WHITE PAPER

WINDFARMER

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EXECUTIVE SUMMARY

In this paper we explain the WindFarmer models used in wind farm energy assessments in detail and show how these models affect the accuracy of wind farm net energy production assessments.

The following models are discussed:

- Mast association method
- Eddy Viscosity and Modified PARK wake models
- Large Wind Farm model

Different model combinations have been used and the results have been compared with actual production data for five wind farms. The total absolute error normalised against actual net yield for these model combinations are summarised in Table 1.

Table 1: Total absolute error normalised against actual net yield for different WindFarmer model combinations

Mast association method	Wake model	Large Wind Farm model	Total error in net yield in %
Yes	Eddy Viscosity	Yes	1.2
No	Eddy Viscosity	Yes	2.3
Yes	PARK	Yes	2.6
Yes	Eddy Viscosity	No	3.2
No	PARK	No	4.3

The DNV GL recommended settings are the mast association method, the Eddy Viscosity wake model and the Large Wind Farm model and this model combination has the lowest overall errors.

This DNV GL recommended settings result in the best estimates for wind farm net energy yields but this should not be generalised given the small number of wind farms used in the analysis.

1 INTRODUCTION

Wind farm energy production assessments require high-precision input data and models to calculate an accurate estimate of the wind farm net yield. This paper focuses on the calculation models in WindFarmer and their impact on the accuracy of the estimated wind farm net yield. The WindFarmer models are developed and constantly refined based on wind farm data in order to provide users the best tool and models for their assessments.

The following steps are typically carried out in a wind farm energy assessment:

- Measurement of the local wind climate at the wind farm site
- Long-term extrapolation of measured wind climate using long-term reference data
- Extrapolation of the measured wind climate to the wind turbine positions using a flow model
- Calculation of the wind farm wake effects based on the turbine layout and the wind climate at the turbine locations
- Calculation of the wind farm yield based on the local wake affected wind climate and the turbine power curve
- Estimation of other loss factors to calculate the final wind farm net yield

In order to demonstrate the impact of the selected model on the accuracy of the wind farm net yield, calculation results have been compared with the actual wind farm production for different models. The analysis has been carried out for five wind farms where production data are available. Details are shown in Table 2.

Table 2: Wind farms used in the model validation

Wind farm	Number of turbines	Number of turbines in neighbouring wind farms	Terrain	Number of months with production data
1	13	0	Onshore – Complex terrain, forestry	100
2	46	0	Onshore – Simple terrain	79
3	29	115	Onshore – moderately complex terrain	84
4	113	1033	Onshore – complex terrain	66
Horns Rev	80	0	Offshore	N/A

The following WindFarmer models are validated in this document:

- Mast association method
- Eddy Viscosity and Modified PARK wake models
- Large Wind Farm model

The WindFarmer models are described in more detail in the WindFarmer Theory Manual and more validation results are available in the WindFarmer Validation Report.

For DNV GL energy production assessments, the mast association method is used and the array efficiency is calculated with the Eddy Viscosity wake model and the Large Wind Farm model. In this validation the wind climate has been modelled with WAsP. The error of the predicted annual net energy production is shown in Figure 1 for the five wind farms used in the analysis.

Overall, the total absolute error normalised against actual net yield is 1.2% when using the DNV GL recommended settings.

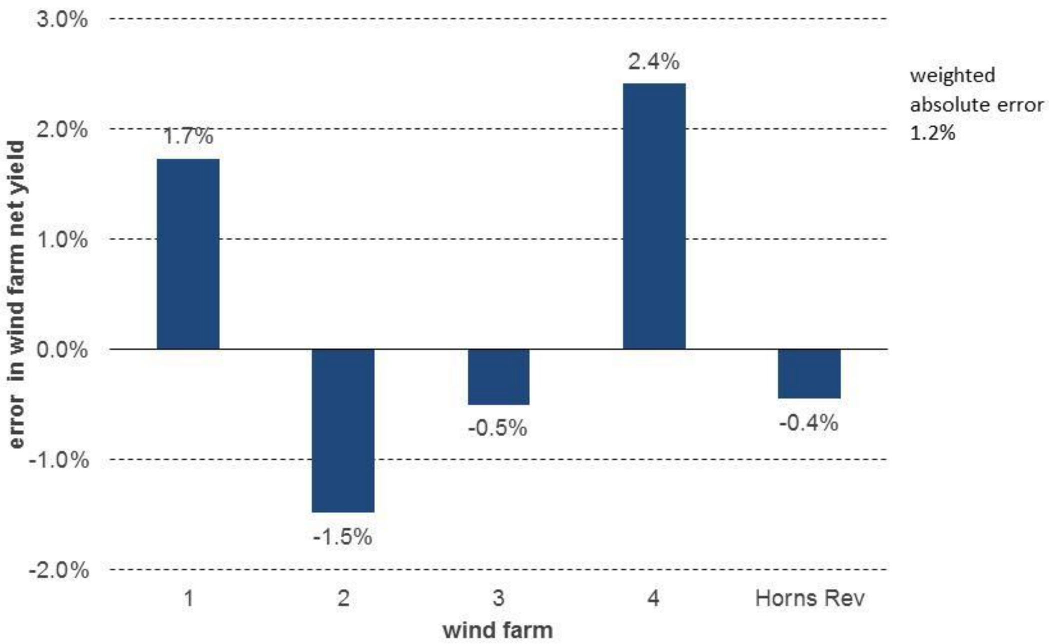

Figure 1: Prediction error for wind farm net yield with mast association method, Eddy Viscosity wake model and Large Wind Farm model

The calculation models are described in more detail in the next sections and their influence on the accuracy of the estimated wind farm net yield is evaluated.

2 WINDFARMER MODELS

2.1 Mast association method

In order to calculate the energy yield of a wind turbine, the wind climate at the turbine must be known. An important parameter of the wind climate is the wind speed and direction probability. This is usually measured at a few met masts on the wind farm site and extrapolated to the turbine locations using a flow model.

The flow model input is typically the measured wind speed and direction distribution measured at the masts in the form of a table of annual frequencies. Most flow models calculate the wind climate at the turbine locations based on these annual statistics and do not consider individual wind speed cases. The wind climate at the turbines is expressed within the flow model in the form of a continuous probability distribution, usually a Weibull distribution, so that the potentially complex measured wind speed distribution is replaced with a simplified distribution described by only 2 parameters, resulting in much of the measured information being lost in the flow modelling step. This can be a problem at wind farm sites where the measured distribution cannot be described by a 2-parameter Weibull distribution without introducing significant errors in the wind speed probabilities.

An example for a poor Weibull fit is shown in Figure 2. The histogram data come from a met mast located in complex terrain and represent an all-directional wind speed distribution. Data have been recorded at the mast from August 2012 to February 2014 and have been correlated with long-term data to produce a distribution that represents a period from 2004 to 2014. The mean wind speed is 6.3 m/s so an IEC class 3 turbine type is usually selected for this kind of wind climate.

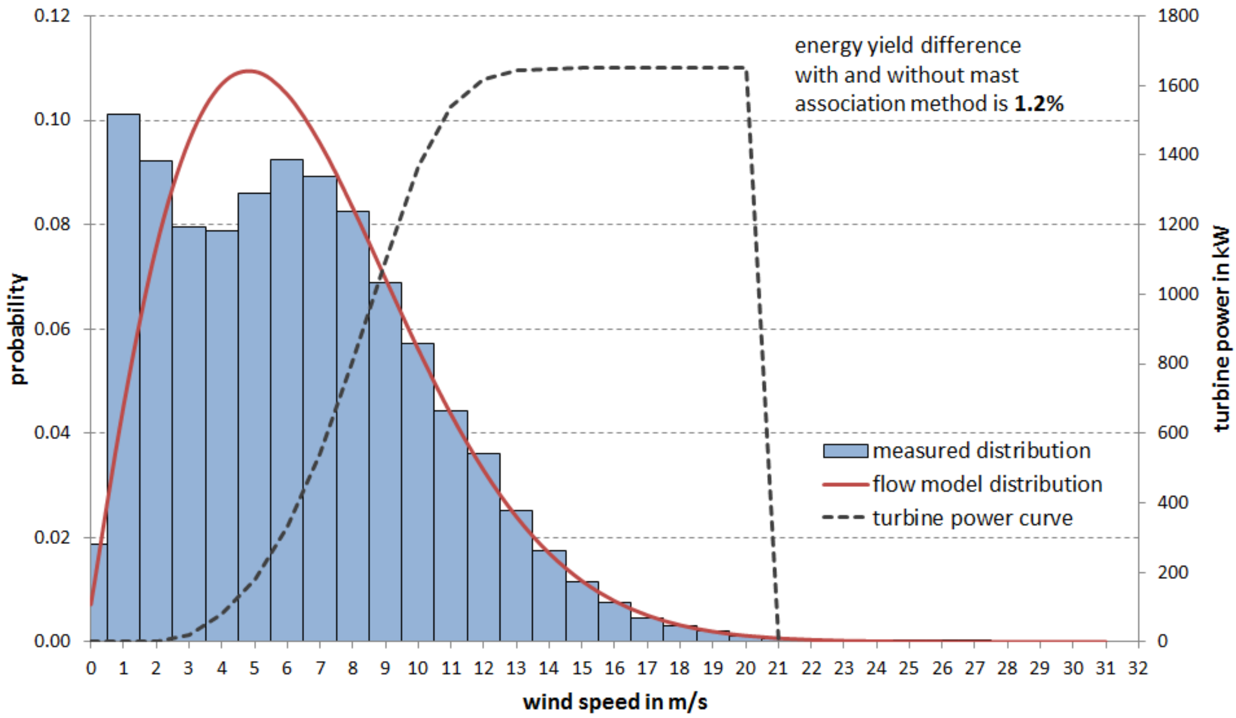

Figure 2: Measured and modelled wind speed probability distribution

In this example, the probabilities of wind speeds below the cut-in wind speed of the wind turbine are underestimated in the modelled distribution. They are overestimated in the wind speed range where a turbine power curve is steepest.

The WindFarmer mast association method can be used to calculate turbine energy production using measured frequency distributions to mitigate against this issue.

- Each turbine location is associated with one of the measurement locations at the site, the "initiation measurement" for that turbine (this could also be a mast, remote sensing device or synthetic data node). Which turbine is associated with which measurement is generally decided based on geographic similarity of exposure between measurement and turbine.
- Using the chosen flow model, the predicted ratio of mean wind speeds in each direction sector at the initiation measurement and turbine locations is derived for each turbine (the 'directional speed-up factors').
- For each wind speed step defined at the measurement locations, the corresponding wind speed at the turbine is calculated from the speed-up factor. The corresponding power output of the turbine is determined from the turbine power curve.
- The turbine power output in each step is combined with the measured probability at the measurement location to calculate the turbine annual energy yield.

When placing a turbine directly at the mast location it is expected that the energy yield of the turbine is a combination of the turbine power curve and the measured distribution (i.e. the flow modelling step is not needed). This allows us to directly examine the effect of converting the measured distribution to a parameterised distribution, such as a Weibull distribution, on the energy content of that distribution. In the example above, the energy yield is overestimated by 1.2% when the output from the flow model is used in the energy calculation instead of the measured distribution.

It should be noted that the association method also allows the directional wind speed differences between the turbines to be considered in the wake calculation which becomes important when looking at a wind farm instead of a single turbine.

The differences in the wind farm net yield accuracy with and without the mast association method are shown in Figure 3.

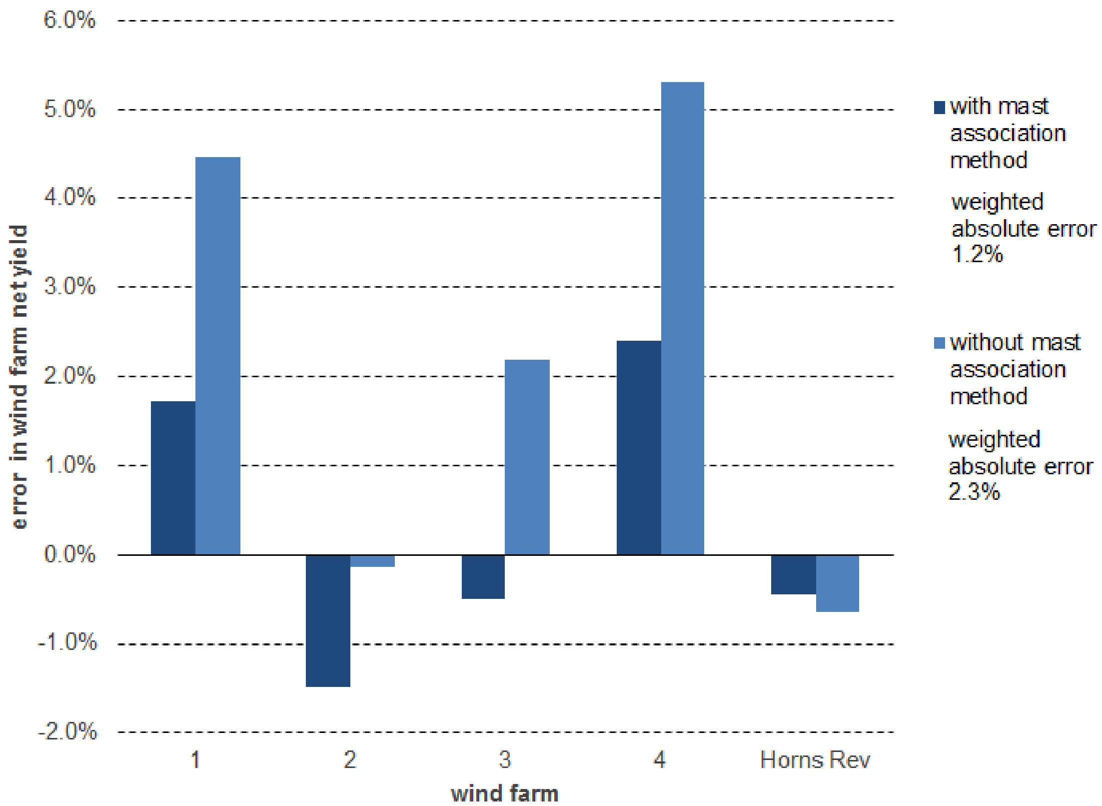

Figure 3: Prediction error for wind farm net yield with and without mast association

The energy yields are larger without the association method applied for all onshore cases. For Horns Rev there is almost no difference which is mainly caused by the uniform wind climate across the site so that there are no wind speed differences to consider in the wake calculation. Overall, the total absolute error normalised against actual net yield is 2.3% when not using the mast association method and 1.2% when using the association method.

2.2 Wake models

Two wake models are available in WindFarmer - 'Modified PARK' and 'Eddy Viscosity'. The PARK model assumes linear expansion of the wake with downwind distance and a constant wind speed deficit across the wake cross section. The only model parameter is the wake decay constant. Wake calculations with the PARK model are fast so that it is often used to optimise wind farm layouts to maximise the annual net yield. The Eddy Viscosity model uses the ambient turbulence intensity as an input parameter and takes into account the added turbulence caused by wind turbine wakes inside a wind farm. The recovery of the wake is strongly influenced by the ambient turbulence as this affects the momentum transfer from the free flow into the wake. The wind speed deficit is largest in the centre line of the wake and decreases with distance from the centre line. The wake behind a single turbine modelled with both wake models is shown in Figure 4.

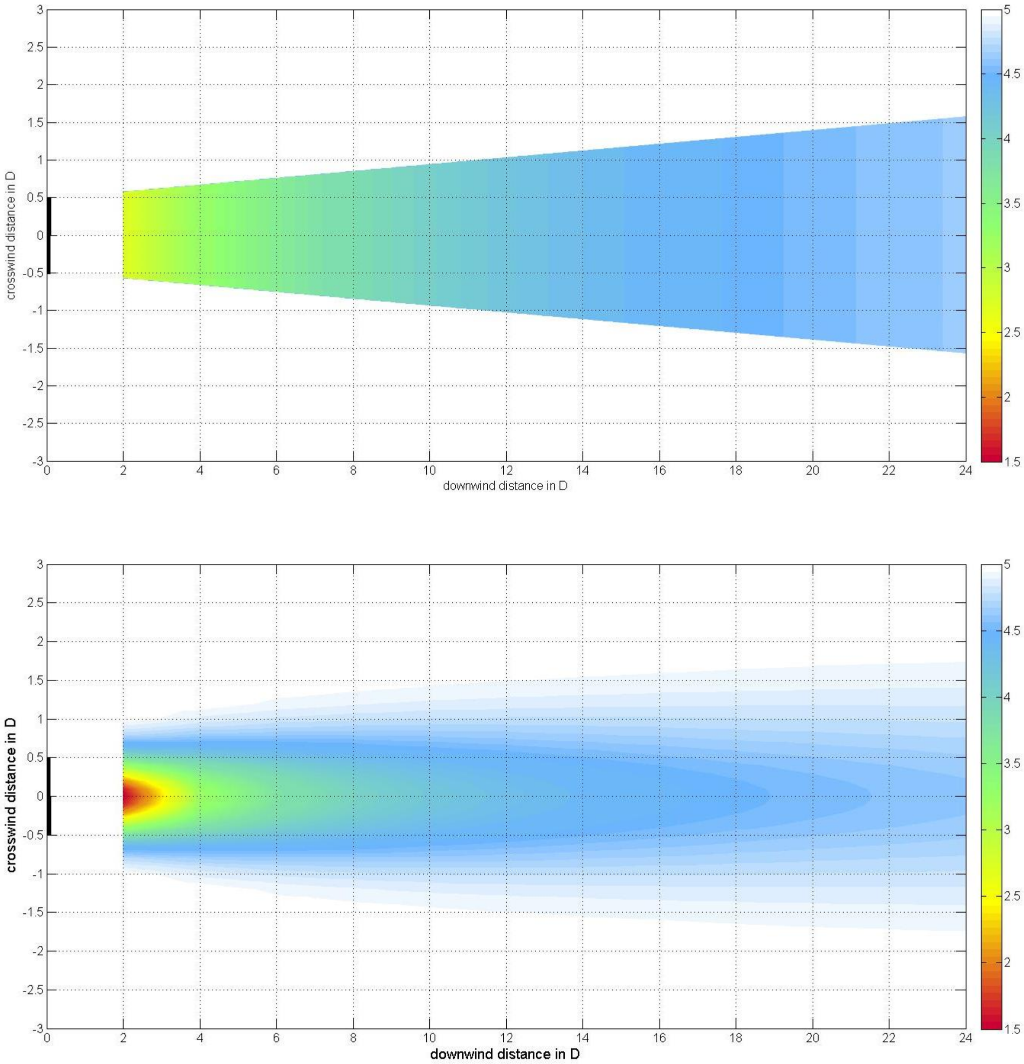

Figure 4: Wind speed behind a single turbine modelled with the PARK model (top) and Eddy Viscosity model (bottom)

The major differences between the two models can be seen when looking at a single wake in more detail. Time series data for the power of individual turbines and an on-site met mast have been analysed for the Nørrekær Enge II wind farm in Denmark, shown in Figure 5. Production data from Turbine B1 in the wake of Turbine A1 (identical turbines, separated by 8.2 rotor diameters) have been evaluated and compared with results from both wake models.

The data were binned according to the wind speed and direction measured at the mast that is located close to the upstream wind turbine (Turbine A1). The data presented here are for a direction bin between 253 and 263 degrees where Turbine A1 is directly upwind of Turbine B1 at 258 degrees. The wind speed bin ranges from 7.5 to 8.5 m/s.

Figure 5: Nørrekær Enge II wind farm layout and mast position

The power output of wake-affected Turbine B1 relative to the power output of the upstream turbine is shown in Figure 6. The data have been filtered to include turbulence intensities ranging from 9 to 10 %. The wake effects have been calculated for a fixed turbulence intensity of 9.5 %. As expected, it can be seen that the PARK model produces a simplified rectangular wake profile, with the centre-line deficit being underestimated. The Eddy Viscosity model profile more closely resembles the measured wake.

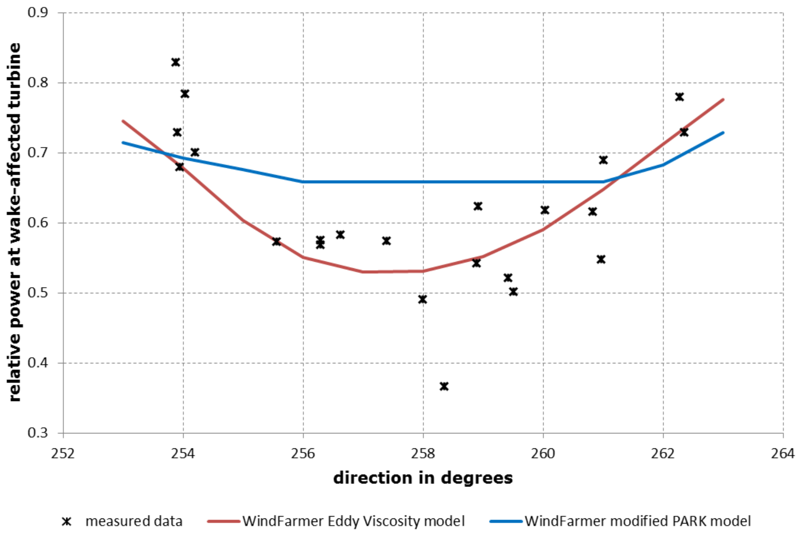

Figure 6: Measured and modelled relative turbine power in the wake of a single turbine as a function of wind direction

The wake loss at a turbine in a single wake and its dependency on the ambient turbulence intensity is shown in Figure 7. The data have been binned according to turbulence intensity between 7 and 14 % in steps of 1 % and the model inputs have been set accordingly. The Eddy Viscosity model is able to more closely model the observed decrease of the wake loss with increasing turbulence intensity, while the PARK model result remains constant as the wake expansion is described by the fixed wake decay parameter, here 0.07.

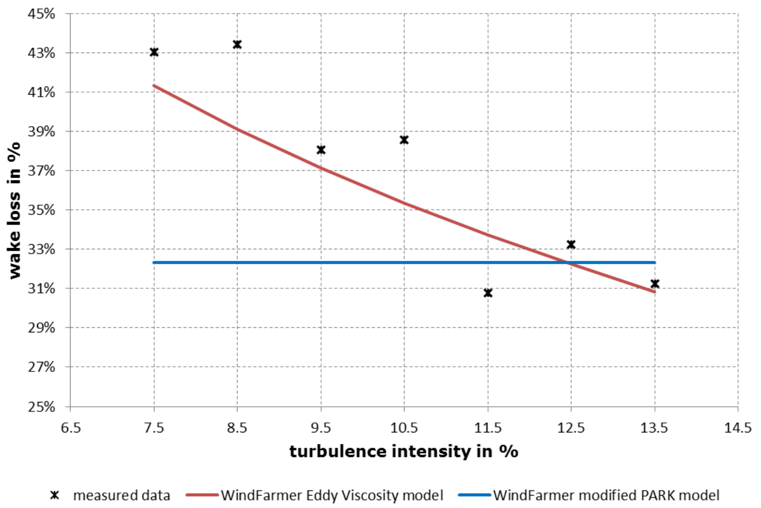

Figure 7: Measured and modelled wake loss behind a single turbine as a function of turbulence intensity

The differences in the wind farm net yield accuracy with the WindFarmer Eddy Viscosity and PARK models are shown in Figure 8. The wake decay constant for the PARK model is 0.07 for the onshore wind farms and 0.04 for Horns Rev. The turbulence data required for the Eddy Viscosity model are based on on-site measurements and vary with wind speed. The turbulence intensity is lower for Horns Rev than for the onshore wind farms. The Eddy Viscosity model does not require any parameter adjustments for offshore wind farms.

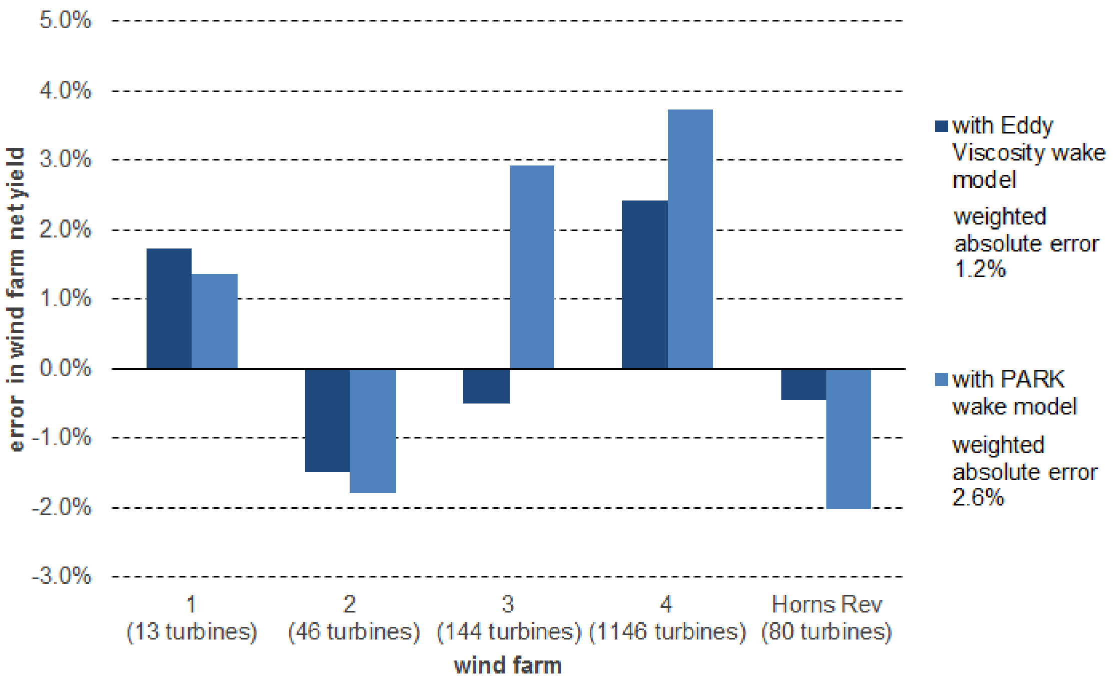

Figure 8: Prediction error for wind farm net yield with Eddy Viscosity and PARK wake model (total number of turbines considered in calculation shown in brackets)

The Eddy Viscosity model produces a lower error than the PARK model in 4 out of 5 cases, with the difference between the two models tending to be larger for large wind farms. It appears that the WindFarmer Eddy Viscosity model is particularly advantageous when modelling wake effects in large wind farms or clusters. Overall, the total absolute error normalised against actual net yield is 2.6% when using the PARK wake model and 1.2% with the Eddy Viscosity wake model.

2.3 Large Wind Farm model

Wake models have been developed for single turbines where the wake recovers due to the momentum transfer from the free flow at higher altitude and the sides into the wake. Large wind farms disturb the local boundary layer by the extraction of momentum and can be thought of an area of higher roughness. The Large Wind Farm model has been developed based on production data from large offshore wind farms to improve the modelling of array effects in large wind farms. It has been found that the power output of wind turbines deep inside the wind farm is much lower than that calculated with the standard wake models but only in wind directions where turbines are spaced closely in crosswind direction. The Large Wind Farm model is designed to address this. Validations with large onshore wind farms have shown that the model improves the prediction of the array efficiency without having to adjust any of the model parameters used for single turbines or small wind farms.

The WindFarmer correction for large wind farms is based on the following parameters:

- The wind farm layout
- Turbine hub height
- Turbine rotor diameter
- Base roughness length
- Wind farm roughness length

The Large Wind Farm model corrects the wind speed of the ambient flow and does not depend on wind speed or the operational state of the turbines.

The difference in modelled wind speeds with and without the Large Wind Farm model can be seen in Figure 9 for an offshore wind farm consisting of an 8 by 12 array of turbines with a spacing of 8 rotor diameters in both east-west and north-south directions. Wind speed variations in a westerly wind direction sector of 30 degrees width centred at 270 degrees at a free wind speed of 10 m/s derived using the WindFarmer Eddy Viscosity wake model are shown.

The correction starts at the 4th row of turbines in this case and increases with distance from the leading row of turbines. Turbines at the northern and southern edges of the array are less affected by the correction than turbines in the middle. It should be noted that the model has a threshold so it levels out in a larger arrays with many turbine rows and a recovery function ensures that the correction vanishes far downstream of the wind farm.

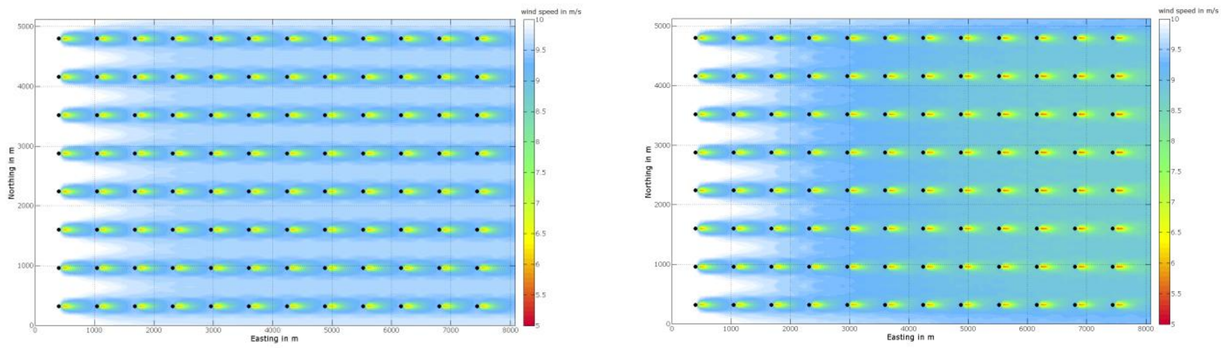

Figure 9: Wind speed over a wind farm with WindFarmer Eddy Viscosity wake model with (right) and without (left) the Large Wind Farm correction applied

The improvements in the accuracy of the modelled wake loss for the Horns Rev and Nysted offshore wind farms are shown in Figure 10. Measured relative power for individual turbines and model errors are shown for a direction sector of 30 degrees centred at 270 degrees for Horns Rev and centred at 278 degrees for Nysted for a wind speed of 10 m/s.

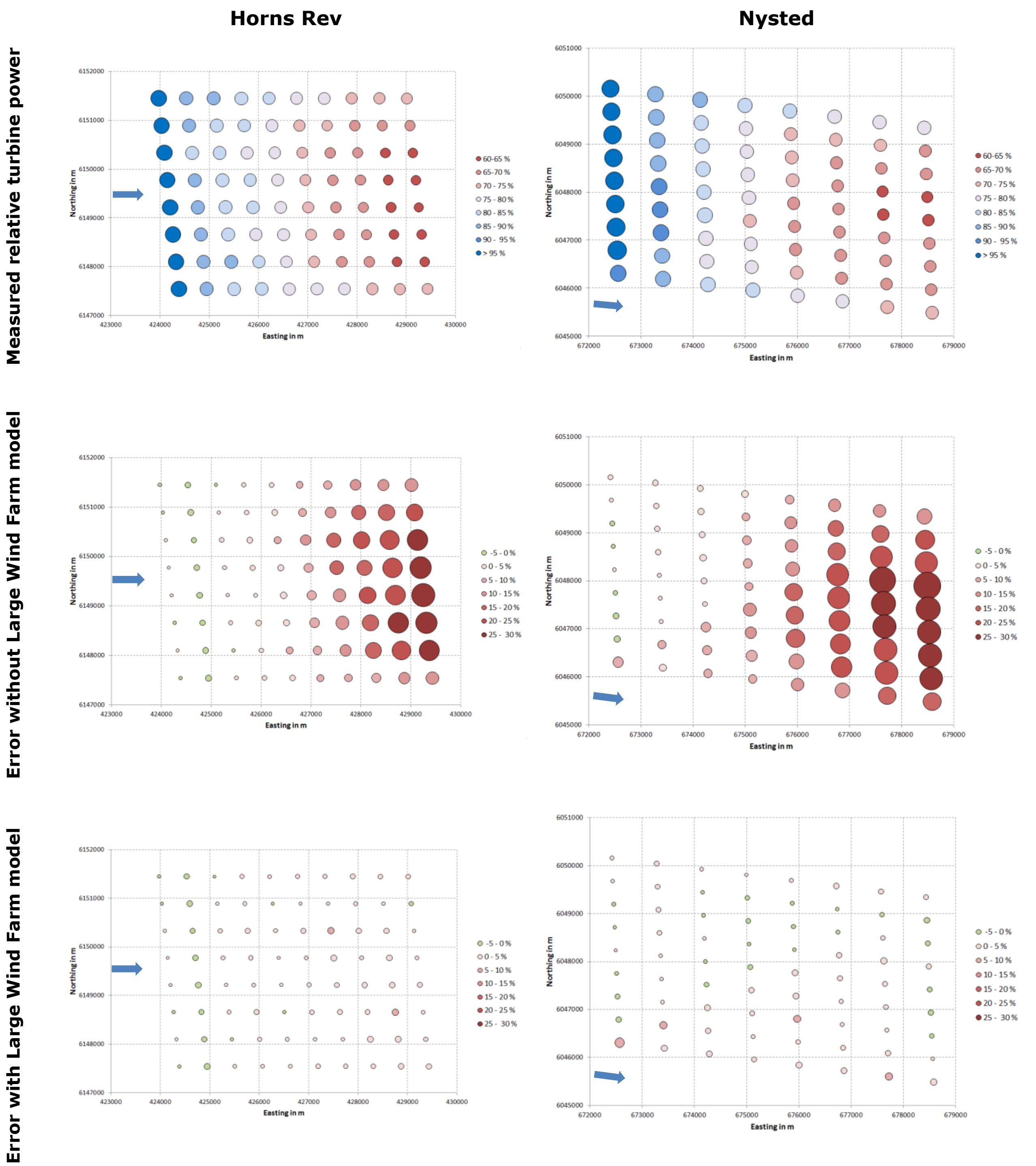

Figure 10: Relative turbine power measured in Horns Rev and Nysted (top), model error without (middle) and with (bottom) the Large Wind Farm model applied

It can be seen that the power from turbines deep inside the array are over-predicted with errors of up to 30% for individual turbines when the Large Wind Farm model is not applied. The application of the Large Wind Farm model reduces the model error significantly. The maximum over-prediction error for a single turbine is about 5%.

The differences in the wind farm net yield accuracy with and without the Large Wind Farm model are shown in Figure 11.

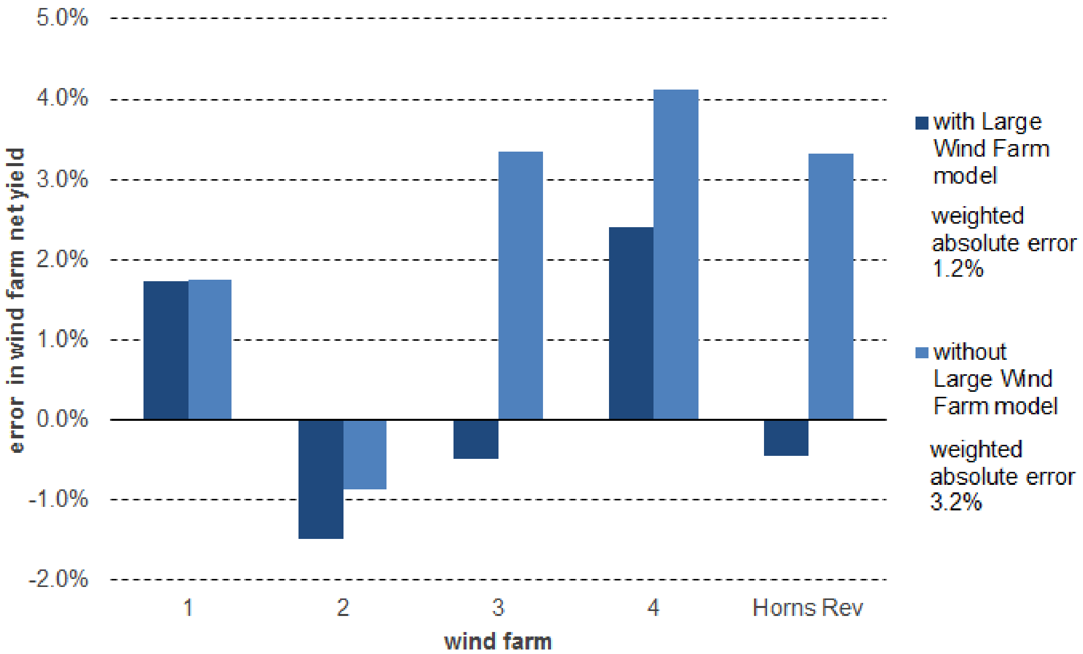

Figure 11: Prediction error for wind farm net yield with and without Large Wind Farm model

The Large Wind Farm model has no effect at wind farm 1 because it only consists of 13 turbines and so it is not a deep array of turbines. The Large Wind Farm model significantly improves the accuracy of the net yield results for the large arrays 3 and 4 and Horns Rev. Overall, the total absolute error normalised against actual net yield is 3.2% without the Large Wind Farm model and 1.2% with the Large Wind Farm model.

3 CONCLUSIONS

In this paper we have explained some aspects of the WindFarmer models in detail and have shown how they affect the accuracy of wind farm energy production assessments. DNV GL continuously validates the models used in energy assessments and improves existing models or introduces new models whenever needed. These models are available to all WindFarmer users so that everyone benefits from the research undertaken by DNV GL. WindFarmer users have the freedom to use their preferred model combination.

The analysis indicates that using a combination of the most sophisticated models in WindFarmer gives the most accurate results but this should not be generalised given the small number of wind farms used.

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