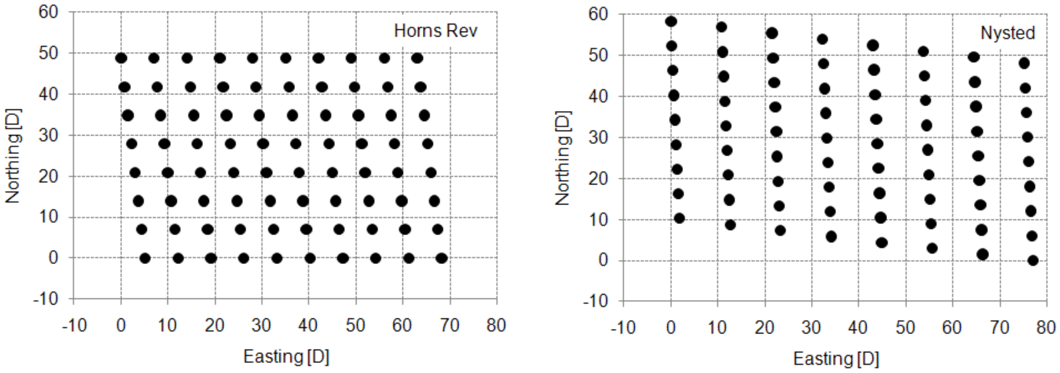

Figure 17: Horns Rev and Nysted layouts

Production data have been available from the UPWIND project. For more data see [6]. The data presented here are for a 30 degrees wind direction sector centred along one symmetry axis, which is 270 degrees for Horns Rev and 278 degrees for Nysted. The free wind speed is 10 m/s.

Results from the Modified PARK and Eddy Viscosity wake models with and without the correction for large wind farms applied are shown in Figure 18.

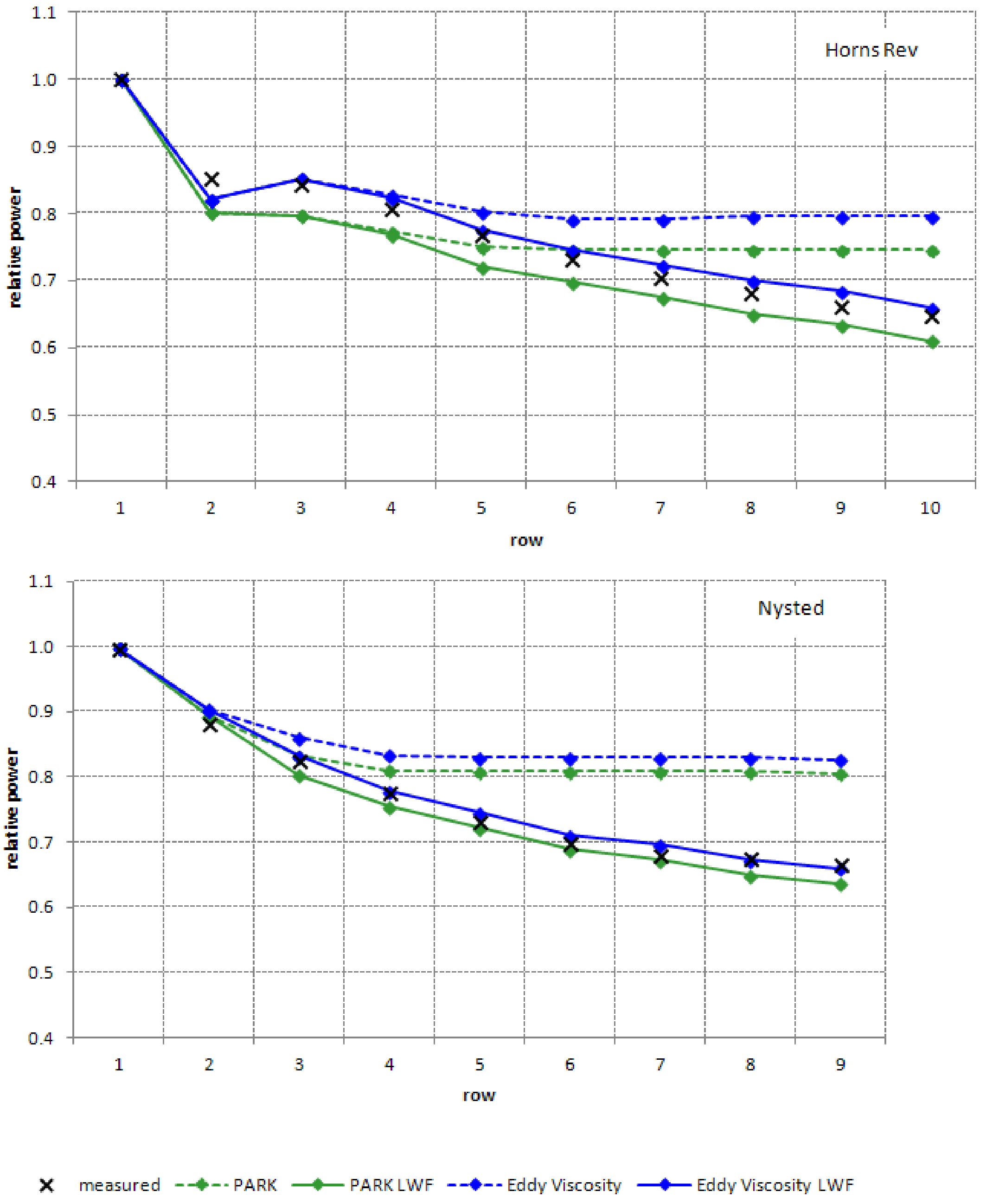

Figure 18: measured and modelled relative power for Horns Rev and Nysted wind farms

The large wind farm correction has improved the wake modelling for large wind farms, especially for turbines deep in the wind farm array.

4.3 Wake recovery behind large wind farms

Measurements of the wind speed deficits at met masts downwind from the Nysted and Horns Rev wind farms are available in [7]. For both wind farms, the met masts are located 2 and 6 km west of the wind farm. For Horns Rev, the masts are located in the line between the 4th and 5th row, oriented in East-West direction. In Nysted the masts are exactly aligned with the middle row for a wind direction of 278 deg.

The measured data and the modelled results are shown in Figure 19 for a direction sector of 30 deg, centred at 270 deg for Horns Rev and 278 deg for Nysted. The free wind speed is around 8 m/s.

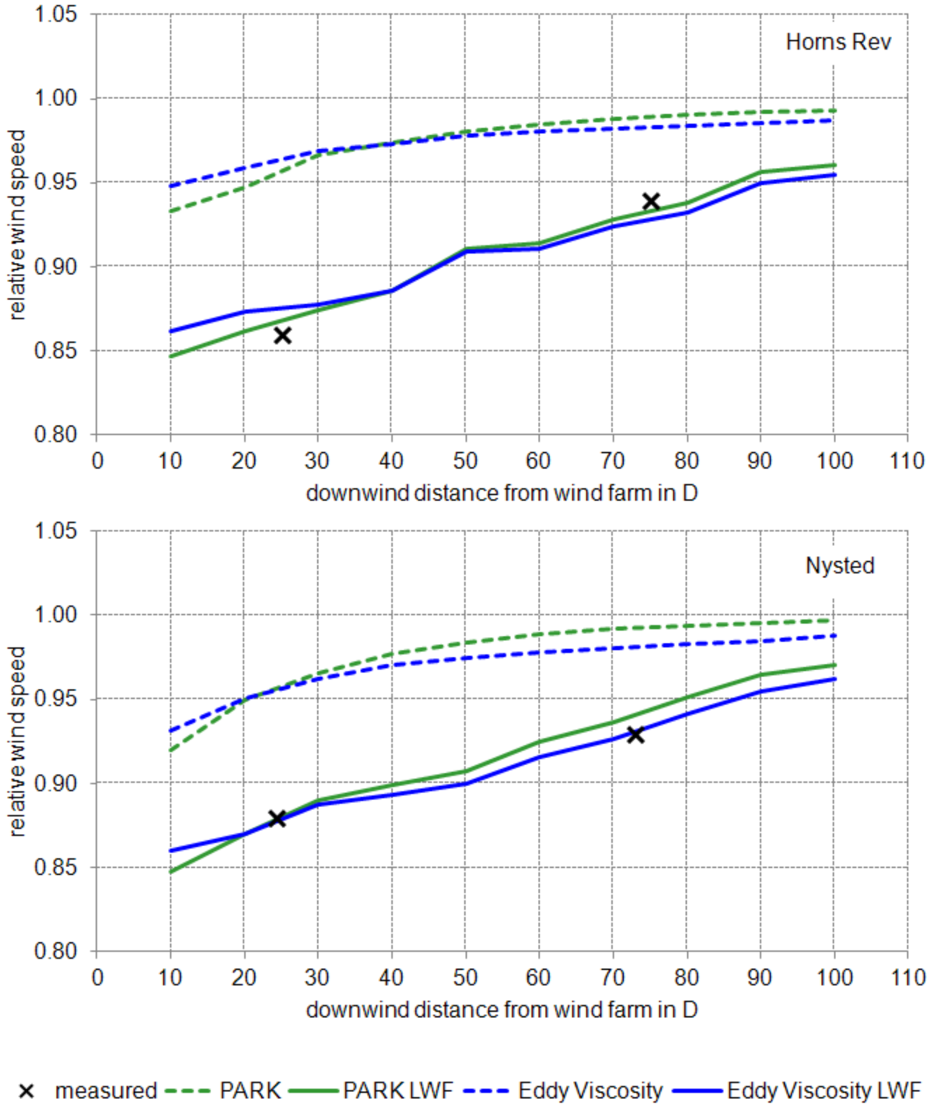

Figure 19: measured and modelled wind speed downwind of Horns Rev and Nysted wind farms

Without the correction for large wind farms, the wind speed deficits behind the wind farms are under-predicted. With the correction, the wind speed deficits are modelled very well with the PARK and Eddy Viscosity models.

5 SHADOW FLICKER

Shadow flicker measurements have been carried out at a turbine in Oldenburg, Germany in 2006. The turbine hub height is 28.1 m and the rotor diameter is 22.9 m. The locations of the turbine and the observation points have been measured with a high-precision GPS device with an accuracy of a few cm. The bearing of the turbine rotor has been derived from photographs taken during the shadow flicker periods by determining the major and minor axes of an ellipse enclosing the rotor area, as shown below.

Figure 20: photograph taken at the beginning of the shadow flicker period at 13th July 2006

The measured shadow flicker periods are summarised below:

Day	Start time	End time	Duration (min:sec)	Turbine bearing at start (deg)	Turbine bearing at end (deg)
27 April 2006	18:52:27	19:04:56	12:29	58	58
2 May 2006	19:21:14	19:32:00	10:46	148	145
4 May 2006	19:18:05	19:34:10	16:05	103	101
5 May 2006	19:17:18	19:34:10	16:52	127	119
13 July 2006	20:00:40	20:14:15	13:35	335	353

Table 3: measured shadow flicker periods

In the WindFarmer calculations, the difference between True North and Grid North is taken into account. This difference is 0.64 degrees for the turbine location, using the Gauß-Krüger projection in zone 3 and the Potsdam Datum. Time steps of 1 minute have been used in the calculation and the measured start time has been rounded to the next full minute and the stop time has been rounded to the last full minute. The results are shown in Figure 21.

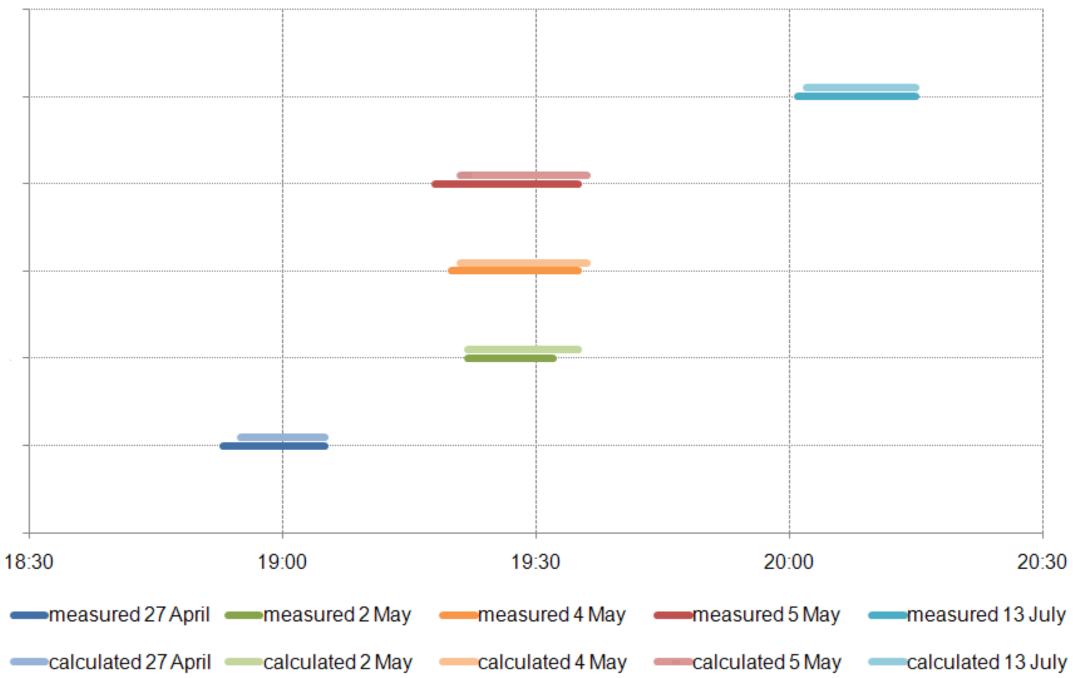

Figure 21: Measured and calculated shadow flicker periods

The average difference between the calculated and measured start and stop time of the shadow flicker period is with 1.4 minutes small. The duration of shadow flicker is predicted accurate within the chosen time-step of 1 Minute. The main source of uncertainty in the measurement is the precise location of both turbine and receptor.

6 ZVI AND PHOTOMONTAGE

The purpose of the ZVI map is to show the areas of the surrounding landscape from which the wind farm can seen by an observer. In the following example, the observer height is assumed to be 1.8 m. The ZVI was generated from an Ordnance Survey digital terrain model of the area, based on a 50 m grid. Woodland and buildings are not included in the model. The exclusion of these screening effects gives a conservative result.

An example ZVI map for a 20 turbine wind farm is presented in Figure 22.

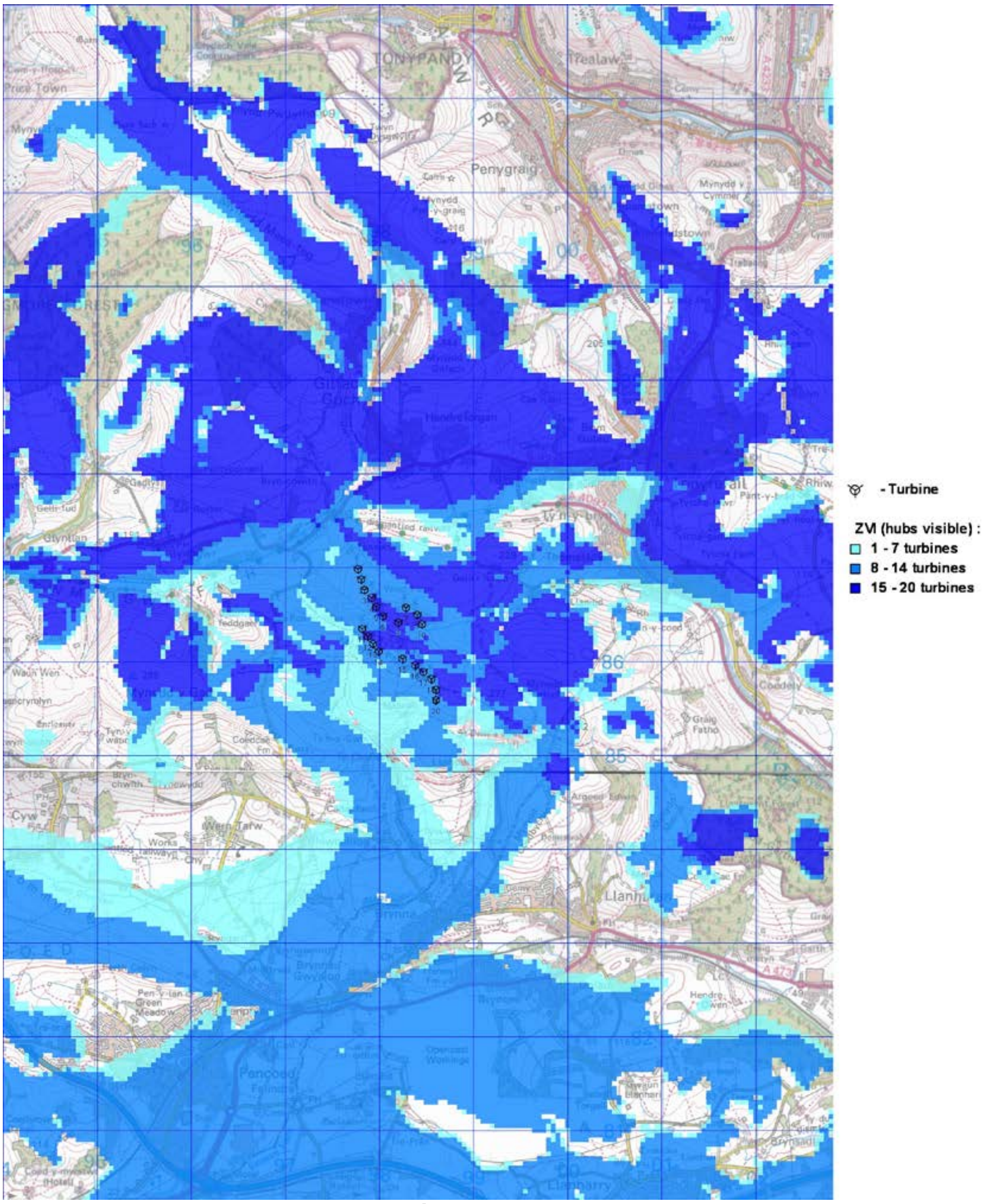

Figure 22: ZVI map

A photograph was taken from a viewpoint to create a photomontage. No photograph was available of the wind farm site prior to the erection of the wind farm. The wind turbines have therefore been digitally removed from a photograph taken after the completion of the wind farm, before creating the photomontage. The real photograph and the photomontage are shown in Figure 23 and Figure 24.

Figure 23: photograph of the wind farm

Figure 24: photomontage of the wind farm

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