Modelling the impact of wakes on power output at Nysted and Horns Rev

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Summary

The aim of this research as part of the UpWind project is to improve wind farm modelling and address the issue of providing more accurate power output predictions for wind. Specifically the focus is on wake modelling in large offshore wind farms. Detailed case studies of power losses due to wakes at the large wind farms at Nysted and Horns Rev have been analysed. Despite relatively high stochastic variability in the observational data, similarities in the depth and width of the wake are presented. The case studies are simulated with a range of wind farm and computational fluid dynamics (CFD) models. Results shown indicate power losses due to wakes can be modelled, provided that the standard models are subject to some modifications. We also present some of the first simulations of large offshore wind farms using CFD. Despite this progress, wake modelling of large wind farms is still subject to an unacceptably high degree of uncertainty.

Introduction

As wind farms offshore increase in size, one of the research challenges is to evaluate how to model interactions between the individual turbines, the atmosphere and neighbouring turbines so as to accurately predict power output before wind farm construction. Here we present research from the UpWind project where specific case studies at Nysted and Horns Rev have been simulated with a range of wind farm and CFD models to evaluate wind farm modelling. The UpWind project presents a unique platform for model evaluation because the co-operation of a number of groups means that more models can be evaluated on standardised cases. It is also fortunate that DONG Energy and Vattenfall have allowed data from a number of cases studies to be used in this project.

Preliminary evaluation of the models presented in [1] suggested that standard wind farm models were under-predicting wakes (i.e. over-predicting power output) while computational fluid dynamics models

(CFD) were over-predicting wake losses. Re-evaluation of model parameterisations and constants improved model performance in some cases [2]. However, a wide range of model predictions remains, together with high variability of the observations even for specific and narrow wind speed and direction bins. Some of the difficulty in evaluating models arises from what might be termed 'natural variability' – deviations of wind speed and direction from stationary conditions such as when a front passes or from eddies on varying scales. Part of the difficulty also derives from issues pertaining to measurement error and model limitations [3]. Here we examine a new set of simulations from the two large Danish wind farms.

Observations

The data are from the SCADA systems from the large offshore wind farms at Nysted (2004-2006) and Horns Rev (2005). Figure 1 shows the locations and layouts of the wind farms and Table 1 gives their main features. Further details of the wind farms at Horns Rev can be found in [4] and for Nysted in [5, 6]. The wind farms and wind turbines are of similar size (although turbines at Horns Rev are pitch regulated, while those at Nysted are active stall regulated with two-speed generators). The main issue of interest in wake modelling is to quantify the degree to which differences in turbine spacing impact power losses.

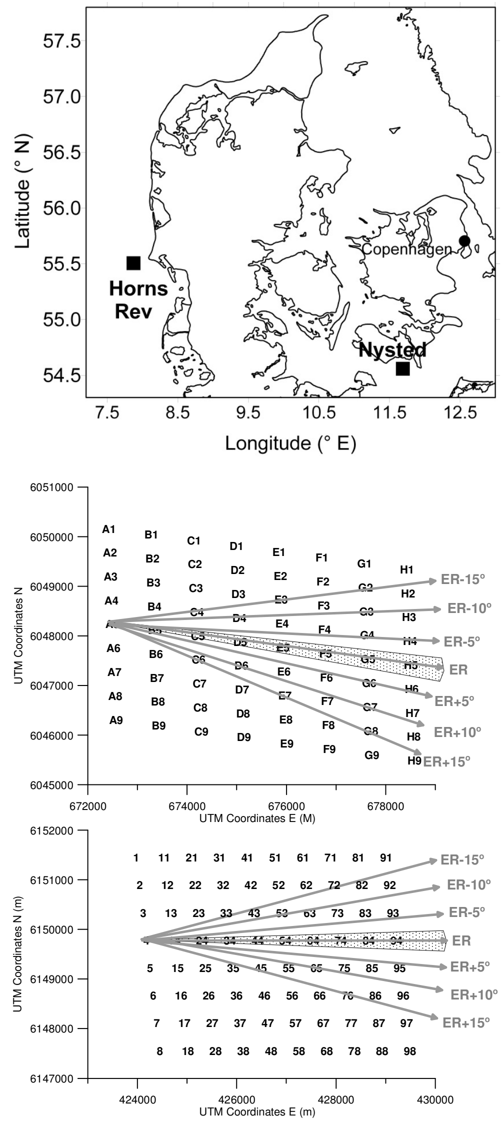

Figure 1. Top: Location of Horns Rev and Nysted wind farms. Middle: Layout of the Nysted wind farm. Bottom: Layout of the Horns Rev wind farm. Grey lines shown on the two wind farm layouts are the directions used for the case studies shown in Figures 3 and 4. Exact Row (ER) denotes a direction with minimum distance between a row of turbines.

Table 1. Comparison of Horns Rev and Nysted wind farms

Wind farm	Nysted	Horns Rev
Owner	DONG Energy (80%) E.On Sweden (20%) [*3]	DONG Energy (40%) Vattenfall (60%) [*1]
Turbine number	72 [*3]	80 [*1]
Turbine	Siemens 2.3 MW [*3]	Vestas 2 MW [*2]
Turbine type	Active stall, 2-speed	Pitch, variable speed
Rotor diameter (D)	82.4 m [*4]	80 m [*2]
Hub-height	69 m [*3]	70 m [*2]
Array	8 (E-W) x 9 (N-S) [*3]	10 (E-W) x 8 (N-S) [*2]
Distance between turbines	10.3 D (E-W) and 5.8 D (N-S) [*4]	7 D (E-W and N-S) [*2]
Rated capacity	166 MW [*3]	160 MW [*1]
Annual production	595 GWh [*4]	600 GWh [*1]
Household supplied	145,000 [*3]	150,000 [*1]
Year commissioned	2003 [*4]	2002 [*2]
Water depth	6-10 m [*3]	6-14 m [*2]
Distance from land	10 km [*4] (closest)	14-20 km [*2]

1 *www.hornsrev.dk*

2 *www.vattenfall.com*

3 *www.nystedhavmoeller*

4 www.eon.se

Data used for model evaluation

To evaluate the ability of the models to predict wake losses, a number of case studies were simulated examining wake losses in the direction of the west-east row which is close to the prevailing wind direction giving a high number of cases. This maximises power losses due to wakes because flow is exactly down the row of turbines see e.g. [2]. Exact flow along the row (shown as ER) corresponds to 270º at Horns Rev and 278º at Nysted.

Subsequently, it was decided to run a series of identical case studies for both Horns Rev and Nysted for a series of direction around ER and these are discussed below. The choice of direction and the variability included are both important. As shown in [3] choosing the exact row angle ±1º includes only the wake centre, ±5º includes the wake centre and about half the wake, extending to ±10º includes most of the wake and beyond ±15º also includes non-wake conditions. This also illustrates the importance of accurate wind direction measurements.

Figure 2 shows a comparison of the case studies for the observed power output at Horns Rev and Nysted when the freestream wind speed is 8.0±0.5 ms^{-1}. Each frame shows the average normalised power for a column of turbines moving through the wind farm from west to east. From ER the direction is then shifted by ±5, 10 and 15º. For each set of observations, directions at the centre angle ±2.5º are included. Recall that these cases should be close to the maximum power loss due to wakes and are not representative of the whole data set.

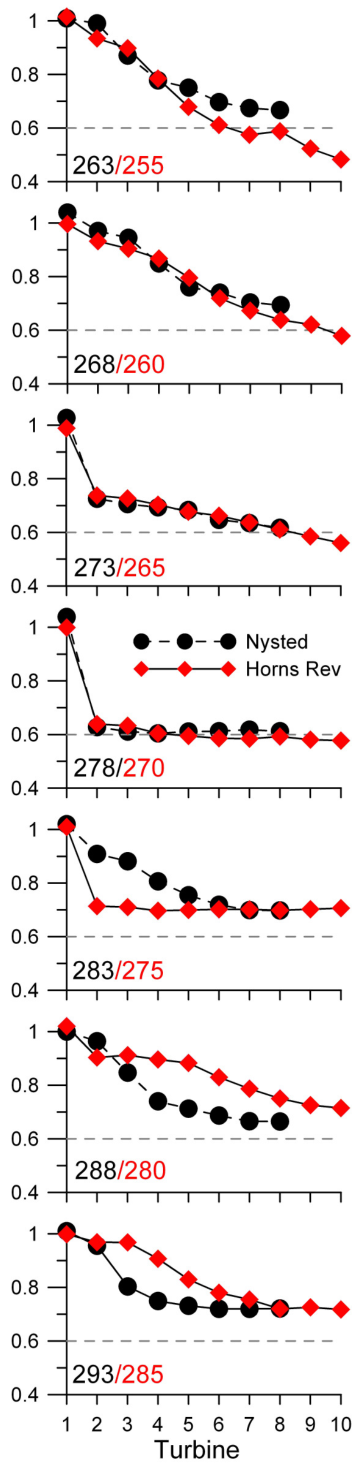

Figure 2. Comparison of normalised power (y-axis) at Horns Rev and Nysted for a wind speed of 8.0±0.5 ms^{-1} and directions as shown (Nysted/Horns Rev) ±2.5º.

The last data selection is that there must be two simultaneous ten minute observations meeting the criteria which attempts to ensure stationarity and removes some errors due to issues like frontal passages. However, this also limits the number of observations in each category. Despite differences in the wind farm layouts (Figure 1), there is considerable agreement between the observed power drop at Horns Rev and Nysted. As discussed above, the observations have been selected to represent each other as closely as possible using the exact row directions and the same wind speeds from both sites. The differences remaining should focus on the different spacing (7x7D) at Horns Rev and (5.8x10.5D) at Nysted, although there may also be some trade off between the turbine spacing in the downwind and lateral directions. Also because the turbine spacing is different the turbine number in Figure 2 does not represent the distance between the turbines. From ER to ER-15º there is agreement between the two data sets and the results indicate that from ER to ER±5º there is no lateral merging but at larger angles lateral merging occurs. At Horns Rev there is also a reasonable amount of symmetry (e.g. compare 265º and 275º) while there are larger differences at Nysted and between for 260º and 280º. For angles from ER to ER+15º there are considerable differences between the two data sets which may arise from processing and merit further investigation. Power observations from Nysted and Horns Rev for wind speeds of 6.0±0.5 ms^{-1} and 10.0.0±0.5 ms^{-1} show similar discrepancies.

Models

There are essentially two types of models that are used to estimate power losses due to wakes. One is a wind farm model using a wake model that has been simplified or parameterised in order that description of wind farm resources and wakes can be made relatively quickly. Industry standard models typically fall into this category giving average results at individual turbine locations. The second is a CFD type model which solves basic equations of the atmosphere and produces results on a fine mesh in space and time. Despite considerable progress, these are currently too computing/time intensive to be used in most industry applications. An overview of the models used in this project is given in Table 2.

Table 2. Overview of models used in the UpWind wakes research

Name	Company	Reference
WAsP	Risø DTU	[7], [8]
GH WindFarmer	Garrad Hassan	[9]
Linearized Flow	Risø DTU	[10], [11, 12],[13]
Wakefarm (ECN)	ECN	[14]
CENER Fluent	CENER	[15],[16]
NS FLow	CRES	[17]
NTUA	NTUA	[17]

Case studies: Horns Rev and Nysted

Data from the case studies were simulated for both Horns Rev and Nysted. For Horns Rev these are 'Round 2' results so for both Windfarmer and the ECN model results could be optimised to the data. Results from the NTUA model are the first results from the full CFD code run for three central rows. These models and the observations were analysed for ±2.5º sectors. For the WAsP results, no optimisation was used, the wake decay coefficient was set to 0.04 and the simulations are for a ±5º sector.

Figure 3 shows results from Horns Rev and illustrates good model agreement in most directions. As noted above, there is asymmetry in the observations which is not reflected by the models and for 255º appears to be a data issue (see Figure 5). ECN and GH models appear to capture shape of the wake as it moves through the wind farm.

Figure 4 shows results from Nysted. Again there is reasonable agreement between the observations and the models but with a high degree of variability. WAsP appears to be predicting a narrower wake than observed.

One of the main issues lies in the data processing. Although we have developed a procedure for analysing the data, the results are still highly dependent on how data are selected and this leads to a high degree of uncertainty in the model comparisons. Also, the standard deviation of the observations is relatively large (see Figures 3 and 4) ranging from 0.15 to 0.35 at Nysted and 0.11 to 0.32 at Horns Rev.

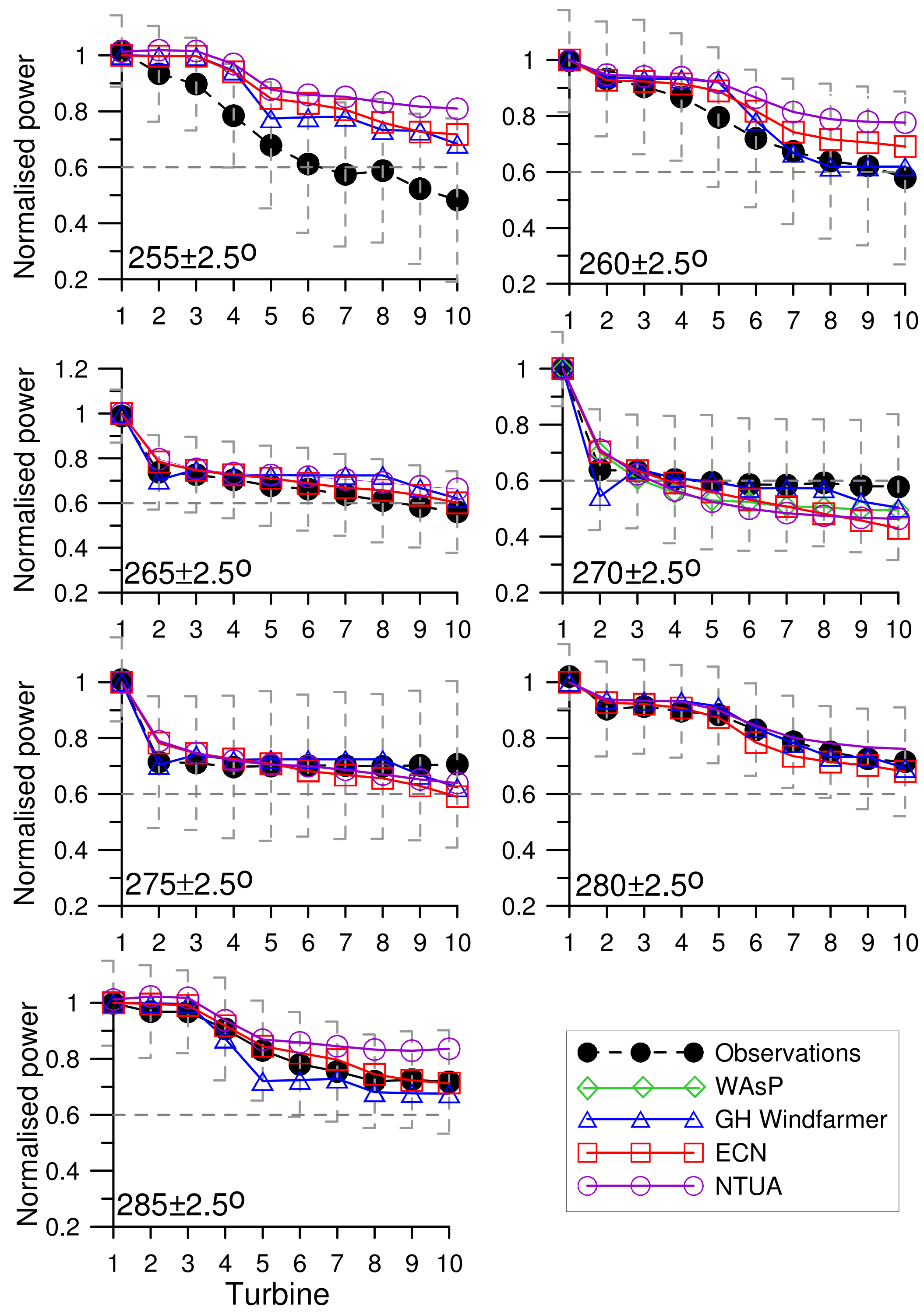

Figure 3. Case studies of normalised power at Horns Rev: comparison of models with observations for U=8.0±0.5 ms^{-1}. Error bars shown are ± one standard deviation of the observations. Note that observations, NTUA, GH WindFarmer and ECN simulations are ±2.5º the centre angle but WAsP simulations are ±5º.

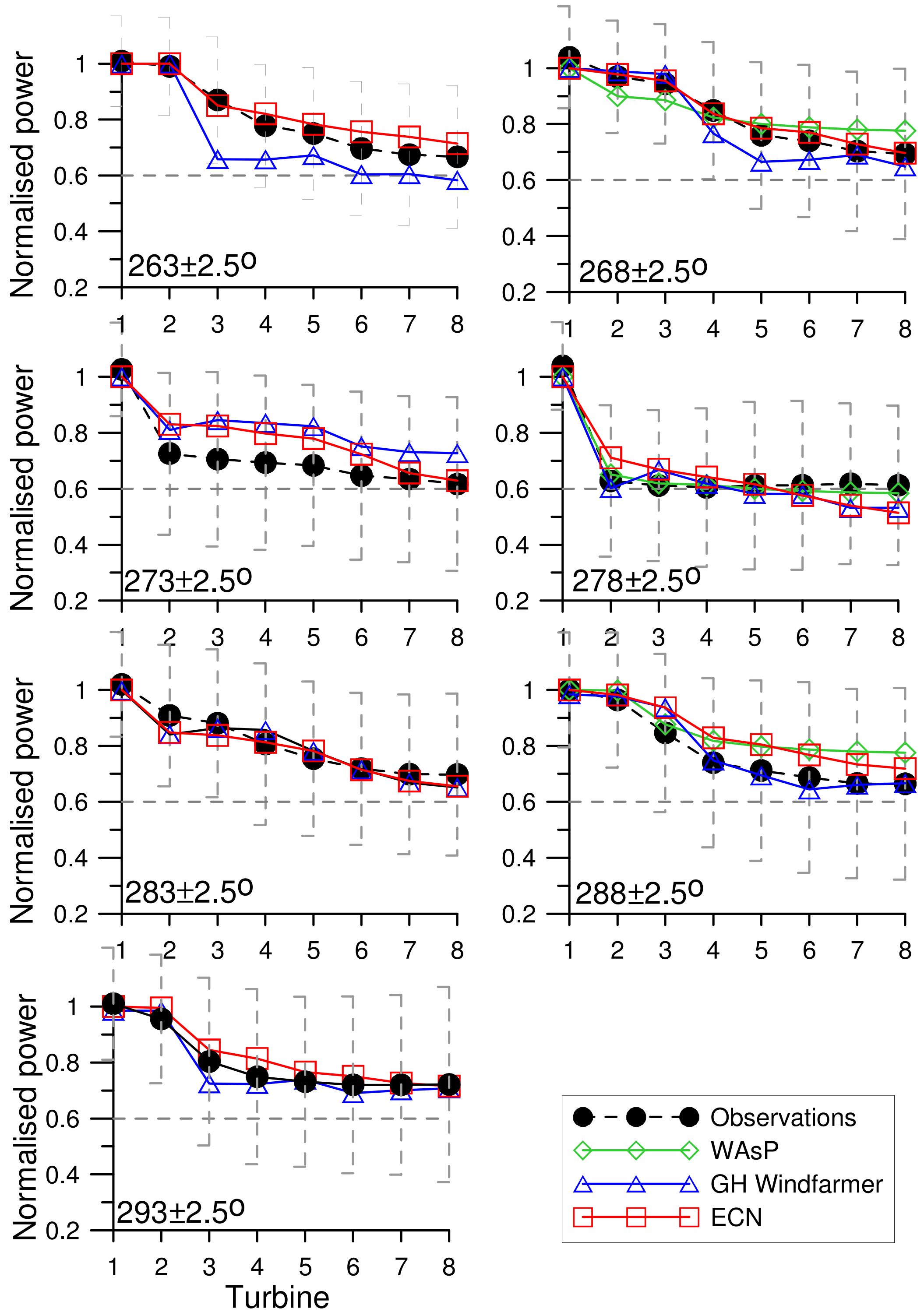

Figure 4. Case studies of normalised power at Nysted: comparison of models with observations. Error bars shown are ± one standard deviation of the observations. Note that observations, GH WindFarmer and ECN simulations are ±2.5º the centre angle but WAsP simulations are ±5º.

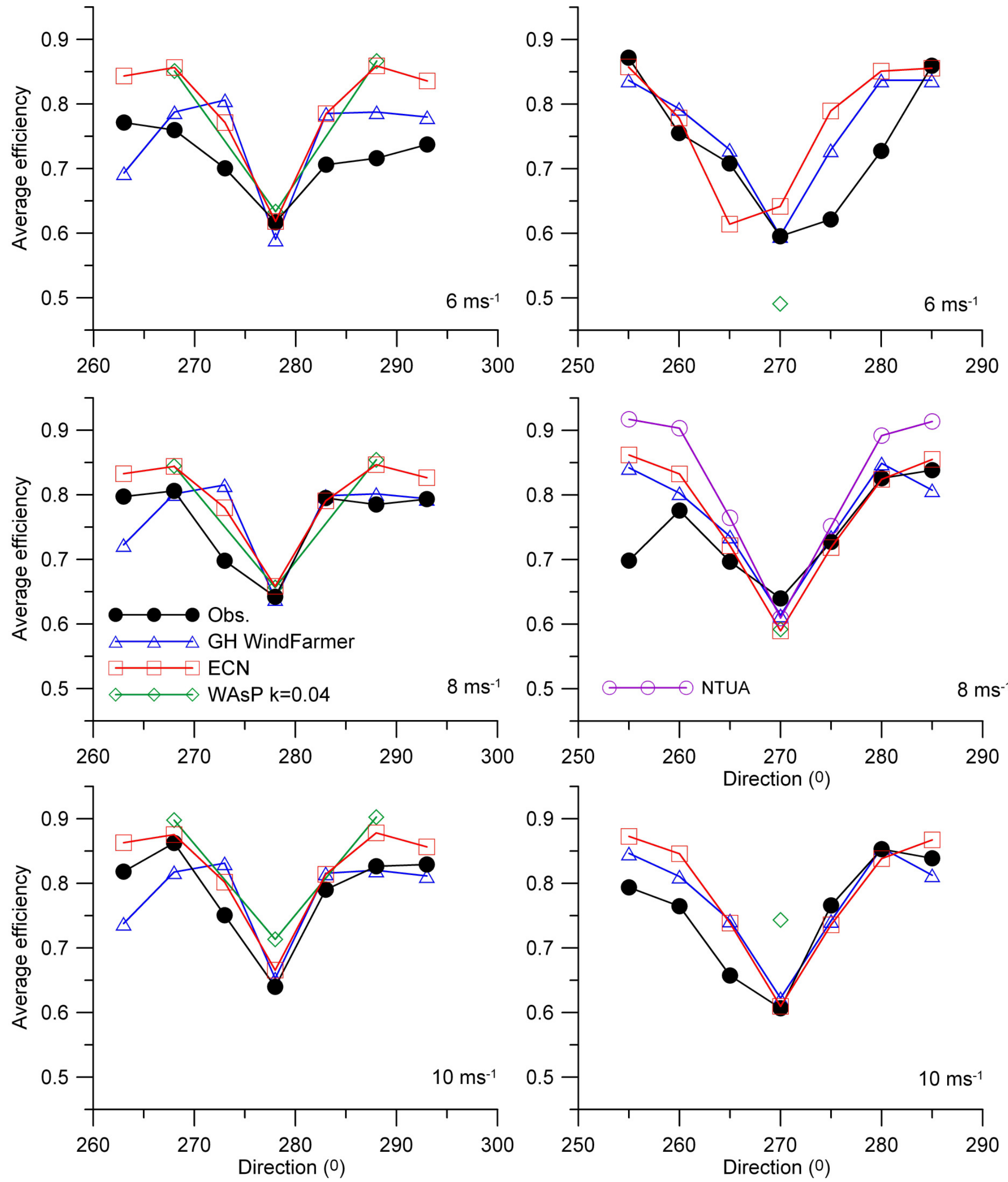

Figure 5. Average efficiency by direction (±2.5º). Left: Nysted. Right: Horns Rev.

Wind farm efficiency

It is difficult to find a single metric which numerically describes the model agreement with observations. Here we use the wind farm efficiency, e, defined as:

$$e = \frac{1}{n}\sum_{t=1}^{n}\frac{p_t}{p_0}$$

Where p_t is the power of each turbine,
p_0 is the power of the freestream turbine and,
n is the number of turbines in the wind farm.

Efficiencies are shown by model for each direction and wind speed class in Figure 5.

All of the models do a good job predicting the wind farm efficiency at Nysted for both 8 and 10 ms^{-1}, with less agreement away from the wake centre for 6 ms^{-1}. At Horns Rev the results are more variable but there is also more uncertainty in the data because there are fewer observations (one year of data rather than two). At 8 ms^{-1} and 10 ms^{-1} the results from the ECN and GH models are consistent in the wake centre and likely within data uncertainty for the other directions. WAsP seems to be performing well at 8 ms^{-1} but giving very different results for the other wind speeds. Given this was not the case for Nysted it suggests there may have been an error in the model application. Results from NTUA (for Horns Rev at 8 ms^{-1}) are particularly impressive given that this is the first application of CFD to multiple turbines in multiple rows.

Asymmetry in the observations and in some of the model results requires further investigation. An example is for the data from Horns Rev at 8 ms^{-1} at 255º which may be due to the limited number of observations which meet all of the data selection criteria.

Conclusions

Offshore data sets provided by DONG, Vattenfall and E.OnSweden comprise case studies at Horns Rev and Nysted. We focus on the prevailing westerly flow direction for a range of wind speed bands between 5 and 11 ms^{-1}. The two data sets show broad similarities as expected in terms of wake depth and width although the layout of the two wind farms in terms of turbine spacing is different. Despite considerable care in data processing and selection, the standard deviation of the normalised power for the average turbine in the row remains relatively high. In general when looking at power output for these low to moderate wind speeds and for flow down the row of turbines, wake losses are maximised and are not typical of the data set as a whole. Our model simulations are able to capture power losses in the row to some degree and also the wind farm efficiencies for a range of directions although the uncertainty bands on both models and data are large. Some of the models have been optimised for the data sets and show a good degree of agreement whereas more work remains to be done with some of the other models. In particular the first simulations with CFD to a multi-turbine, multi-row wind farm is very promising.

Acknowledgements

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References

1. Barthelmie RJ, G Schepers, S van der Pijl, O Rathmann, ST Frandsen, D Cabezón, E Politis, J Prospathopoulos, K Rados, K Hansen, W Schlez, J Phillips and A Neubert. *Flow and wakes in complex terrain and offshore: Model development and verification in UpWind*. in *European Wind Energy Conference*. 2007. Milan.

2. Barthelmie RJ, ST Frandsen, O Rathmann, K Hansen, E Politis, J Prospathopoulos, D Cabezón, K Rados, S van der Pijl, G Schepers, W Schlez, J Phillips and A Neubert. *Flow and wakes in large wind farms in complex terrain and offshore*. in *European Wind Energy Conference*. 2008. Brussels.
3. Barthelmie RJ, K Hansen, ST Frandsen, O Rathmann, JG Schepers, W Schlez, J Philips, K Rados, A Zervos, ES Politis and PK Chaviaropoulos, *Modelling and measuring flow and wind turbine wakes in large wind farms offshore.* Wind Energy, 2009. **WE-08-0099**.
4. Jensen LE, C Mørch, PB Sørensen and KH Svendsen. *Wake measurements from the Horns Rev wind farm*. in *European Wind Energy Conference*. 2004: EWEA (on CD).
5. Barthelmie RJ, ST Frandsen, PE Rethore and L Jensen. *Analysis of atmospheric impacts on the development of wind turbine wakes at the Nysted wind farm*. in *European Offshore Wind Conference*. 2007. Berlin 4-6 December 2007.
6. Cleve J, M Grenier, P Enevoldsen, B Birkemose and L Jensen, *Model-based analysis of wake-flow data in the Nysted offshore wind farm.* Wind Energy, 2009. **DOI: 10.1002/we.314**.
7. Mortensen NG, DN Heathfield, L Myllerup, L Landberg and O Rathmann (2005) *Wind Atlas Analysis and Application Program: WAsP 8 Help Facility*. Risø National Laboratory, Roskilde, Denmark. 335 topics. ISBN 87-550-3457-8, http://www.risoe.dk/vea/projects/nimo/WAsPHelp/Wasp8.htm.
8. Rathmann O, RJ Barthelmie and ST Frandsen. *Wind turbine wake model for wind farm power production.* in *European Wind Energy Conference*. 2006. Athens.
9. Schlez W, A Neubert and G Smith. *New developments in precision wind farm modelling*. in *Deutsche Windenergie Konferenz*. 2006. Bremen.
10. Ott S. *Applying flow models of different complexity for estimation of wind turbine wakes*. in *European Wind Energy Conference and Exhibition*. 2009. Marseilles.
11. Frandsen ST, RJ Barthelmie, O Rathmann, HE Jørgensen, J Badger, K Hansen, S Ott, PE Rethore, SE Larsen and LE Jensen, *Summary report: The shadow effect of large wind farms: measurements, data analysis and modeling*. 2007, Risø National Laboratory/DTU:Risø-R-1615(EN). Roskilde. p. 34.
12. Frandsen ST, HE Jørgensen, RJ Barthelmie, O Rathmann, J Badger, K Hansen, S Ott, PE Rethore, SE Larsen and LE Jensen. *The making of a second-generation wind farm efficiency model-complex*. in *European Wind Energy Conference* 2008. Brussels.
13. Berg J and S Ott. *A new linearised flow model for complex terrain*. in *European Wind Energy Conference*. 2009. Marseille.
14. Schepers JG, *ENDOW: Validation and improvement of ECN's wake model*. 2003, ECN:ECN-C--03-034 (March 2003). Petten, The Netherlands. p. 113.
15. Cabezón D, A Iniesta and E Ferrer. *Comparing linear and non linear wind flow models*. in *Proceedings of the European Wind Energy Conference EWEC 2006,* Athens.
16. Cabezón D, J Sanz, I Martí and A Crespo. *CFD modelling of the interaction between the Surface Boundary Layer and rotor wake. Comparison of results obtained with different turbulence models and mesh strategies.* in *European Wind Energy Conference and Exhibition 2009*. 2009. Marseille, March 2009.
17. Politis ES, K Rados, JM Prospathopoulos, PK Chaviaropoulos and A Zervos. *CFD modeling issues of wind turbine wakes under stable atmospheric conditions*. in *European Wind Energy Conference*. 2009. Marseille, March 2009.