WAKES IN LARGE OFFSHORE WIND FARMS; MODEL EVALUATION IN UPWIND

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Summary

The paper presents research conducted in the Flow workpackage of the EU funded UPWIND project which focuses on improving models of flow within and downwind of large offshore wind farms. The main activity is modelling the behaviour of wind turbine wakes in order to improve power output predictions. The core of the activity is a model/measurement evaluation based on data from Horns Rev. Here we utilise data from the Horns Rev wind farm in a model evaluation exercise which focuses on understanding the different behaviour of wakes in CFD and wind farm models and how these compare with measurements for a range of wind speeds and direction sectors. It is already known that unmodified wind farm models under-predict wake losses in large (multi-row) wind farms while preliminary evaluation of CFD models suggest over-prediction. The issue is to quantify losses correctly and to understand why this discrepancy between how wakes behave in small and large wind farms arises. Emphasis is placed on flow within and downwind of large offshore wind farms and some new model development and modification. Results from the ongoing project will be presented which aim to illustrate wake behaviour offshore.

1. Introduction

The central core of most wind farm models was developed in the 1980's for small wind farms in simple or moderately complex terrain [1]. Large wind offshore farms now consist of multiple rows which extend over 25 km^2 and more. Evaluation in the ENDOW project [2] and at Middelgrunden [3] illustrated that most current wind farm models broadly capture wakes losses in small offshore wind farms and a further experiment at Vindeby [4, 5] showed it was not possible to distinguish any particular model or group of models as outperforming the others in terms of the accuracy of prediction of single wakes. Wind farms being developed today are larger, particularly those offshore. Thus 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. 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 project that aims to develop the next generation of large wind turbines.

2. Measurements

For model evaluation high quality measurements are required. Measurements from smaller test sites such as Vindeby were readily available (e.g. [6]) and additional experiments were used to evaluate wakes at different distances [4]. However it was not until data were published from large offshore wind farms that the discrepancy between model predictions from wake losses and measured wake impacts became clear [7]. Measurements of wake losses are typically derived from power output and require extensive processing. For particular cases of wind speed and wind direction, the width of the wake sector considered is very important since choosing a narrow sector (e.g. ±5°) gives a large drop in power at the second turbine compared to the power generated by the freestream flow but, in large arrays, the subsequent power drop is small [8]. Choosing a larger sector gives more observations but also likely includes multiple overlapping wakes at the back of the wind farm. In this case the drop in the power output at the second turbine is more moderate but the power output continues to decrease along the row.

Figure 1 shows the layout of the large wind farm at Horns Rev in Denmark. The wind farm is owned by DONG Energy A/S and Vattenfall AB and consists of 80 Vestas V80 wind turbines located in a 8 by 10 grid, with a basic spacing of 7D as shown in Figure 3 [9]. The wind farm is 14 km from the west coast of Denmark. Highest wind speeds are found in the southwest sectors where the flow also has a long fetch over sea. 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 in Figure 1). 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 (see Figure 1). For case 1, flow is directly along the row. Figure 2 shows observed power output for each turbine in the row (power output is normalized by the first turbine in the row). As shown, the observed power drop depends on the width of the sector considered. The wind speed is calculated from the power output as 8.0±0.5 m/s. At these wind speeds the thrust coefficient is high so this can be seen as one of the most extreme cases in terms of power losses due to wakes.

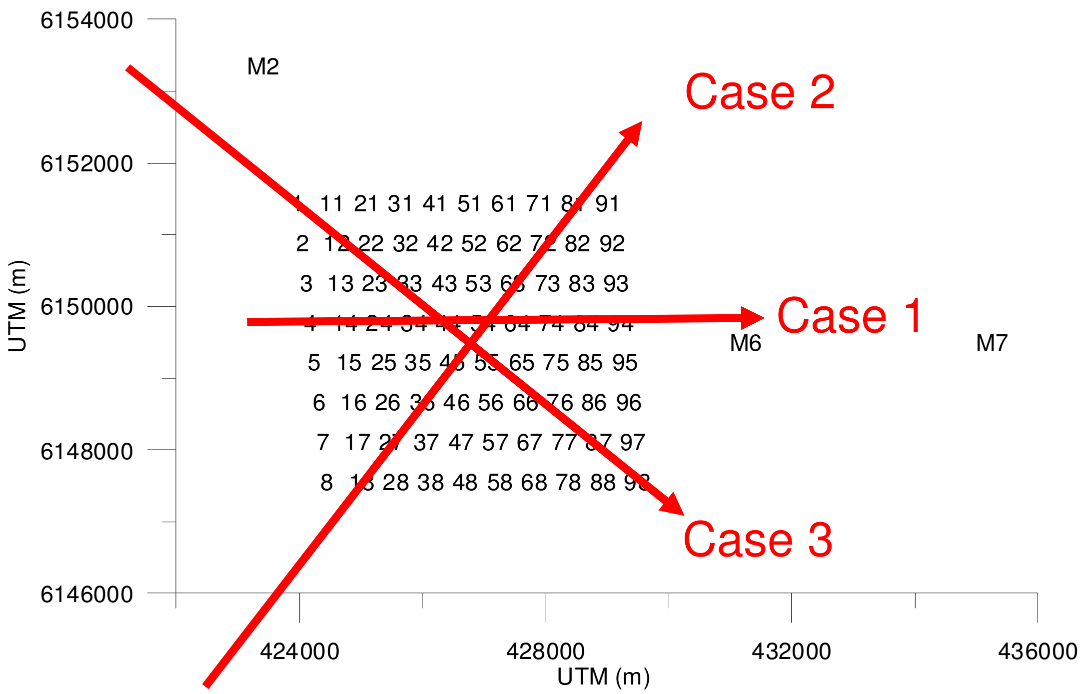

Figure 1: Horns Rev layout including definition of Case 1 (7D), Case 2 (9.4D) and Case 3 (10.5D) flow directions. Turbine locations are given by numbers and the location of the downstream masts are marked with M6 and M7.

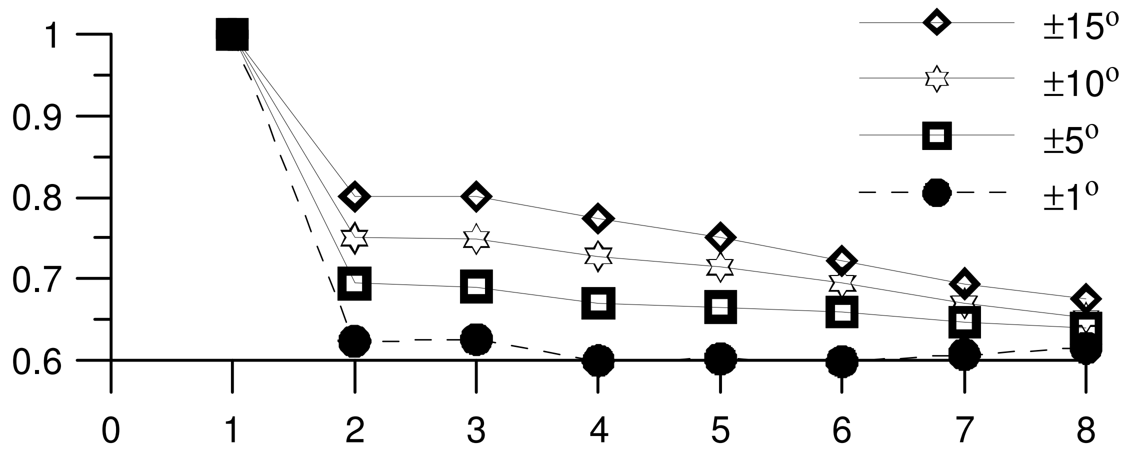

Figure 2: Effect of wake width used in the calculation (given in degrees) on the power output down the row at Horns Rev (Case 1 in Figure 1). Power is normalised so that the power at the freestream wind speed is 1. Wind speed at the first turbine calculated from the power output is 8.0±0.5 m/s.

3. Models

The comparison between wake models and measurements uses the full spectrum of models from whole wind farm codes which use moderately simple wake models to full CFD models. Models are described in detail elsewhere [2] so here only brief details are given here. The most straightforward models are those using one equation to determine the wake width/velocity deficit at particular distances from the turbine and then apply a 'top-hat' profile assuming the wake is axisymmetric. An example is the WAsP model where a description of the basic module may be found in [10] although it has recently been undergoing modifications [11]. The main advantage of the program is that it is fast and robust. It is not intended for single simulations. For the wake simulations discussed below it is important to note that the program is being used in a way which is not recommended.

There are a whole group of models which are based on a semi-empirical model described in [12]. These include GH WindFarmer where multiple wakes are calculated by consecutive downstream modelling of individual wakes. Due to the empirical components in 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. ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Polytecnica de Madrid. Using these models and the simpler models descried above it is not possible to model the near-wake physics explicitly. Hence they are not valid at less than ~3D from the turbine.

The remaining models are computational fluid dynamics codes. The CENER model is based on the commercial CFD code Fluent. The CRES–flowNS [13] model integrates the governing equations by means of an implicit pressure correction scheme, where wind turbines are modelled as momentum absorbers by means of their thrust coefficient. NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy.

The wind farm models are designed to predict average power output from a wind farm and depend to some degree on sufficient data being available to characterize the wind resource. For example, WAsP uses the Weibull shape and scale factors for each wind direction sector and hence is not designed to operate optimally for single simulations. On the other side, the CFD codes require effort to set up and are computationally demanding. It is therefore more difficult to describe complex simulations with long time series or a large number of wind turbines. In the model comparisons below it must be noted that some of the models are performing beyond their operational limits.

4. Multiple wake simulations

Although these simulations are not specifically for offshore they do serve to illustrate how the CFD codes operate in multiple wake situations. Eventually these simulations will be run specifically for comparison with data from operating wind farms. In order to estimate the effect of a neighbouring wake on the wind turbine efficiency, multi-wake simulations for the worst case in terms of efficiency will be examined. Initial model simulations are shown below for five machines. The turbine is a paper case 5 MW, reference turbine, with 126 m rotor diameter (D) and 90 m hub height. A parametric analysis has been carried out for different values of the distance between the wind turbines (3, 5 and 7 D) and different values of C_t (*0.3, 0.5* and *0.7*). The level of inlet turbulence intensity 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:

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

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

Results of the simulations with the CRES–flowNS code are shown in Figure 3. 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 minor even when the distance between the machines is small (3 D). However, for lower values of C_t there is a noticeable increase in the deficit of the second wind turbine which becomes greater as the wind turbines move close to each other (in a 3 D distance). In general, there is no significant change 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.

5. Wakes within large wind farms

The main issue for the current project is that there appears to be a fundamental difference between the behaviour of wakes in small wind farms where standard models perform adequately [14] and those in large multi-row wind farms where current wind farm models appear to under-predict wake losses [7]. It can be postulated that this is due to the interaction of turbulence generated by wind turbines wakes with the overlying atmosphere [15] and that a new generation of models is required to deal with this complex interaction of wakes with each other and the boundary-layer [16].

The mean deficit along a row of turbines has been calculated and presented in Figure 4 for different wake widths. The offshore wind farm at Horns Rev is characterized with low turbulence (<8%) and many operational hours in near neutral stability. The preliminary evaluation shown in Figure 4 is for a westerly wind direction with flow exactly along the rows as shown in Figure 1.

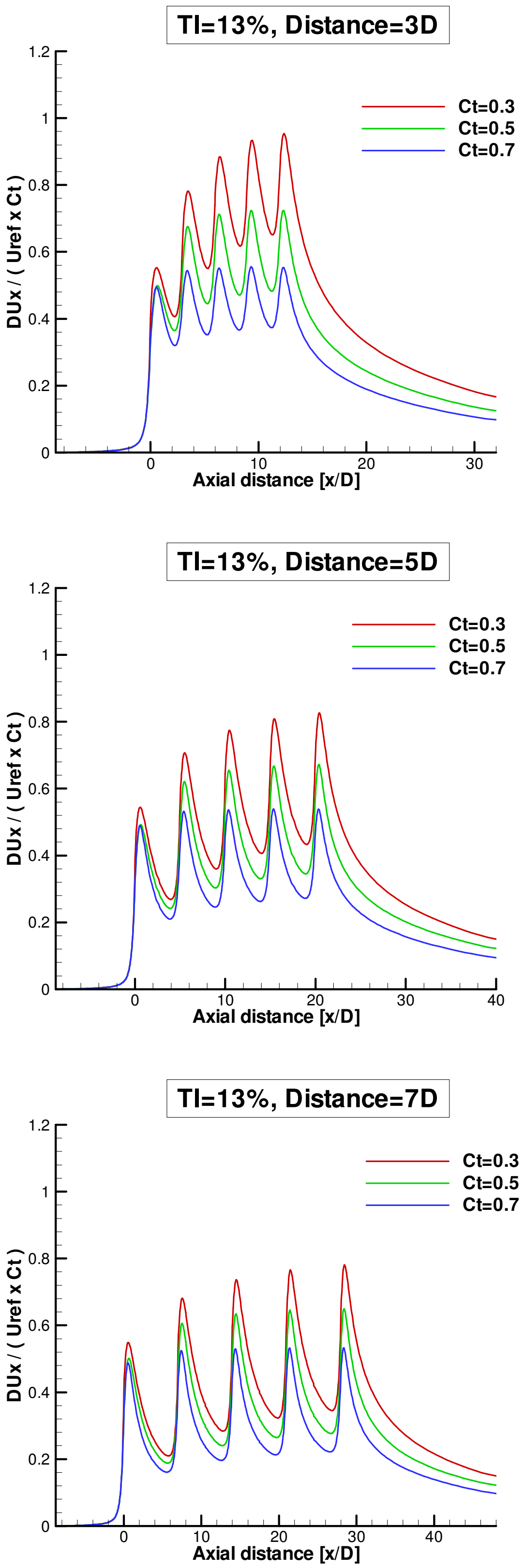

Figure 3: CFD simulations of five wind turbines in flat terrain - Effect of C_t on velocity deficit at hub height. Distance between wind turbines is from the top panel down 3D, 5D and 7D and inlet turbulence intensity at hub height is 13%.

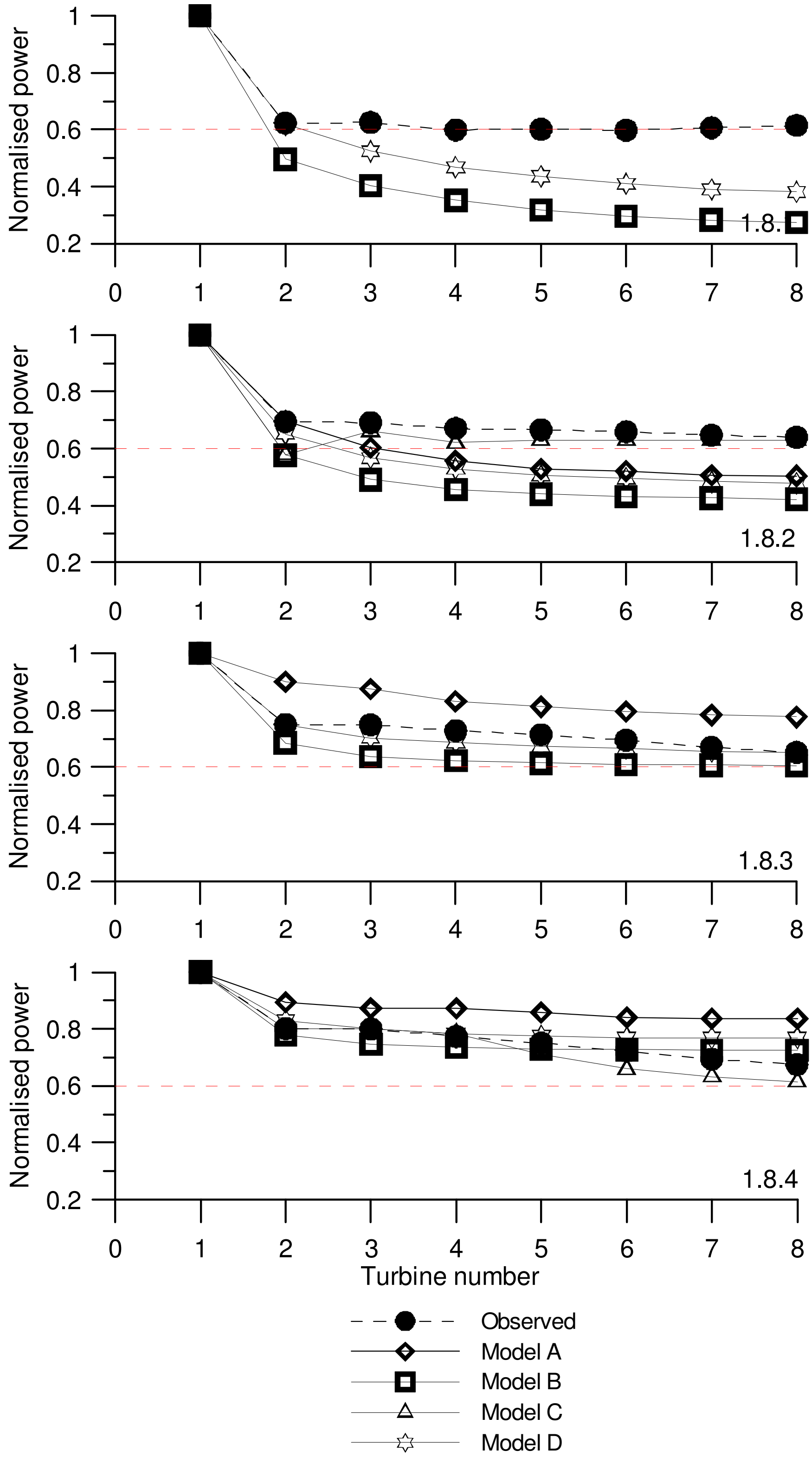

Figure 4: Comparison of models and measurements for Horns Rev (direction 270°, case 1 in Figure 1). The initial wind speed calculated from the power output of the first turbine is 8±0.5 m/s. From the top down the width of the wake sectors considered in the four panels are ±1°, ±5°,±10° and ±15°.

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 deficit at the second and subsequent turbines of around 40% which is identified during 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 [17]. It was shown here that the width of the wake is approximately ±10° at standard wind farm distances (clearly this depends to some degree on the turbine, the wind farm layout and the wind speed) so this is width of wake considered in the following simulations.

As shown the performance of the models is somewhat variable. For very small wake widths models tend to over-predict wake losses, potentially because the do not account for the directional variability. As the wake widths increase to capture a larger fraction of the wake the predictions divided into two groups. In general the wind farm models under-predict power losses due to wakes while the CFD models over-predict wake losses. While the wind farm model predictions can be tuned to better fit the observations e.g. using a lower wake decay coefficient or the added roughness approach described below, further investigation is needed to understand the cause of differences between the CFD models and the observations.

Figure 5 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 ±10° case illustrates the uncertainty in the measurements which is mainly due to the small number of observations. The observations show that as the equivalent wake spacing increases the initial power loss (at the second turbine) decreases but the power loss in the row increases moving down the row. By the fifth turbine all three wake spacing have a similar power output compared to the freestream. The models all predict closer to the observed power output for the larger wake spacings.

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 below

6. Flow downwind of large offshore wind farms

In addition to understanding of power losses within wind farms there is considerable interest in understanding the behaviour of wind and turbulence behind large wind farms. This is mainly directed at the development of clusters of offshore wind farms. There are several of these under development see for example Horns Rev and Horns Rev II in Denmark and the preferred development of offshore wind farms in three areas of the UK. GH have made an additional feature available in their Windfarmer model to allow assessment of these effects according to the current state of knowledge (Figure 8). RISOE have taken several approaches including the development of a new analytical model [16], modifications to the WAsP model [11], modification of added roughness models and development of a canopy type model [18]. 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 (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.

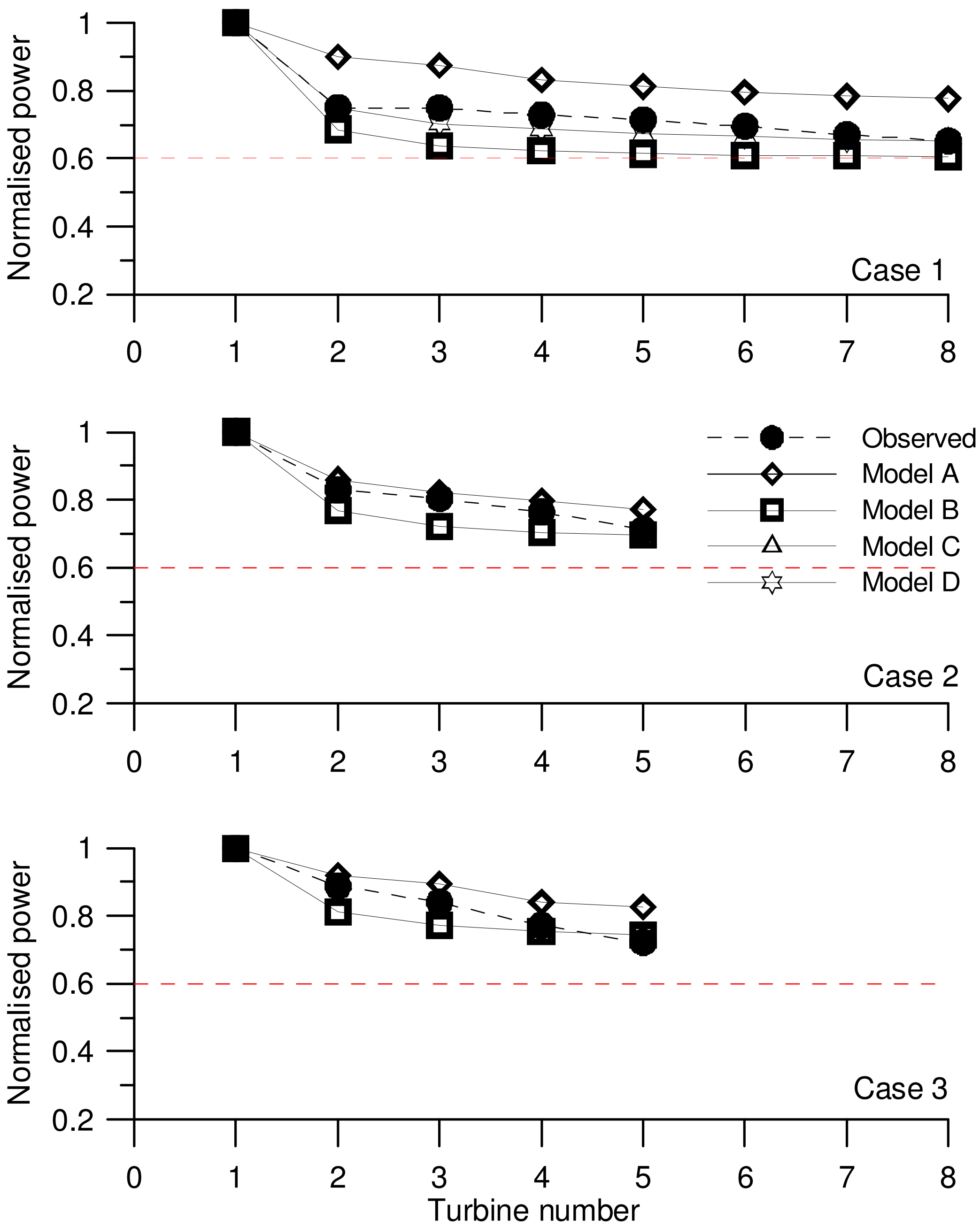

Figure 7: Preliminary comparison of models and measurements for three cases (Directions and turbine distances shown in Figure 1) and 8 ±0.5 m/s at Horns Rev. Width of the sector considered is ±10°.

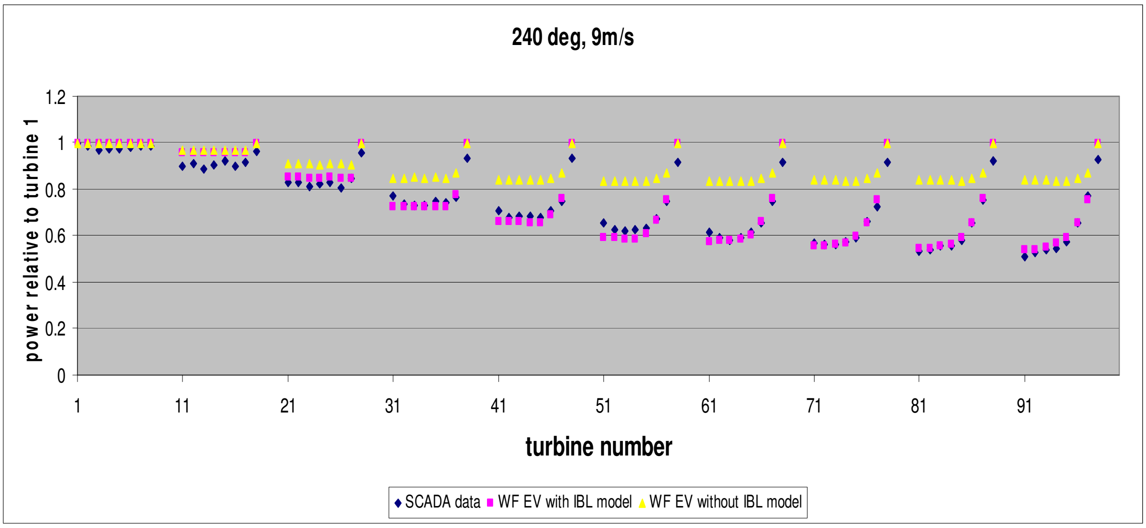

Figure 8: Energy yield at Horns Rev (240°, 9 m/s). Turbine numbers are shown in Figure 1. Observed data (SCADA) compared with predictions from the Windfarmer model without modifications (WF EV without IBL model) and with modifications (WF EV with IBL model), from [19]

7. Wakes wiki

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 and Middelgrunden and it is hope that this will expand to incorporate some the of the large wind farm data. Users can register and access the wiki at www.see.ed.ac.uk/powwowwiki.

8. 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 offshore wind farms. 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. Emphasis has also been placed on prediction of flow downwind of the wind farm to confirm understanding of the physical processes and to assist in development of clusters of large wind farms in close/moderate proximity offshore.

9. Acknowledgements

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