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Comparison of Wake Models with Data for Offshore Windfarms

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ABSTRACT

A major objective of the ENDOW project is to evaluate the performance of wake models in offshore windfarm environments in order to ascertain the improvements required to enhance the prediction of power output within large offshore wind farms [1]. The strategy for achieving this is to compare the performance of the models in a wide range of conditions which are expected to be encountered during turbine operation offshore. Six models of varying complexity have been evaluated initially against the Vindeby single wake data in [2] where it was found that almost all of them overestimate the wake effects and also significant inconsistencies between the model predictions appeared in the near wake and turbulence intensity results. Based on the conclusions of that study, the ENDOW wake modeling groups have already implemented a number of modifications to their original models. In the present paper, new single wake results are presented against experimental data at Vindeby and Bockstigen wind farms. Clearly, some of the model discrepancies previously observed in Vindeby cases have been smoothed and overall the performance is improved.

1. THE WAKE MODELS

Wakes appear in the wind flow field downstream of operating wind turbines. In general, they are characterized by lower wind speeds and higher turbulence levels with respect to the upstream conditions.

This paper presents an evaluation of wake models in offshore environments against experimental data obtained from operating offshore wind farms. It is part of the work carried out for Work Package 2 of the ENDOW project [2] with the major objective to evaluate and improve existing wake models accounting for complex stability variations. The six modeling partners and their models are briefly presented below as from their organisations:

Partner 1: RISØ Risø National Laboratory

Risø has developed two different wake models – an advanced model based on interfacing a CFD code to an aeroelastic code [3] and a semi-analytical engineering model [4]. The engineering model is based on an approximate solution of the boundary layer equations neglecting the pressure term, assuming a circular symmetric wake deficit and adopting a similarity assumption for the shape of the wake deficit. The estimated wake deficit is thus subsequently superimposed on the undisturbed wind shear field to yield the resulting downstream mean wind profile.

In the advanced model, a CFD actuator disc model is interfaced to an aeroelastic code enabling a detailed modeling of turbine as well as flow field. The flow field emerging from the CFD calculation is used as input to the aeroelastic calculation, that is subsequently producing aerodynamic forces, which are used to modify the CFD actuator disc model. The iteration is continued until equilibrium is achieved.

Partner 2: MIUU Uppsala University

MIUU has developed an analytical model based on the Taylor hypothesis using the transport time for the wake development [5].

Partner 3: GH Garrad Hassan

GH uses an axis-symmetric CFD Navier Stokes solver with eddy-viscosity closure (WindFarmer) [6]. The model is initiated at a distance of 2D behind the rotor with an empirical wake profile. The initial profile is of Gaussian shape and varies with thrust coefficient and ambient turbulence intensity. The eddy-viscosity is defined using the turbulence intensity in the wake [7].

Partner 4: RGU Robert Gordon University

RGU has developed a CFD fully elliptic turbulent 3D Navier-Stokes solver (3D-NS) with k-e turbulence closure based on a previous axisymmetric model [5]. Initial data required to start the 3D-NS calculations are the velocity and turbulence intensity profiles in the atmospheric boundary layer upstream the rotor. The computational domain includes the rotor of the wind turbine(s) (Figure 1), which is approximated by means of a semi-permeable disk to simulate the pressure drop across a real rotor disk (thrust).

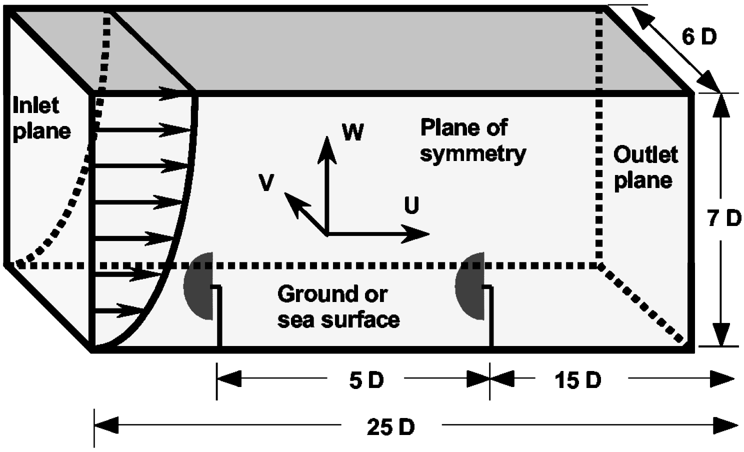

Figure 1. Typical computational domain of a CFD wake model for two wind turbine rotors in tandem arrangement

Partner 5: UO University of Oldenburg

The wind farm model FLaP of UO uses an implementation of the wake model proposed by Ainslie, 1988 [6]. It is a two-dimensional (axis-symmetrical) model solving the momentum and continuity equations with an eddy-viscosity closure. The eddy-viscosity is modelled as a combination of contributions from the ambient turbulence of the free flow and the shear generated turbulence in the wake. The wake model starts at the end of the near wake with an empirical wake profile as boundary condition. The near wake length is calculated after Vermeulen (1980) [8] taking into account ambient, rotor generated and shear generated turbulence intensity. The mean turbulence intensity in the wake is calculated from modelled eddy-viscosity.

Partner 6: ECN Netherlands Energy Research Foundation

ECN uses the Wakefarm program [9]. This program is a slightly modified version of the UPMWAKE program, which has been developed by the Universidad Politecnica de Madrid. It is a parabolic CFD method in which the turbulent processes in the far wake are modelled through a k-ε model. The near wake is modelled with the standard momentum theory, to which empirical corrections are added.

2. RESULTS – DISCUSSION

2.1. Vindeby Wind Farm

The single wake case for the Vindeby wind turbine 6E (rotor diameter 35 m, hub height 38) was investigated (Figure 2).

The following parameters were considered to be the most important for the wake development:

- Free wind speed at hub height, Uo, which is related to the rotor thrust coefficient, Ct
- Ambient Turbulence Intensity at the hub height, Io,
- Atmospheric stability (neutral, stable, unstable)

A systematic range of 48 case studies was identified to cover the expected range of conditions (Table I) at Vindeby.

Table I. Wake model scenarios (48 combinations in total: i.e. 4x4x3)

Parameters	Options			
4x wind speed [m/s] with thrust coefficient	5 0.92	7.5 0.76	10 0.58	15 0.35
4x turbulence Intensity [%]	6	8	10	15
3x atmospheric stability Monin-Obukhov [m]	Neutral ±10000	Stable 200		Unstable – 200

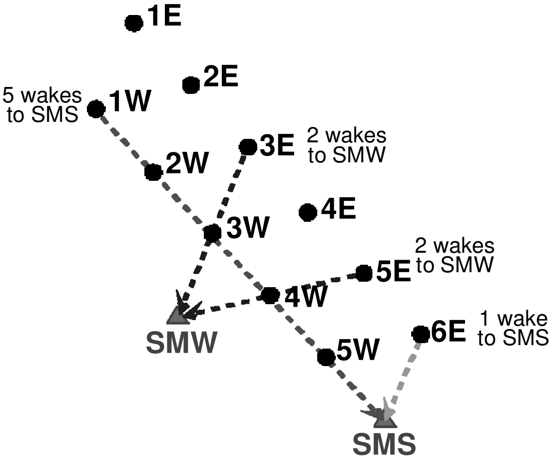

Figure 2. Layout of the wind farm at Vindeby (● shows each of the eleven wind turbines and ▲ the two sea masts)

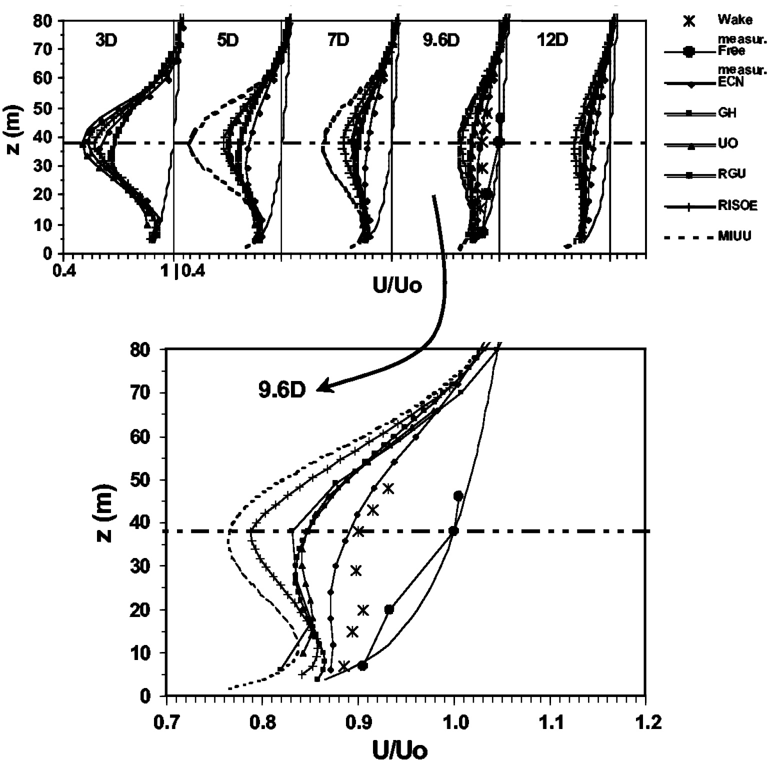

Figure 3. Velocity profiles normalized with the undisturbed wind speed at hub height on the vertical centre plane downstream of the 6E wind turbine for ambient turbulence intensity 6%. Free wind speed at hub height, Uo = 7.5 m/ s, thrust coefficient, Ct = 0.76, Monin-Obukhov length, L = – 10000m.

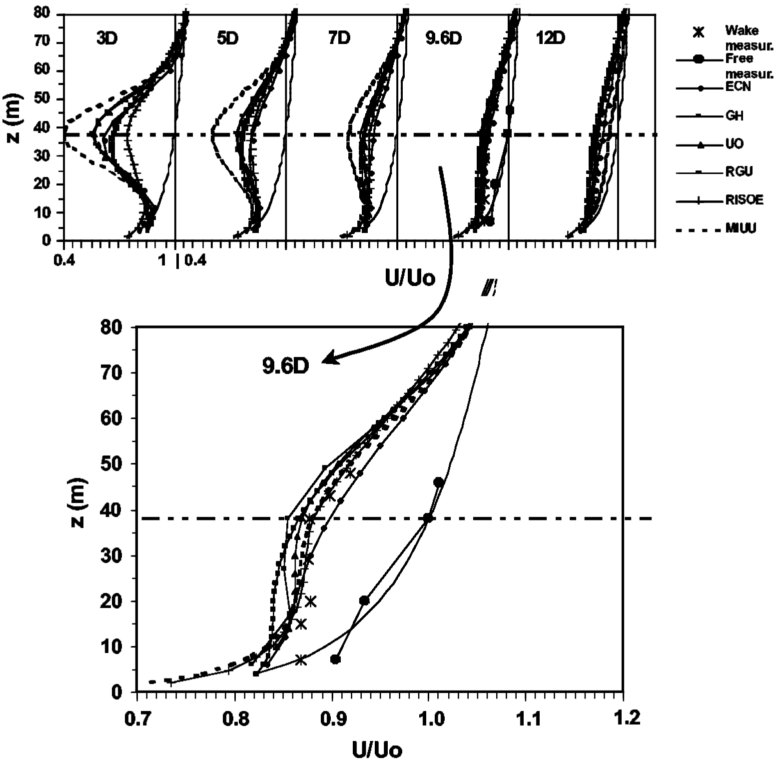

Figure 4. Same as in Figure 3 but for ambient turbulence intensity 8%

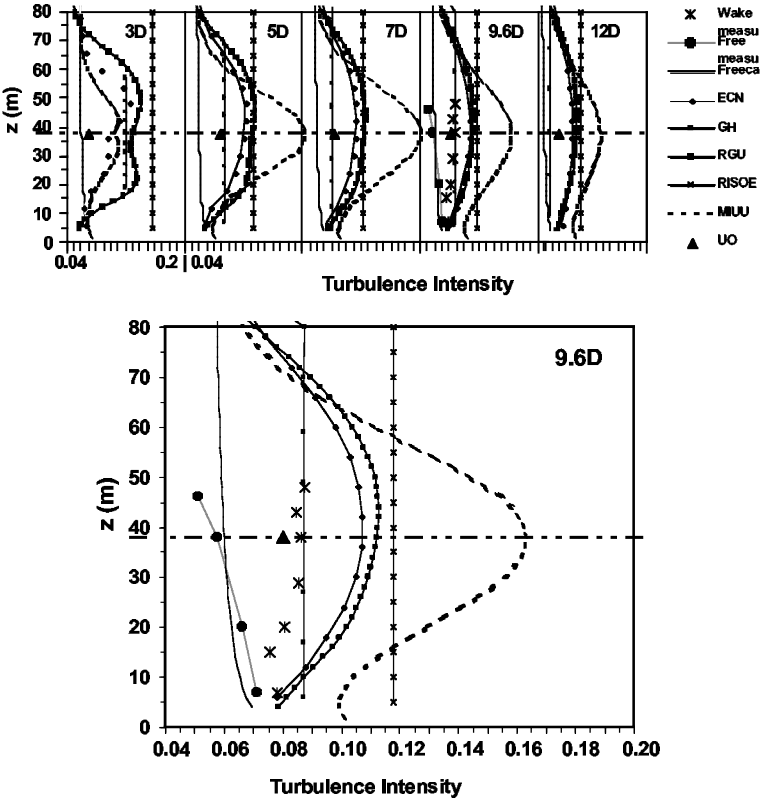

Figure 5. Turbulence intensity profiles normalized with the undisturbed wind speed at hub height on the vertical centre plane downstream of the 6E wind turbine for ambient turbulence intensity 6%. Free wind speed at hub height, Uo=7.5 m/ s, thrust coefficient, Ct = 0.76, Monin-Obukhov length, L = – 10000m.

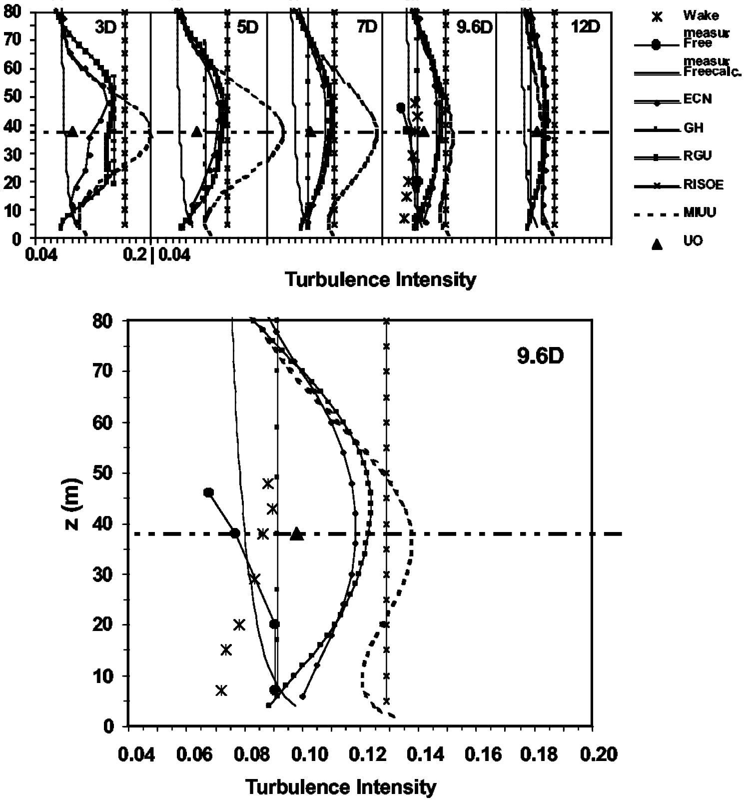

Figure 6. Same as in Figure 5 but for ambient turbulence intensity 8%.

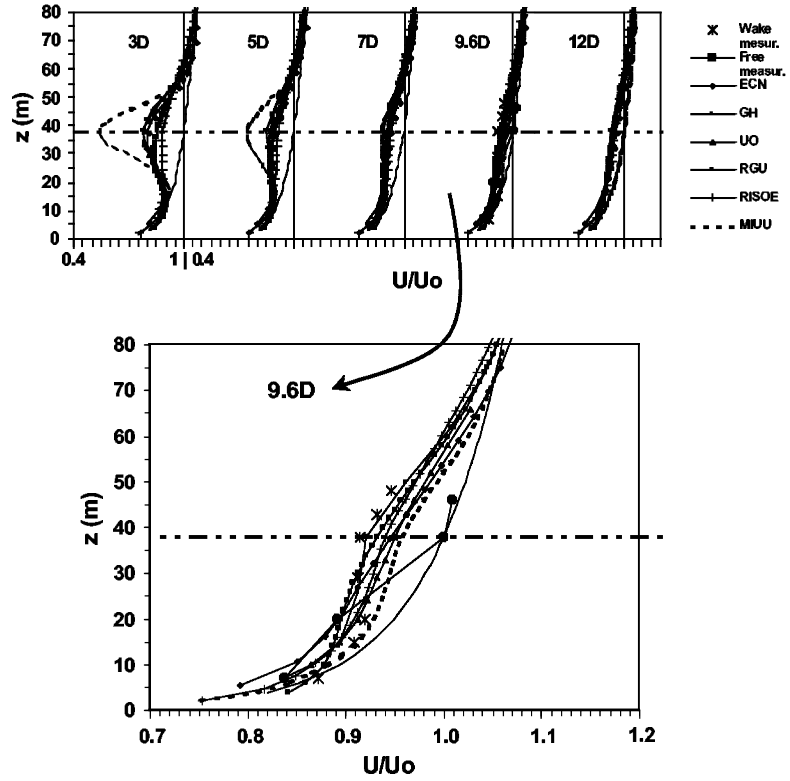

Figure 7. Velocity profiles normalized with the undisturbed wind speed at hub height on the vertical centre plane downstream of the 6E wind turbine. Ambient turbulence intensity 8%, free wind speed at hub height, Uo = 15 m/s, thrust coefficient, Ct = 0.35, Monin-Obukhov length, L = – 10000m.

Examples for some of the above scenarios for neutral atmospheric conditions are presented in Figures 3-7. Velocity profiles and turbulence intensity distributions are given on the vertical centre plane and at five distances downstream the wind turbine rotor: 3, 5, 7, 9.6, and 12 rotor diameters. The meteorological mast measuring the single wake of turbine 6E for northerly winds (23 degrees) is located at 9.6D downstream of the turbine. The experimental data corresponding to ambient conditions close to the modelling cases are presented with symbols. The dotted line represents the turbine hub height. The undisturbed free wind speed and turbulent intensity profiles shown in the plots (single solid line) were obtained by using Monin-Obukhov similarity theory applied to the atmospheric surface layer [10].

Considerable variability in the predictions of the various models is observed. The largest discrepancy appears in the near wake region (3 and 5 rotor diameters). These differences revealed the importance of the near wake parameterisation for the overall wake model performance, a task currently in progress as part of WorkPackage 3 of the ENDOW project. ECN and UO have already made modifications in the near wake treatment. The UO model has been improved drastically compared to previous results (see [2]). This is due to recent UO model extension, mainly taking into account the effect of turbulence and stability on the length of the near wake and an improvement of the eddy-viscosity model [11].

Almost all models overestimate the wake effects at 9.6D in terms of the velocity deficit and the turbulence intensity levels (Figures 3-6). However, the wind speed measurement uncertainty is estimated to about 5% since the data used are bin-averaged over narrow wind direction sectors. When measuring wind speed differences (wake deficit), this uncertainty can be much larger [11]. As shown in [11], the averaging effect on the measured wind speed in the wake results in significant decrease in measured wake deficit compared to its maximum value the models predict on the vertical centre-plane. Therefore, better performance of the various models is expected if the same averaging process is applied to the predictions as well.

Large deviations appear in the low turbulence intensity case (6%), where all models predict an expected slower wake recovery compared to the higher turbulence intensity (8%), while the measurements show similar recovery rates (Figures 3 and 4). This could be a result of the averaging process mentioned above. For ambient turbulence 8% the wake is expected to be wider than for 6%. Thus, wind speed averaging over the same wind direction range may result in similar average values although the minimum values (at the centre-line) are different. Also wake meandering may affect the average measured wind speed towards higher values (smaller deficit) in the wake as a result of the mast measuring point being occasionally in and out of the wake.

Further investigation of these cases is in progress using the whole range of one-minute averaged measurements from Vindeby. Note that RISØ and MIUU velocity predictions are more sensitive to changes of the ambient turbulence intensity than the other models.

Some noted general features are:

- All models predict consistent turbulence intensity levels in the wake compared to the observed values except MIUU which significantly overestimates the turbulence added by the rotor for wind speed 7.5 m/ s (Figures 5 and 6).
- All models show higher rates of wake recovery as the ambient turbulence intensity increases (Figure 3 and 4) and thrust coefficient decreases (Figure 7). This behaviour is expected since higher levels of ambient turbulence result in higher rates of turbulent mixing in the wake whereas lower thrust coefficient values result in less velocity deficit and hence less mechanical generated turbulence (shear) added in the near wake.
- The 3 dimensional CFD models (ECN and RGU) agree quite well in both the velocity and turbulence intensity profiles in the wake. The differences in the near wake (3 diameters) observed in [2] have been smoothed with recent improvements in the near wake modelling implemented by ECN. Also, there is clearly a better performance regarding turbulence predictions after the modifications introduced by ECN in the near wake region and by RGU in turbulence parameterisation.

2.2. Bockstigen Wind Farm

The Bockstigen wind farm layout is presented in Figure 8. Two single wake scenarios were considered:

- Single wake of turbine 2 monitored by the meteorological mast at a downstream distance of 5.4D, for moderate wind speeds coming from the west (11 cases).
- Single wake of turbine three giving a wake flow on turbine four at a downstream distance of 10.3D, for higher wind speeds coming from the south-west (8 cases).

Since there is only one meteorological mast at the wind farm, the undisturbed wind speed for the first scenario was estimated indirectly using a calculated power curve of turbine 2. Also for the same case, an average value for the ambient turbulence intensity was used based on the mast experimental data of the second scenario.

Figures 9-11 display the results from the original wake models against measurements for all case studies simulated.

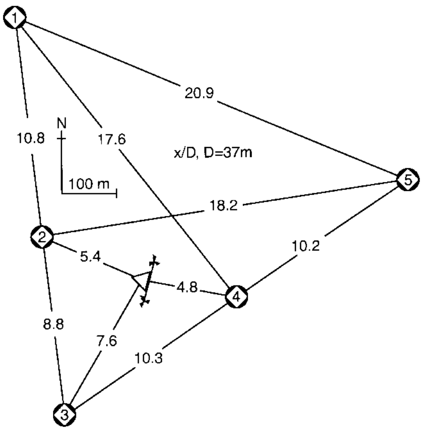

Figure 8. Layout of the Bockstigen wind farm

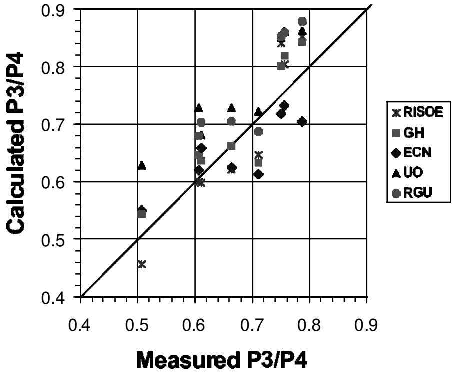

Figure 9. Calculated vs measured power ratio of Turbine 3 to Turbine 4 at Bockstigen wind farm

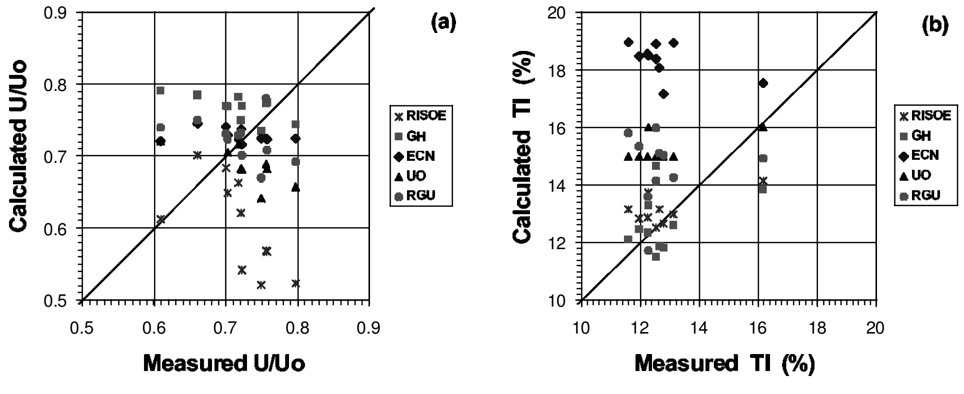

Figure 10. Calculated vs. measured (a) wind speed ratio and (b) turbulence intensity at the meteorological mast in Bockstigen wind farm

In general, the predictions are considered satisfactory, especially for the power output shown in Figure 9 which is the kernel part for the ENDOW design tool development.

RISØ model significantly overestimates the wake effects in terms of velocity deficit (Figure 10a) but it predicts quite well the turbulence intensity levels (Figure 10b). GH model predicts turbulence intensity levels very close to the observed values whereas ECN, RGU and UO overestimate them in almost all cases. This behavior has also been observed in the model comparisons with the Vindeby data [2] for ECN and RGU, and could be attributed to the expression used to translate the turbulent kinetic energy primarily predicted by ECN and

RGU models into turbulence intensity. In both models, this translation is based on the assumption that the anisotropy in the wake is the same as in the undisturbed wind field. The investigators are currently re-examining the above assumption for offshore conditions. In addition, the recent ECN improvements in the near wake modelling already provide reduced velocity gradients resuting in lower turbulence intensity levels in the wake.

MIUU model results compared with measurements are presented in Figure 11 where the normalized wake velocity deficit (ΔU/ U-Ct) is given as a function of the transport time, t, which is the main parameter used in the MIUU model [5]. The agreement between the measurements and the model results is good for the second scenario where the wind speed upstream as well as in the wake is taken from the turbine power curve (crosses). For the first scenario where the wake was measured by the mast, there is a systematic offset as the model overestimates the deficit. According to MIUU this could be due to uncertainties in the calculated wind speed, since the relation between the wind speed and the power production is simply based on an average value.

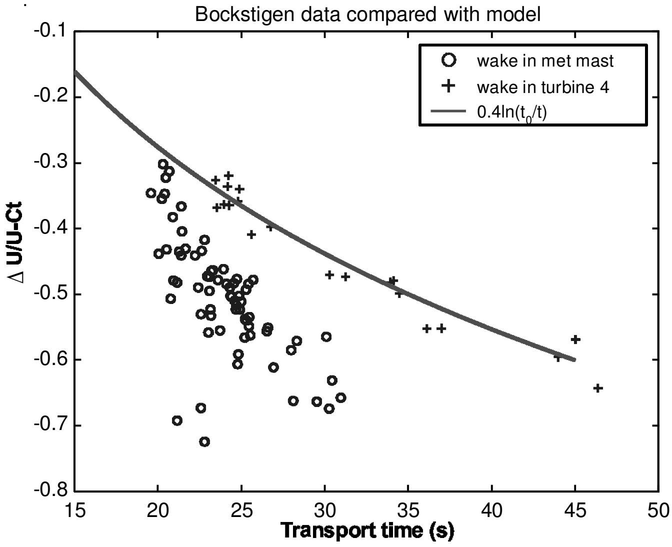

Figure 11. Comparisons of MIUU model wake velocity deficit against mesurements for the Bockstigen cases

3. CONCLUSIONS

Six wake model results have been compared with full-scale measurements at Vindeby and Bockstigen offshore wind farms.

Almost all models overestimate the wake effects at Vindeby for near neutral atmospheric conditions. The predictions present considerable variability especially for the low ambient turbulence intensity case. Better performance of the models is expected if the wind speed bin-average process over a wind direction range is applied to the predictions.

Sensitivity of the predictions to ambient parameters varies significantly from model to model. In general, they expectedly predict faster wake recovery for higher ambient turbulence intensity and thrust coefficient. However, the measurements show little dependency on ambient conditions. Further investigation on this issue is in progress.

The performance of the models in predicting power output of a turbine operating in the wake of another at Bockstigen wind farm is considered satisfactory.

4. FUTURE WORK

The following steps are suggested for further research, including work foreseen in the ENDOW project:

- Comparative investigation of the model performance against the double and multiple wake situations of the Vindeby experimental database (task in progress). A first study is presented by Schlez et al. [12].
- Further improvements of the wake models for multiple wake situations.
- Comparison of wake model predictions against the SODAR measurements by Folkerts et al. [13] to evaluate the near wake parameterisations.

5. ACKNOWLEDGEMENTS

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