Evaluating Models for Wind Turbine Wake Added Turbulence – Sensitivity Study of the Models and Case Study

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Summary

A range of turbulence models for wake added turbulence has been implemented in the WindPRO software. These models have been parameterized according to recommendations from the researchers who published or revised the models or the guidelines from which the model originate. The authors of this paper are in the process of validating these turbulence models by use of case studies. This paper presents the preliminary results from one such case study: The Nørrekær Enge wind farm in Denmark. Using two meteorological masts in and on the perimeter of the wind farm the ambient turbulence at both places has been measured. The difference is the wake added turbulence. An initial setup of 13 different combinations of turbulence and wake models has been tested against these measurements. The tests reveal a varying degree of success, both among the model configurations, but also among the direction sectors investigated. They highlight the importance of choosing a proper set of parameters, but also that test cases a highly sensitive to error.

Introduction

Turbines operating in wakes are subjected to significant higher structural loading than turbines operating in the free wind. Appropriate turbulence calculations should be made before selecting the proper turbine design class when having clusters of turbines. In this study, the wake added turbulence has been calculated using three different wake models and seven different turbulence models. These models are typically very different in detailing level – and possible also in accuracy. The models range is from simple engineering models to the more advanced computational fluid dynamic (CFD) models. The CFD-models are typically also very demanding in terms of calculation time.

Turbulence Models and Wake Models Included in the Analysis

In the analysis the following wake added turbulence models have been implemented and tested: Danish Recommendation: 1992, Eddy Viscosity: 2003 (B. Lange), Quarton:1996 (D.C. Quarton & J.F. Ainslie), Dutch TNO Laboratory, G.C.Larsen: 1998 (EWTS II), S. Frandsen: 1999 (Efficient turbulence model) and the DIBt Richtlinie: 2004. The turbulence model must be used in connection with a wake (wind field) model. In the analysis, the following wake models are included: PARK model: 1996 (N.O. Jensen), Eddy viscosity model: 1988 (J.F. Ainslie), G.C. Larsen: 1998 (European Wind Turbine Standards II). A description of these models including references can be found in the WindPRO manual [1].

Sensitivity Studies

The turbulence model parameters will be subjected to a sensitivity analysis to test the performance of the models under various environmental conditions. The performance of the models will then be compared.

Case Studies

The ambient turbulence level from measurements in a number of international wind farms will be compared with calculated predictions of ambient + wake added turbulence. The performance of the models will be compared.

Progress (February 2006)

The combinations of wake and turbulence models have been tested on the wind farm Nørrekær Enge in Denmark. At this stage the models have been using standard settings with the intention of fine tuning these with a sensitivity study. The preliminary results are reported below.

The case: Nørrekær Enge

Nørrekær Enge is a wind farm in the Northern part of Denmark that was erected in 1988-90. When it was erected it was one of the largest of its kind with 36 130 kW and 42 300 kW Nordtank wind turbines. The utility Elsam operates the wind farm and the production is well documented. The turbines are located as illustrated in figure 1 in two groups with an internal spacing of 6-7 times rotor diameter. From 1991 to 1993 two metering masts have collected wind speed and turbulence readings at hub height (31 m). Their location is shown in figure 1. One is located on the southern edge of the wind farm and is thus undisturbed from sector 4 to 8. The second is located inside the wind farm near the east end and is influenced from all directions. With a distance of only 1800 m between the masts in a non complex landscape it is reasonable to assume that the ambient turbulence for the concurrent period is similar. Any additional turbulence at mast 2 from sector 4 to 8 will be wake added turbulence.

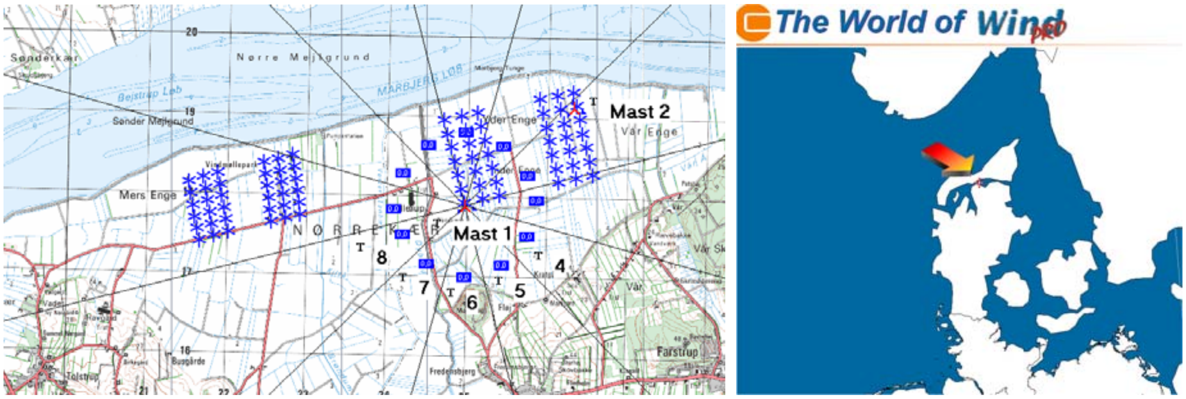


Figure 1. Outline of the test case Nørrekær Enge. The blue symbols are the wind farm, while the red symbols mark the two metering masts. Sector 4-8 are outlined at mast 1.

The measurements

A section of the measurements is isolated where 1) there are concurrent healthy data on both masts and 2) all turbines are in operation. This leaves 24000 measurement points. Turbulence intensity (TI) is calculated from 10 minute mean wind speed readings and standard deviation on same. The TI readings are grouped so mean wind speed and standard deviation is obtained for every 1 m/s wind speed bin and 12 direction bins. From this, representative turbulence is calculated as recommended in IEC 64100 vs. 2 and vs. 3, that is respectively as mean+1*std.dev of TI and as mean+1.28*sts.dev of TI.

Observations from sector 4 to 8 are extracted for the typical wind speeds of 9.5, 14.5 and 19.5 m/s.

Calculation of turbulence

The calculation of wake added turbulence is an integral part of a standard energy production calculation using the WindPRO module PARK. A standard setup for an energy calculation is made using an orographic and roughness description and the wind atlas Danmark 92, which has in previous studies been shown to predict the wind farm production well. Wake models and turbulence models from the list mentioned above is chosen with the appropriate parameter settings. As for ambient turbulence, the readings from mast 1, which is undisturbed in the investigated sectors is imported and used for each sector. This is also used to calculate the wake decay constant for the wake models. The turbulence is calculated for a virtual turbine at the location of mast 2.

The following combinations and parameter settings were tested. “0” means no parameter setting available. Standard parameters are the default parameters used in WindPRO.

Configuration	turbulence model	Parameters	Wake model	Parameters
1	EWTS II	0	N.O. Jensen	0
2	EWTS II	0	EWTS II	1.order
3	EWTS II	0	Eddy vis.	Standard
4	Danish recommendations	Gridded layout	N.O. Jensen, 2005	0
5	Steen Frandsen	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	0
6	Steen Frandsen	Wohler =9, wake prop.=0,06	N.O. Jensen, 2005	0
7	Steen Frandsen	Wohler =12, wake prop.=0,06	N.O. Jensen, 2005	0
8	Steen Frandsen	Wohl =9, wake prop=0,06, large w	N.O. Jensen, 2005	0
9	Quarton	Standard	Eddy Viscosity	Standard
10	B Lange	Standard	Eddy Viscosity	Standard
11	Dutch TNO	Standard	N.O. Jensen, 2005	Standard
12	Dutch TNO	Standard	EWTS II	Standard
13	DIBT	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	Standard

Results

The observed representative (vs.2) TI for mast 1 and mast 2 is shown in figure 2. In some sectors there are no measurements of the higher wind speeds at the mast. Turbulence is higher at mast 2 due to turbulence from the wakes.

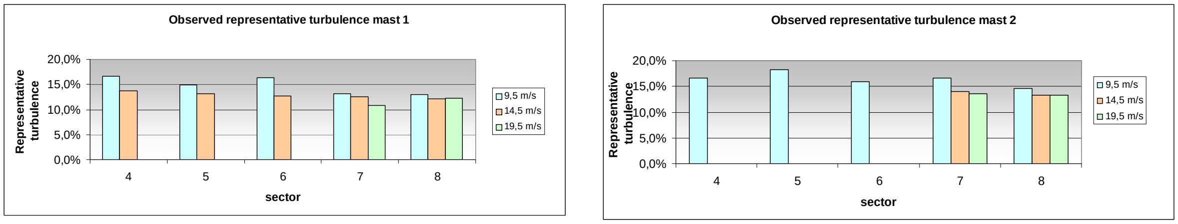
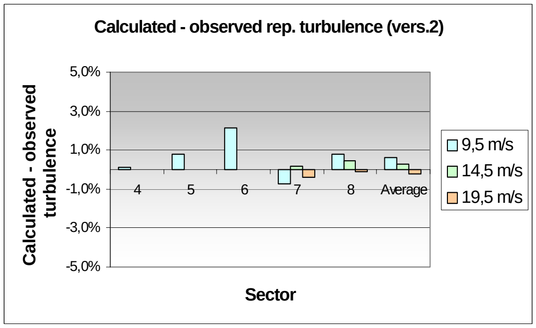
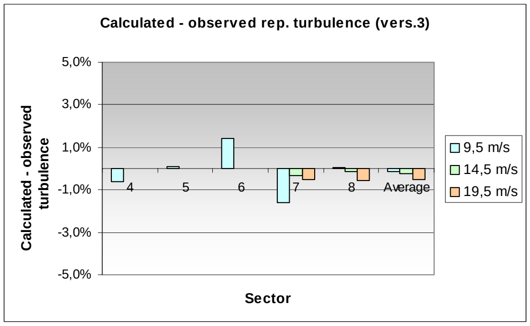


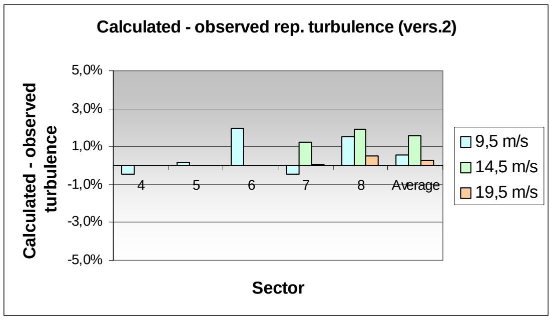
Figure 2. Observed representative (vs.2) turbulence intensity at mast 1 (reference) and mast 2 for three wind speeds and five sectors.

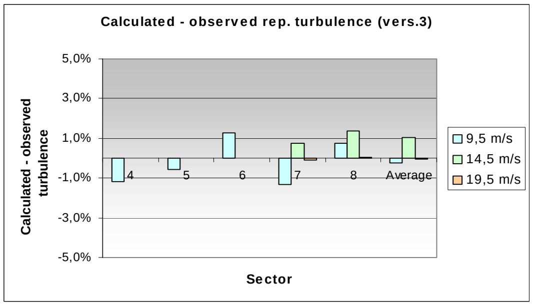
For each of the calculations the difference in calculated TI to the observed TI is plotted for a few representative configurations below. For sector 4 to 6 this is only possible for wind speed at 9.5 m/s. A positive difference of 1% means that the calculation model predicts a turbulence intensity that is 1% higher than observed at mast 2 (eg. 15% vs. 14%).



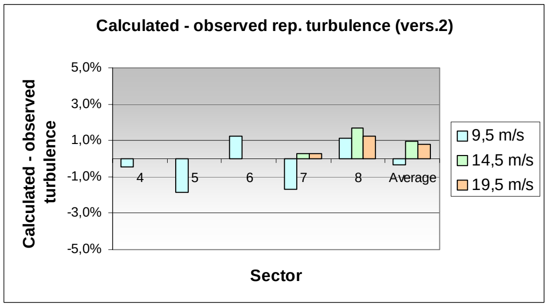


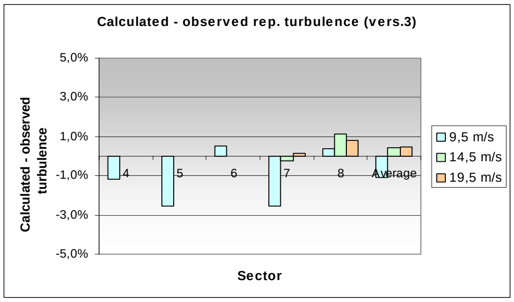
Configuration	turbulence model	Parameters	Wake model	Parameters
2	EWTS II	0	EWTS II	1.order



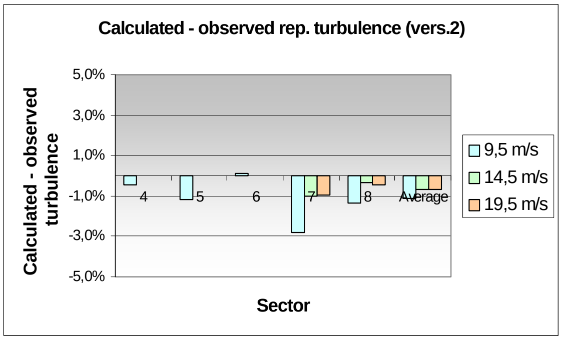


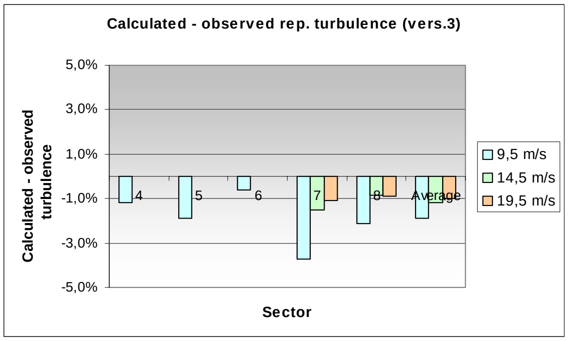
Configuration	turbulence model	Parameters	Wake model	Parameters
4	Danish recommendations	Gridded layout	N.O. Jensen, 2005	0



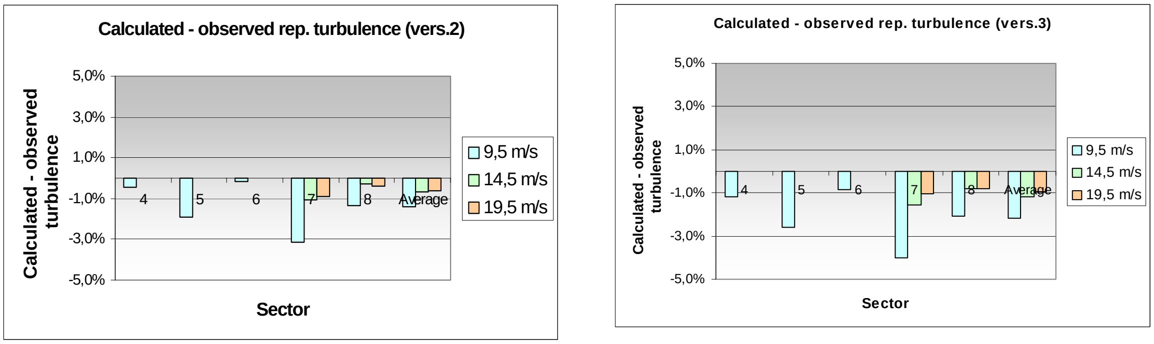


Configuration	turbulence model	Parameters	Wake model	Parameters
5	Steen Frandsen	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	0

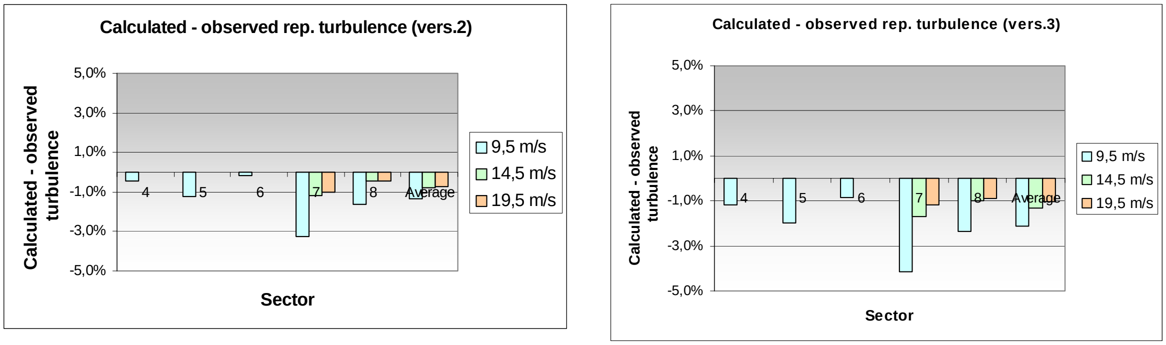




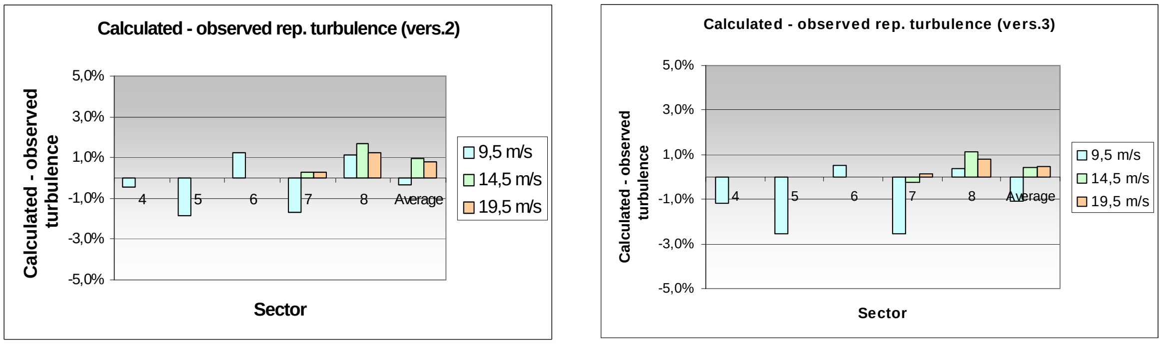
Configuration	turbulence model	Parameters	Wake model	Parameters
9	Quarton	Standard	Eddy Viscosity	Standard



Configuration	turbulence model	Parameters	Wake model	Parameters
10	B Lange	Standard	Eddy Viscosity	Standard



Configuration	turbulence model	Parameters	Wake model	Parameters
11	Dutch TNO	Standard	N.O. Jensen, 2005	Standard



Configuration	turbulence model	Parameters	Wake model	Parameters
13	DIBT	Wohler =3, wake prop.=0,06	N.O. Jensen, 2005	Standard

Figure 3. Difference in calculated TI to the observed TI for some of the calculation configurations.

For some of the configurations the calculated wake added turbulence is closer to the observed representative turbulence as calculated according to version 2, while others are closer with version 3. It can also be seen that the precision varies from sector to sector.

The calculated – observed turbulence results at 9.5 m/s in each sector are illustrated in figure 4 for each of the 13 tested configurations. The number in x axis refers to a turbulence model configuration from the table above. The average figure is an average of all three wind speeds and all sectors.

Where all the models agree in sector 4 where there is no significant wake influence at mast 2, the variation from model to model gets quite significant in the more disturbed sectors. Sector 8 most notably is calculated very differently with the Steen Frandsen turbulence model with a Wöhler curve exponent of 12 (config. nr.7), than with the Dutch TNO turbulence model (config. nr.11 and 12).

The parallel shifts between the sectors could indicate systematic errors in the observed turbulence intensity.

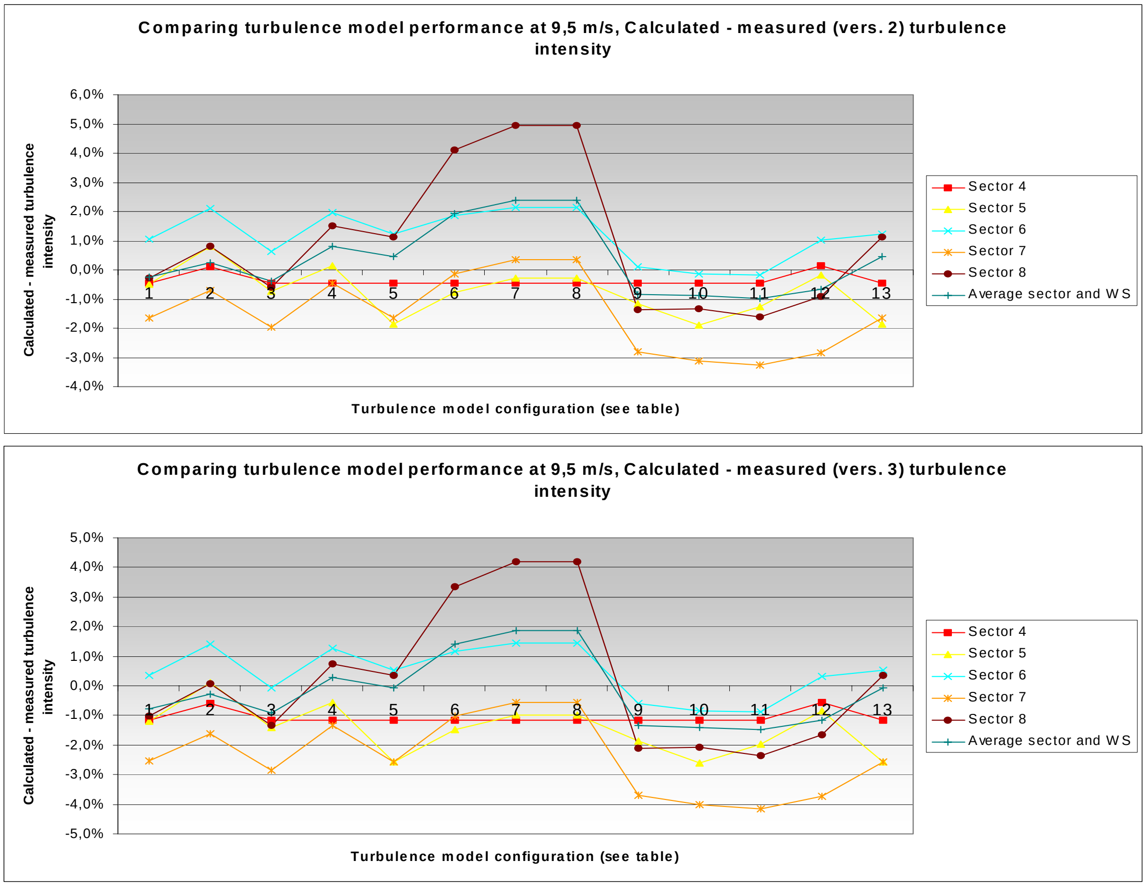


Figure 4. Difference in calculated TI to the observed TI across the configurations tested (please refer to the table) for each sector. The average is an average of all sectors and all three wind speeds.

Conclusion

Testing the different wake added turbulence models and comparing the results with measured data, gives and overview of the model performance in various conditions. This case study begins this work. So far, the following observations based on this example can be made:

Some turbulence models clearly need a parameter calibration, or the user must at least be careful with the parameter settings. The precision varies from model to model, not necessarily with the most advanced being the most precise models.

A case study is very sensitive to the precision of measured turbulence. If the ambient turbulence at the test site is different from the reference site it offsets the results. If a model should be pointed out from this preliminary study then the EWTS II seem to perform better than average.

References

1. Nielsen P, et.al., *The WindPRO manual edition 2.5*, EMD International A/S, 2006.