

Flow and wakes in large wind farms in complex terrain and offshore

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1 Abstract

Power losses due to wind turbine wakes are of the order of 10 and 20% of total power output in large wind farms. The focus of this research carried out within the EC funded UPWIND project is wind speed and turbulence modelling for large wind farms/wind turbines in complex terrain and offshore in order to optimise wind farm layouts to reduce wake losses and loads.

For complex terrain, a set of three evaluations is underway. The first is a model comparison for a Gaussian Hill where CFD models and wind farm models are being compared for the case of one hill-top wind turbine. The next case is for five turbines in flat terrain. Finally a complex terrain wind farm will be modelled and compared with observations.

For offshore wind farms, the focus is on cases at the Horns Rev wind farm which indicate wind farm models require modification to reduce under-prediction of wake losses while CFD models typically over-predict wake losses. Further investigation is underway to determine the causes of these discrepancies.

The project therefore represents a set of unique evaluations of models with observations in different environments. Progress towards improving wind farm models will be described.

2 Introduction

Wind farms being developed are large and often in complex terrain, close to forests or offshore. There is a need for further research to examine the performance of wind farm and wake models in these more difficult environments. In ideal circumstances, wind and turbulence would be predicted on a fine mesh (horizontal and vertical) for the whole wind farm over a range of wind speeds and directions for a long time period. There is a gap between engineering solutions and computational fluid dynamics (CFD) models and a bridge is needed between these in order to provide more detailed information for modelling power losses, for better wind farm and turbine design and for more sophisticated control strategies and load calculations. This is the focus of our work within the UPWIND projects that aims to develop the next generation of large wind turbines.

3 Measurements

For evaluating wakes there are essentially two types of measurements; meteorological and wind farm data. Meteorological data can be divided into two types – mast and sodar/lidar data. The advantage of meteorological mast data is; it is available for a long period, it is accurate and wind speed, direction and turbulence profiles to hub-height are available at a good time resolution and with high data capture. The most obvious disadvantage is that the location of the measurements is giving fixed

wake distances. Measurements are rarely made above hub-height. Both sodar and doppler lidar are able to measure wind speed profiles both beyond and above hub-height and may be particularly useful offshore due to the expense of erecting tall meteorological masts e.g. [1].

Obviously for wake studies in large wind farms, wind farm data are needed. Parameters include power output, nacelle direction and yaw misalignment and a status signal. These data are routinely collected using Supervisory Control And Data Acquisition (SCADA) systems although storage and retrieval of these data for research purposes may be a time consuming process. A more significant issue is that all wind farm data are typically confidential and developers are reticent to share raw data. This is a big issue in model evaluation exercises where data are necessary and also by the nature of the exercise many different groups are involved. Nevertheless it is clear that access to data is critical at this point while the wind farm model evaluation for more challenging environments is conducted. In the POWWOW project, a virtual laboratory has been developed to allow other users of wake models access to data from offshore wind farms which can be made public and to results from wind farm models with which they can compare their own modelling. To date, access has been given to data from Vindeby, Middelgrunden and Horns Rev and may be expanded to incorporate more data and model simulations. Users can register and access the wiki at www.see.ed.ac.uk/powwowwiki.

Power loss modelling should encompass the whole range of wind speeds and directions. In general, computing requirements for CFD models means we are restricted to examining a number of specific wind speed and direction cases and only a moderate number of turbines rather than wind farms with ~100 turbines which can easily be done by wind farm models. On the other hand it can be difficult to extract reasonable simulations from some of the wind farm models for very specific cases when models are being used beyond their operational windows. In addition to this there are a number of specific issues relating to wake measurements:

- Establishing the freestream flow
- Wind direction, nacelle direction and yaw misalignment
- Wind speed gradients across the wind farm
- Accuracy of the site specific power curve and thrust
- Time averaging between models and measurements
- Natural fluctuations in the wind speed and direction in any period
- Wake transport time through the wind farm
- Turbulence intensity and atmospheric stability

4 Models

The model comparison in Section 5 (Complex Terrain) and Section 6 (Offshore) uses the full spectrum of models from whole wind farm codes which use moderately simple wake models to full CFD models. Models are listed below in approximate order of complexity from the simplest (in terms of wake modelling) to the most complex.

WAsP from RISØE

The Wind Atlas Analysis and Application Program (WAsP) is based on a linearised model used in the European Wind Atlas. The WAsP program [2] uses meteorological data from a measurement station to generate a local wind climate from which the effects of obstacles, roughness and complex terrain have been removed. To produce a wind climate for a nearby wind farm or wind turbine site these local effects are reintroduced. In terms of wind farm modelling the wake model in the commercial version is based on [3]. A new wake model ('Mosaic tile') is being developed for use within WAsP [4]. The main advantage of the program is that it is fast and robust. It does not model flow in complex terrain if flow separation occurs although there are methods for improving its predictions in complex terrain [5]. For the simulations discussed below it is important to note that the program is being used in a way which is not recommended.

WindFarmer from GH

In this project the ambient wind speed distribution and boundary layer profile is

calculated by an external wind flow model, WAsP. The wind turbine wake model (based on Ainslie [6]) then makes use of these data superimposing the effect of the offshore wind farm. The initial wake is a function of the wind turbine dimensions, thrust coefficient and local ambient wind speed and turbulence. The eddy viscosity wake model in GH WindFarmer is a CFD calculation representing the development of the velocity deficit using a finite-difference solution of the Navier-Stokes equations in axis-symmetric co-ordinates. The eddy viscosity model thus automatically observes the conservation of mass and momentum in the wake. An eddy viscosity turbulence closure scheme is used to relate the shear stress to gradients of velocity deficit. Empirical expressions are used to model the wake turbulence [7] and the superposition of several wakes that are impacting on one single location. Multiple wakes are calculated by consecutive downstream modelling of individual wakes. Due to the empirical components in GH WindFarmer it is possible to model typically 7200 wind speed and directional scenarios needed for a complete energy assessment of a wind farm in reasonable time. The model has performed well in all environments, including small offshore wind farms [8]. For very large wind farms, the boundary layer profile is modified by the presence of wind turbines. One approach to account for this is to represent the wind farm area by area of higher roughness [9].

WAKEFARM from ECN

ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Polytechnica de Madrid. It is based on parabolized Navier-Stokes equations. Turbulence is modelled by means of the k-epsilon turbulence model. Through the parabolization of the governing equations it is assumed that there exists a predominant direction of flow and that the downstream pressure field has little influence on the upstream flow conditions. These assumptions no longer hold in the near wake where additional modelling is necessary. In the present project a hybrid method is used which is still based on the WAKEFARM model but the near wake expansion and flow-deceleration is accounted for directly. This is achieved by an analogy with the boundary-layer

equations. The (axial) pressure gradients are prescribed as external forces and enforce the flow to decelerate and the wake to expand in the near wake. A free vortex wake method is used to compute these pressure gradient terms a priori.

CENER

The model, based on the commercial CFD code Fluent, allows simulating the rotor effect over the flow as axial momentum sources assigned to the cells corresponding to the rotor volume. The forces are calculated as a function of the thrust coefficient, the incident wind speed and the rotor area. As input, the model needs basic wind farm data including, among others, the thrust coefficients of the wind turbines as well as the surrounding topography. For a certain wind direction, the description of the wake is obtained through the calculation over the whole domain of the general fluid equations in its RANS form with a k- ϵ turbulence closure scheme.

CRES-flowNS from CRES

The governing equations are numerically integrated by means of an implicit pressure correction scheme, where wind turbines are modelled as momentum absorbers by means of their thrust coefficient [10]. A matrix-free algorithm for pressure updating is introduced, which maintains the compatibility of the velocity and pressure field corrections, allowing for practical unlimited large time steps within the time integration process. Spatial discretization is performed on a computational domain, resulting from a body-fitted coordinate transformation, using finite difference/finite volume techniques. The convection terms in the momentum equations are handled by a second order upwind scheme bounded through a limiter. Centred second order schemes are employed for the discretization of the diffusion terms. The Cartesian velocity components are stored at grid-nodes while pressure is computed at mid-cells. This staggering technique allows for pressure field computation without any explicit need of pressure boundary conditions. A linear fourth order dissipation term is added into the continuity equation to prevent the velocity-pressure decoupling. To accommodate the large computational grids needed in most applications for a fair discretization of the topography at hand, a multi-block version of the implicit solver has

been developed. Turbulence closure is achieved using the standard $k-\omega$ model [11], suitably modified for atmospheric flows.

NTUA

NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy. The model [12] (see also [13]) assumes Cartesian grids, uses the $k-\epsilon$ turbulence closure model and accommodates wind turbines embedded in its grid as momentum sinks representing the force applied on the rotor disk that is in turn evaluated from the local thrust coefficient. NTUA has performed preliminary offshore wake calculations for the Horns Rev Wind Farm.

5 Complex terrain cases

Three model simulation types are planned to compare the performance of the CFD models with wind farm models where appropriate. To date, the first set is complete and the second underway. The third is not described further here.

- Simple terrain (Gaussian Hill). Simulations shown in [14] and summarised below.
- Five turbines in flat terrain.
- The complex terrain wind farm. A real wind farm located in a moderately complex terrain is proposed for the comparison and validation of wake models. The study represents a first attempt of comparing and validating the existing wake models on a real moderately complex site and with wind farm measurements.

5.1 Gaussian Hill

The idealized simulation of a single wake in the case of a Gaussian hill constitutes the basis for the comparison of the wake characteristics between flat and complex terrain. The different configurations were simulated with one wind turbine at hilltop and without the wind turbine (to provide the value of wind speed at the wind turbine position for the calculation of the actuator disk force as well as the reference velocity field for the evaluation of the wind speed deficit). The turbine is a 5 MW theoretical

turbine with a diameter (D) of 126 m and 90 m hub height. The input wind velocity profile is assumed logarithmic with 500 m boundary layer height and 10m/s velocity at hub height. Three different levels of turbulence intensity (5%, 13% and 15%) and six different wind directions ($0, \pm 15^\circ, \pm 30^\circ$) were examined. Although there are differences between the two CFD model simulations (Figure 1) the following points can be summarised:

- The wind speed deficit remains significant even 20D downstream from the wind turbine
- Wind speed deficit at hub height is not decreasing smoothly with distance
- Increasing TI results in a faster flow recovery at long distances
- The wind speed deficit decays much faster in flat terrain.

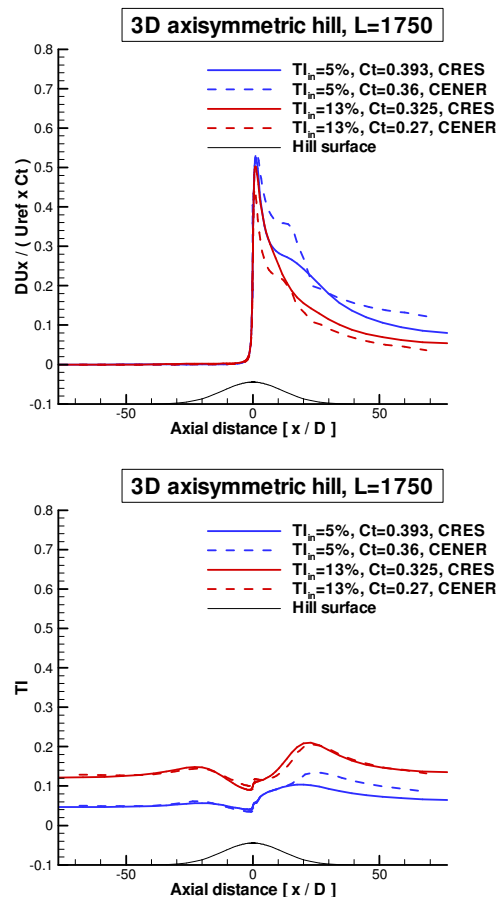


Figure 1. Comparison of two CFD model simulations for the Gaussian Hill. Top: velocity deficit. Bottom: Turbulence intensity.

5.2 Five turbines in a row

In flat terrain wind parks, wind turbines are often aligned in parallel rows, which means that turbines are often partially or completely situated in the wake of a neighbouring wind turbine. In order to estimate the effect of a neighbouring wake on the wind turbine efficiency, multi-wake simulations are needed.

Eventually simulations will be compared with observations. Initially, however, simulations were made to evaluate the impact of the thrust coefficient C_t and turbulence intensity TI . One multi-wake case, probably the worst in terms of efficiency, is simulated: Five subsequent wind turbines positioned one behind the other. A parametric analysis is done for different values of the distance between the wind turbines (3, 5 and 7D, with D being the wind turbine rotor diameter) and different values of C_t (0.3, 0.5 and 0.7). The level of inlet TI at hub height is set equal to 13%. In this manner, the effects of the intermediate distance and the C_t are assessed.

It is noted that the velocity deficit at a (x, y, z) point is expressed in dimensionless form as:

$$\frac{DU}{U_{ref} \times C_t} = \frac{U_{ref}(z) - U_x(x, y, z)}{U_{ref}(z) \times C_t},$$

where U_x is the local axial velocity and U_{ref} is the inlet velocity at height z .

In Figure 2, the axial variation of the velocity deficit at hub height is represented for the case of five wind turbines with the distance between the machines varying from 3D to 7D. For high values of C_t ($C_t=0.7$) the increase of the velocity deficit at the following (2^{nd} - 5^{th}) wind turbines is not significant even when the distance between the machines is small (3D). However, for lower values of C_t there is a significant increase in the deficit of the second wind turbine which is greater if the wind turbines are more closely spaced (3D). In general, there is no significant increase in the velocity deficit after the third wind turbine. High values of the turbulence intensity for the five wind turbines case are observed. In comparison to the one wind turbine case, the level of maximum turbulence intensity is almost doubled (Figure 3).

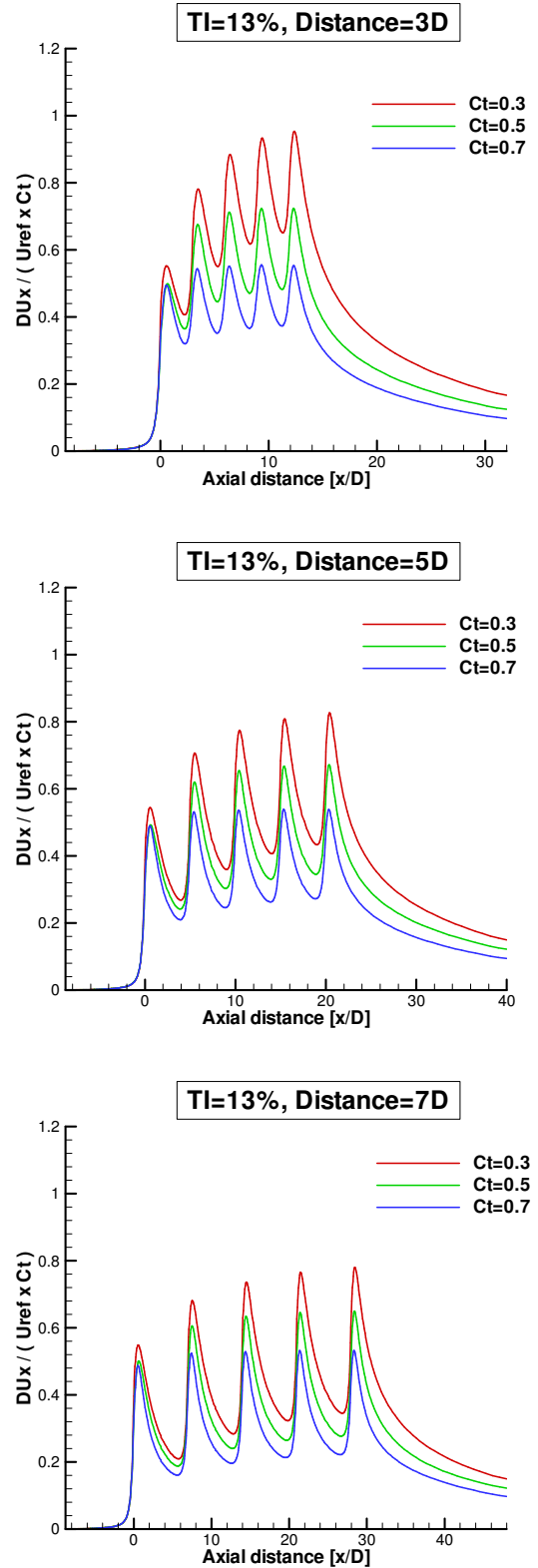


Figure 2: CFD simulations of five wind turbines in flat terrain. Distance between wind turbines is from the top panel down 3D, 5D and 7D and inlet turbulence intensity at hub height is 13%.

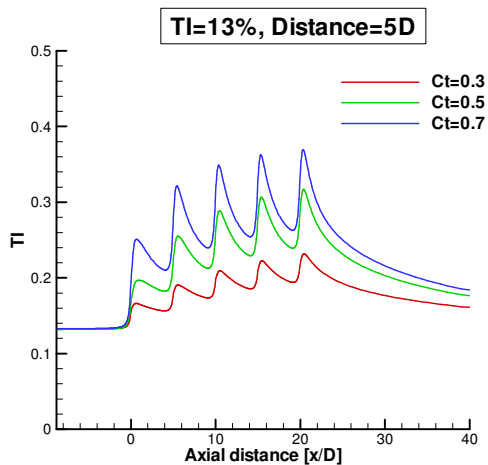


Figure 3: 5W/Ts in flat terrain – Effect of C_t on T_I at hub height. Distance between W/Ts is 5 D and inlet T_I at hub height is 13%.

6 Wake modelling offshore

The main issue for the current project is that there appears to be a fundamental difference between the behaviour of wakes in small offshore wind farms where standard models perform adequately [15] and those in large multi-row wind farms where current wind farm models appear to under-predict wake losses [16]. It can be postulated that this is due to the interaction of turbulence generated by wind turbines wakes with the overlying atmosphere [17] and that a new generation of models is required to deal with this complex interaction of wakes with each other and the boundary-layer [18].

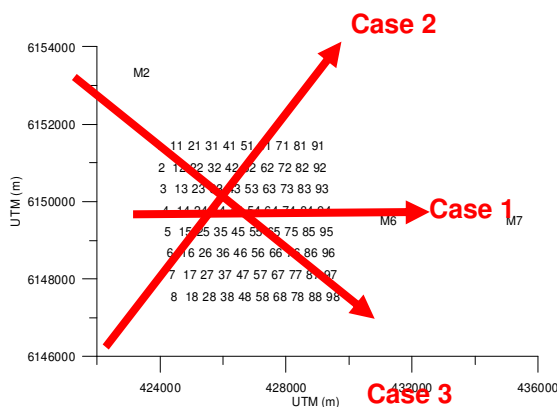


Figure 4: Horns Rev layout including definition of Case 1 (7D), Case 2 (9.4D) and Case 3 (10.5D) flow directions. Turbine locations are given by numbers and the location of the meteorological masts are marked with MX.

6.1 Wake modelling

A number of flow cases have been defined for the Danish offshore wind farm Horns Rev that is owned by DONG Energy A/S and Vattenfall AB, consisting of 80 Vestas V80 wind turbines located in a 8 by 10 grid, with a basic spacing of 7D as shown in Figure 4 [19].

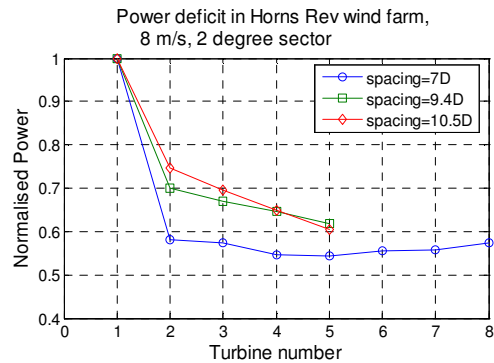


Figure 5: Observed power deficit inside Horns Rev wind farm for $V=8\pm 0.5$ m/s inflow for different spacing.

Electrical power, nacelle position and wind turbine status signals have been extracted from the SCADA system with a reference period of 10-minutes and merged with meteorological measurements from three masts (M2, M6 and M7). The undisturbed power values are used to define 3x3 flow cases, corresponding to wind speeds levels of 6 ± 0.5 , 8 ± 0.5 and 10 ± 0.5 m/s, which are combined with three different spacings 7 D, 9.4 D and 10.5 D (Figure 5). The offshore wind farm at Horns Rev is characterized with low turbulence ($< 8\%$) and many operational hours in near neutral stability. The mean deficit along a row of turbines has been calculated and presented in Figure 6 for different wake widths. The wind speed calculated from the power output of the first turbine is 8 ± 0.5 m/s. At these low to moderate wind speeds, the thrust coefficient is relatively high. Thus the wake losses shown are likely to be the most severe but wind directions in the relatively narrow wind direction bins will also occur relatively infrequently. The major finding is an almost constant power loss to about 60% of freestream values during the pure wake situation for a very small sector of 2° . If larger wake widths are considered the deficit decreases down wind. This is due in part to the wake shape as illustrated in Figure 7.

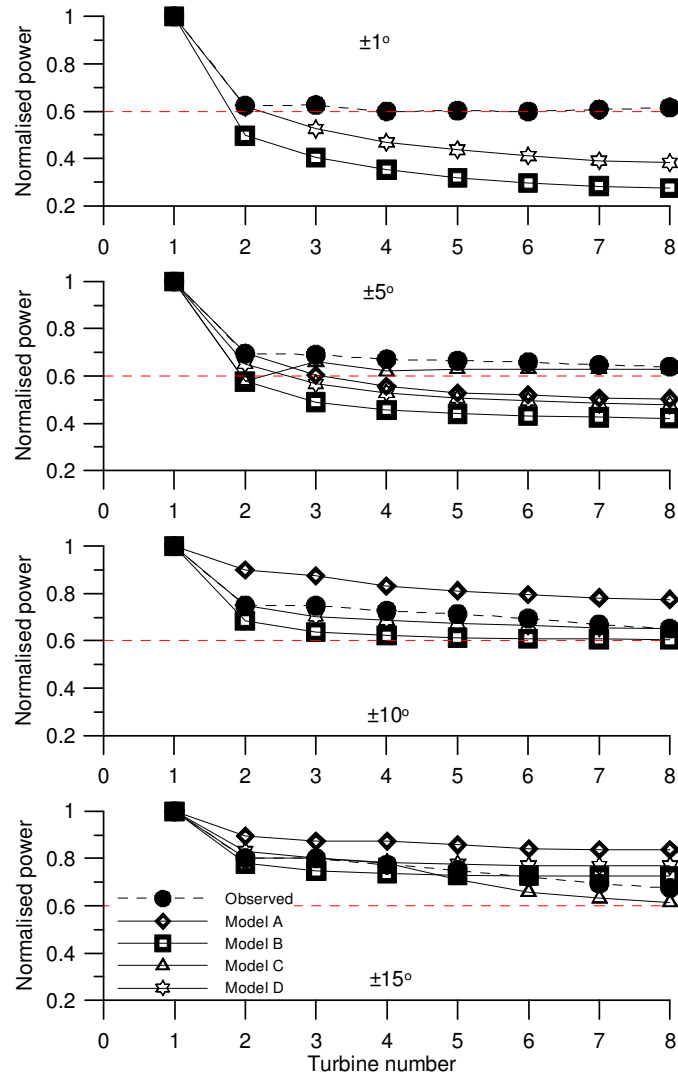


Figure 6: Comparison of models and measurements for Horns Rev (direction 270°, case 1 in Figure 2) for 8 ± 0.5 m/s for different widths of wake sectors.

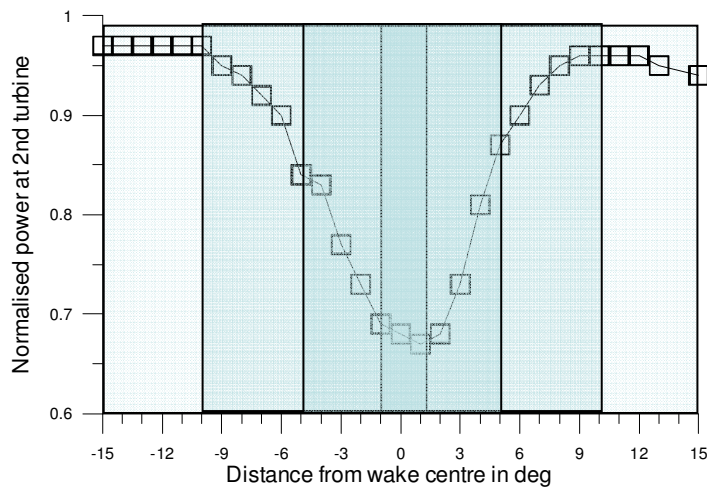


Figure 7. Wake width illustrating the portion of the wake captured by the measurements for $\pm 1^\circ$, $\pm 5^\circ$, $\pm 10^\circ$ and $\pm 15^\circ$ for comparison with Figure 6.

Figure 8 shows two different flow directions for wind speeds in the 8 m/s bin. Results are similar to those for Case 1 but comparing the observed wake losses for Case 2 and Case 3 in the $\pm 1^\circ$ case illustrates the uncertainty in the measurements which is mainly due to the small number of observations. It has become apparent that standard wind farm

models are lacking one or more components which account for the modification of the overlying boundary-layer by the reduced wind speed, high turbulence atmosphere generated by large wind farms. This effect is likely to be particularly important offshore due to the low ambient turbulence. This is described further in section 6.2.

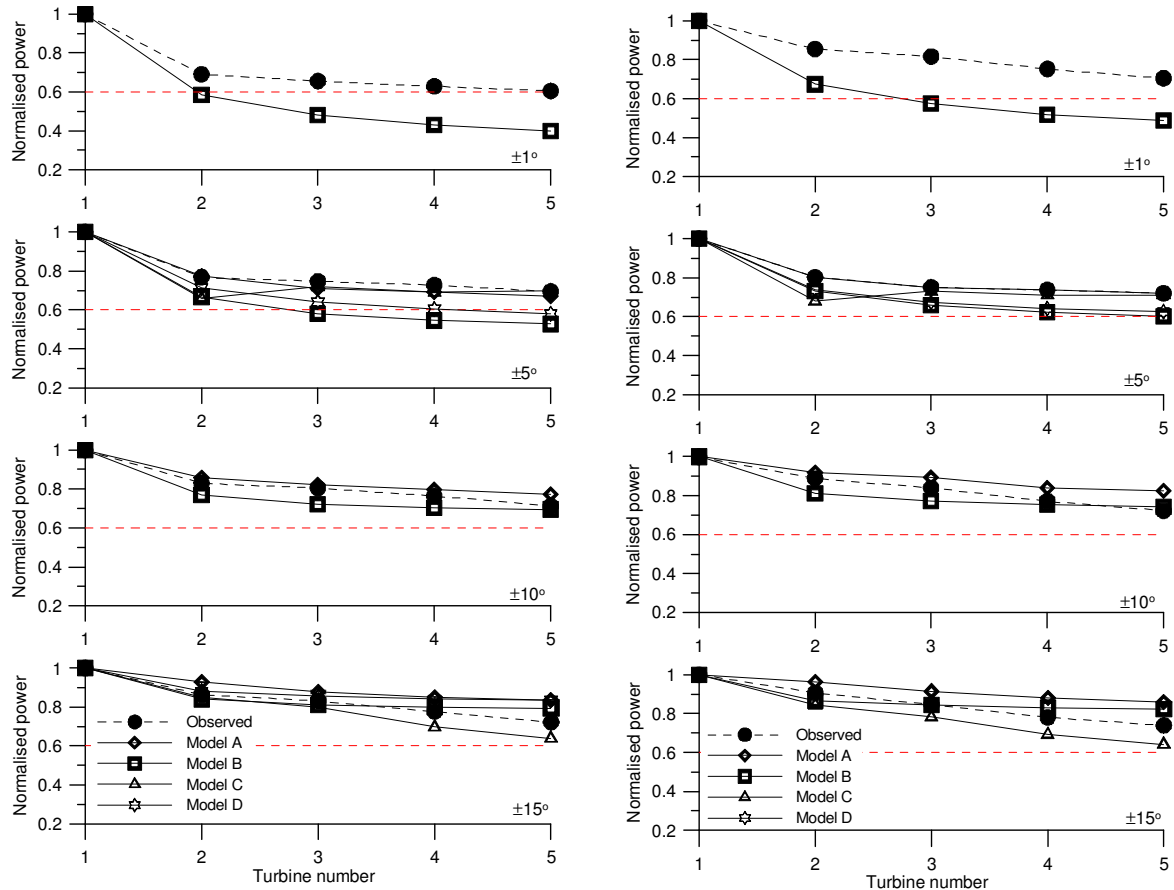


Figure 8: Preliminary comparison of models and measurements for two cases (Left: Case 2 and Right: Case 3 in Figure 4) and 8 ± 0.5 m/s at Horns Rev. From the top down, the width of the wake sectors considered in the four panels are $\pm 1^\circ$, $\pm 5^\circ$, $\pm 10^\circ$ and $\pm 15^\circ$.

6.2 Large offshore wind farms

It has become apparent that power losses from wakes exceed those predicted using standard wind farm models. GH have made an additional feature available in their WindFarmer model to allow assessment of these effects according to the current state of knowledge. RISOE have taken several

approaches including the development of a new analytical model [18], modifications to the WAsP model [20], modification of added roughness models and development of a canopy type model [21]. In all, seven models were compared with data from the offshore wind farms at Horns Rev and Nysted in Denmark. As yet it has not been possible to undertake a full model

comparison using a years data from the wind farm. This is more straightforward with the parameterised models than with the CFD models which are intensive in terms of their computing resource requirements. Comparisons have therefore tended to focus on a limited range of wind speeds with high thrust coefficient for westerly winds which are well-represented in the database, have flow directly down rows of wind turbines and have downstream masts at distances between 4 and 11 km for comparison with models. In general, models where some tuning of the turbulence intensity is undertaken (either directly or through increased roughness) show good agreement with measurements. The wind speed determined from power output within the wind farm can drop to less than 80% of its freestream value (according to the initial wind speed and direction angles considered). Recovery to approximately 90% of the freestream value appears to occur with the first 5 km downwind of the last turbine in the wind farm. However, further recovery is more gradual and appears to extend for an additional 15-20 km downwind. Considerable work remains to be done in terms of model evaluation and this also relies on additional data from large offshore wind farms becoming available in order that the impact of a range of wind turbine types and wind farm configurations can be determined.

7 Conclusions

Within the Upwind project research in support of upscaling of wind turbines to the 12 MW size and beyond is underway. The research presented in this paper focuses on special issues relating to the development of large wind farms both in complex terrain and offshore. The results presented here are preliminary focusing on the comparison of different complexities of wake model in a number of scenarios. Significant work remains to be done including developing a physical understanding of the causes of over- or under-prediction of wake losses in large offshore wind farms by the different types of models. A cross-cutting theme is the introduction of CFD models in both complex terrain and offshore and in their representation of multiple wind turbines.

8 Acknowledgements

Research funded in part by EU project UPWIND # SES6 019945 and POWWOW # SES6 019898. RB acknowledges the Scottish Funding Council via the Edinburgh Research Partnership. We would like to acknowledge DONG Energy A/S and Vattenfall AB, owners of the Horns Rev wind farm.

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