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Prediction Of Waves, Wakes and Offshore Wind

Wp4: An overview of wind turbine wakes and short-term forecasting

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Abstract:

In most wind farms, the layout of the turbines is evaluated to quantify the power loss due to wind turbine wakes. As wind farms increase in size it has become evident that wake losses in large offshore wind farms are under-predicted (sometimes known as the deep array effect). Hence there are a number of research projects underway to evaluate the cause of these discrepancies and to operationalise new models or modify existing models. A major issue is that wind farm data are confidential and that to date relatively few operators have been willing to allow access in order that models can be evaluated/improved. A further issue is that the comparison of data with models is not straightforward.

The work of WP4 has been focused on providing data for evaluation of wind farm models. A wakes virtual laboratory with open access has been designed. This provides several data sets for model evaluation including long-term data, campaign data and wake cases. In addition data from a complex terrain wind farm has been made available to the EU Upwind project. Although this cannot be made openly available it is being provided to a group of dedicated wind farm/wake modellers who are evaluating a range of models from the state of the art wind farm models to CFD.

These data sets are mainly being used currently to evaluate wake losses on relatively long time scales. In short-term forecasting wake losses must also be incorporated into the prediction of power output from wind farms but the accurate prediction of wake losses can be subject to large errors. Many current short-term forecasting models use statistical methods based on wind farm data to predict power output by wind speed bin and direction sector. This then includes the effects of topography, roughness, obstacles and wakes and avoids the issue of predicting wake losses directly. However, in the absence of wind farm data, physical models must be used and therefore need to be evaluated.

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STATUS, CONFIDENTIALITY AND ACCESSIBILITY							
	Status			**Confidentiality**		**Accessibility**	
S0	Approved/Released	**x**	**R0**	General public	**x**	Private web site	
S1	Reviewed		**R1**	Restricted to project members		Public web site	
S2	Pending for review		**R2**	Restricted to European. Commission		Paper copy	
S3	Draft for commends		**R3**	Restricted to WP members + PL			
S4	Under preparation		**R4**	Restricted to Task members +WPL+PL			

PL: *Project leader* **WPL:** *Work package leader* **TL:** *Task leader*

1. Introduction

As wind farm sizes increases, power lost due to wind turbine wakes becomes an important part of the prediction process. On an average basis for a moderate size of wind farm, power losses due to wakes are predicted to be of the order 5-15% and clearly on a case by case basis can be much larger.

To include wake losses in short-term prediction there are two potential approaches. One is to use the power output from the wind farm to essentially create a wind speed and direction based 'power curve' for the whole wind farm. However, as with other statistical approaches this requires that data are available. The second approach is to use a physically-based model. However, wake and/or wind farm models have not been fully evaluated for very large wind farms even on an average basis.

The purpose of this document is to discuss issues relating wake measurements to models and to examine current approaches to modeling wakes used in short-term forecasting software.

2. Wind farm and wake models

There are several surveys of wake and wind farm models available e.g. [1, 2]. For small and moderate sized wind farms offshore, current wind farm models appear to predict power losses due to wakes to a satisfactory level [3], [4]. For large wind farms only a few evaluations of modelling of power losses due to wakes have been carried out in the public domain e.g. [5]. Given the wide-range of model performance, further research is required in order to reduce uncertainties in power output prediction prior to wind farm construction.

The model comparison in [6] 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.

2.1 WAsP from Risoe

The Wind Atlas Analysis and Application Program (WAsP) is based on a linearised model used in the European Wind Atlas. The WAsP program [7] 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 [8]. A new wake model ('Mosaic tile') is being developed for use within WAsP [9]. 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 [10]. For the simulations discussed below it is important to note that the program is being used in a way which is not recommended.

2.2 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 [11]) 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 [12] 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 [13]. 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 [14].

2.3 WAKEFARM from ECN

ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Polytecnica 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.

2.4 CENER CFD Flow model

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.

2.5 CRES CFD Flow model

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 [15]. 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–ω model [16], suitably modified for atmospheric flows.

2.6 NTUA CFD flow model

NTUA CFD model solves the 3D Reynolds averaged incompressible Navier-Stokes equations with second order spatial accuracy. The model [17] (see also [18]) assumes Cartesian grids, uses the k-ε 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.

3. Measurements

There are essentially two types of measurements; meteorological and wind farm data. Some wind farms retain the meteorological mast(s) that was/were established for the resource determination and if these data are available in addition to wind farm data it is an added bonus particularly with regard to questions such as 'What is the wind farm power curve?' (depending on the mast location). At few offshore wind farms such as Vindeby, Bockstigen, Horns Rev and Nysted one or more meteorological masts were added after construction to aid research.

3.1 Meteorological measurements

Meteorological data can also be divided into two types – mast and remotely sensed data. Examples of wind farms supported by meteorological mast data include Nørrkær Enge [19], Bockstigen [20], Middelgrunden[3, 21] Vindeby [22], Horns Rev [23, 24] and Nysted [25, 26]. The advantage of meteorological mast data is that it is usually available for a long period, it is typically accurate (although this can depend on the mast structure) and wind speed, direction and turbulence profiles to hub-height are usually available at a good time resolution and with high data capture. The most obvious disadvantage is that the location of the measurements is fixed so from a wake perspective the wake distance is fixed e.g. [27],[28]. However, wake analysis has to be made for specific directional sectors and the wake distances can vary according to the layout of the wind farm and the position of the mast. Measurements are rarely made above hub-height.

3.2 Wind farm measurements

Obviously for wake studies in large wind farms, wind farm data are needed. Parameters required would typically be the power output, nacelle direction and yaw misalignment and additional operational information such as 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. A few examples are found in [26] and [29]. 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.

3.3 Remote sensing

Remote sensing is providing additional types of information for use in wind energy. We exclude here satellite data although these have been used both for wind resource and for wakes estimation e.g. [30]. 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 in this environment [31]. Data from both instruments requires additional processing and maybe subject to some accuracy or operational limitations but progress has been made to the point where Doppler lidar in particular may become a standard instrument. As yet, there have been limited studies using sodar or lidar in wake studies e.g. [32], [33].

3.4 Issues comparing models and measurements

There are some major issues in wind farm model validation studies which will be discussed below. As stated above we concentrate here on power loss modelling which should encompass the whole range of wind speeds and directions and we also consider that the range of wind farm/wake model extends from engineering through to full CFD models. 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 WindFarmer and WAsP. On the other hand it can be difficult to extract reasonable simulations from some of the wind farm models for very specific cases. For example, WAsP relies on having a Weibull fit to wind speed distributions and fairly large directional sectors (30°). Therefore for specific wind speeds and narrow directional bins models like WAsP are never going to produce very exact solutions because they are being used beyond their operational windows. In addition to this there are a number of specific issues:

- Establishing the freestream flow. The major issues in determining the freestream flow are the displacement of the measurement mast from the array (assuming there is a mast), adjustments in the flow over this distance especially in coastal areas and differences in height between the measurement and the turbine hub-height. If power measurements are used to determine wind speed they will be subject to any errors in the site specific power curve.
- Wind direction, nacelle direction and yaw misalignment. Because of the difficulty in establishing true north when erecting wind vanes (especially offshore where landmarks may not be determinable) it can be difficult to establish a true freestream direction. In a large wind farm, each turbine may have a separate bias on the direction, which is very difficult to determine.
- If there is a gradient of wind speeds across the wind farm as there may be e.g. in coastal areas, near a forest or caused by topography these variations will need to be accounted for before wake calculations are undertaken.
- In terms of modelling wakes both the power curve and thrust coefficients must be known but these will vary according to the specific environment.
- Comparing the modelled standard deviation of power losses in a row with the measured standard deviation raises a number of issues. The two most important are ensuring that the time averaging is equivalent between models and measurements and taking into account that there will be natural fluctuations in the wind speed and direction in any period.
- In the large wind farm context the time scale of wake transport must be considered. A large wind farm with 100 turbines in a 10 by 10 array with an 80 m diameter rotor and a space of 7 rotor diameters has a length of nearly 6 km. At a wind speed of 8 m/s the travel time through the array is more than 10 minutes.
- Determining turbulence intensity and stability may be critical. Turbulence intensity is a key parameter in many models. The accuracy of temperature measurements used to derive stability parameters is often inadequate.

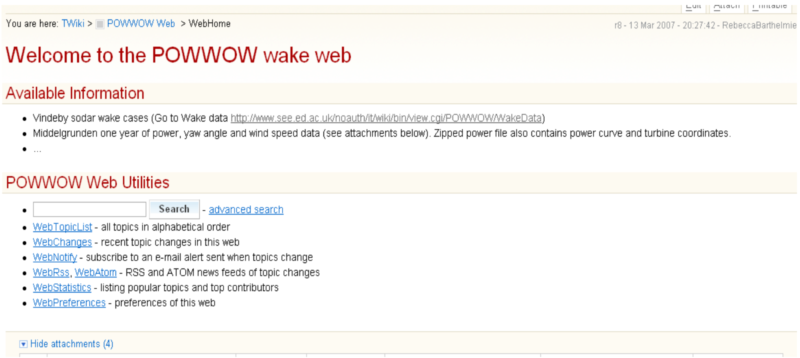
4. POW'WOW Wakes Virtual Laboratory

The wakes virtual laboratory was setup to help overcome some of the difficulties wind farm modelers face in obtaining data sets with which to develop or evaluate their models. It was developed at UEDIN and is currently based at a UEDIN site. However, there are plans to move it to a more permanent location with an expanded remit so that it can continue after the POW'WOW project has finished.

The availability of these data has been advertised at a number of international conferences and workshops e.g. The 2007 and 2008 European Wind Energy Conferences, the American Wind Energy Workshop on Wind Resources 2008 (an invited presentation was given on the status of wakes research), the World Renewable Energy Congress, European Offshore Conference 2007 etc.

Access to the data is open although users have to register (www.see.ed.ac/powwowwiki). There are currently about 20 users registered who have accessed data. The data contained includes:

1) Middelgrunden. Time series of a year and a half of wind speed, power output and yaw angle from 10 offshore wind turbines located in Copenhgen Harbour. Data supplied by Middelgrundens Wind Turbine Cooperative.
2) Vindeby. Data from a ship-borne sodar experiment funded by the EU through the ENDOW project. Wind speed profiles given for wakes at a number of rotor diameters (1.7 D to 7.4 D).
3) Horns Rev. Wake case studies used in the UPwind project (also funded by the EU) made available by agreement with DONG Energy.



r8 - 13 Mar 2007 - 20:27:42 - RebeccaBarthelmie

Welcome to the POWWOW wake web

Available Information

- Vindeby sodar wake cases (Go to Wake data http://www.see.ed.ac.uk/noauth/it/wiki/bin/view.cgi/POWWOW/WakeData)
- Middelgrunden one year of power, yaw angle and wind speed data (see attachments below). Zipped power file also contains power curve and turbine coordinates.
- ...

POWWOW Web Utilities

- advanced search
- WebTopicList - all topics in alphabetical order
- WebChanges - recent topic changes in this web
- WebNotify - subscribe to an e-mail alert sent when topics change
- WebRss, WebAtom - RSS and ATOM news feeds of topic changes
- WebStatistics - listing popular topics and top contributors
- WebPreferences - preferences of this web

5. Wakes Workshop

UOLD held a workshop in 2008. A description and the online proceedings can be found at:
http://forwind.de/events/index.php?article_id=14&clang=0

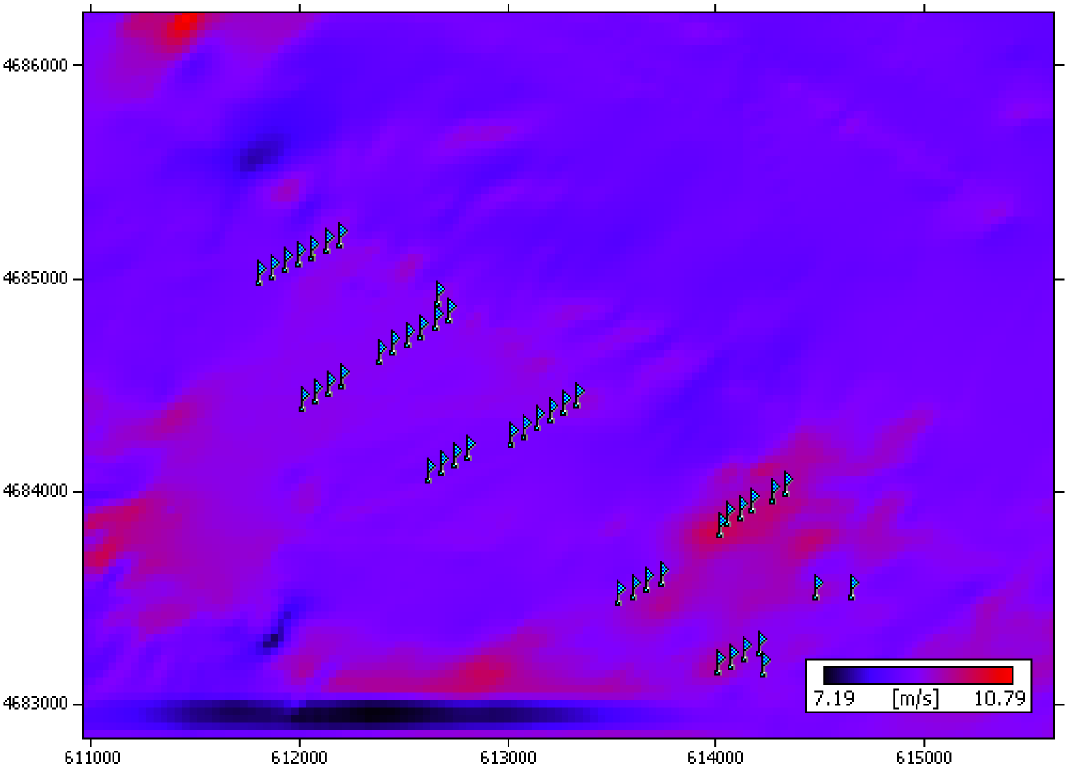
6. Complex terrain test case

Predicting power output in complex terrain remains a difficult task on both resource and short-term forecasting time scales. CENER has designed a test case for wakes in complex terrain, including the following activities:

- Selection of a wind farm in complex terrain in Spain.
- Negotiation with the owner of the wind farm in order to make available the wind farm data for the partners of UpWind project.
- Analysis of the wind farm data including meteorological mast data and turbine data (power production and nacelle wind speed).
- Design of the experiment: sectors to be simulated and procedure to compare wake results.

The model simulations are underway and will be presented at the European Wind Energy Conference 2009.

Case 1. Wind 8.5 m/s, direction 325º



7. Short-term prediction survey

Short-term forecasting of wind energy is important in two contexts: grid integration [34] and where the price obtained for electricity varies [35] e.g. Nordpool. For an overview of current techniques for short-term prediction used in wind energy see e.g. [36, 37]. In general, short-term forecasting offshore appears to have reduced errors compared to short-term forecasting on land [38] [39], especially in complex terrain, due to the relative uniformity of the wind field and the persistence of winds in the power producing classes [40].

In order to assess the state of the art in wind energy prediction available commercially, a survey was distributed via the POW'WOW network. Of the four companies that responded two use entirely statistical approaches, one uses a physical approach and one uses a physical approach modified by a statistical approach if wind farm data are available.

7.1 GH Forecaster

Name of system:	GH Forecaster
Web reference:	http://www.garradhassan.com/services/ghforecaster/
Group operating:	Garrad Hassan
Method of wake prediction:	Eddy Viscosity Model, plus statistical adjustment if nacelle wind speed feedback is available.
References:	The Eddy Viscosity Model was developed for use in the GH WindFarmer product, the best reference is the GH WindFarmer theory manual as there are a number of papers that this references. http://www.garradhassan.com/products/ghwindfarmer/

7.2 WPMS

Name of system:	WPMS
Web reference:	www.iset.uni-kassel.de
Group operating:	Software developed by ISET e.V., the software is operated by the customers: RWE, E.ON, VE-T, Terna, Verbund, National Grid, etc.
Method of wake prediction:	Artificial neural networks are used to describe the nonlinear dependence of meteorological parameters (mainly > wind) and wind farm power production - this implicitly includes the effects of wakes in the wind farm.
References:	B. Lange, K. Rohrig, F. Schlögl, Ü. Cali, R. Jursa: Wind Power Forecasting. in: G. Boyle (ed.): Renewable Electricity and the Grid", Earthscan, London, September 2007 Lange, B., K. Rohrig, B. Ernst, F. Schlögl, Ü. Cali, R. Jursa, J. Moradi: Wind power forecasting in Germany – Recent advances and future challenges. Zeitschrift für Energiewirtschaft. Vol. 30 no. 2 (2006), pp. 115-120 Mackensen, R., B. Lange, K. Rohrig: Integrating Wind Energy into Public Supply Systems – German State of Art. 2nd International Conference on Integration of Renewable and Distributed Energy Resources Napa California, USA, December 2006 Rohrig, K., B. Lange: Application of Wind Power Prediction Tools for Power Systems Operations. IEEE Power Engineering Society General Meeting, Montreal, Canada, June 2006 Lange, B., K. Rohrig, B. Ernst, F. Schlögl, Ü. Cali, R. Jursa, J. Moradi: Wind power prediction in Germany – Recent advances and future challenges. Proceedings of the EWEC 2006, Athens (published on website www.ewea.org)

7.3 Prediktor

Name of system:	Prediktor
Web reference:	www.prediktor.dk
Group operating:	Risø DTU, Wind Energy Dept
Method of wake prediction:	PARK (now integrated in the wind farm power curve)
References:	For a full list please see web site. Recent examples: Gregor Giebel (ed.), Jake Badger, Lars Landberg, Henrik Aalborg Nielsen, Torben Skov Nielsen, Henrik Madsen, Kai Sattler, Henrik Feddersen, Henrik Vedel, John Tøfting, Lars Kruse, Lars Voulund: *Wind Power Prediction using Ensembles*. Risø-R-1527, September 2005. Giebel, G., R. Brownsword, and G. Kariniotakis: *The state-of-the-art in short-term prediction of wind power. A literature overview.* Version 1.1. 36 p. (2003) G. Giebel, A. Boone: *A Comparison of DMI-Hirlam and DWD-Lokalmodell for Short-Term Forecasting*. and Poster, European Wind Energy Conference, London 2004

7.4 MSEPS

Name of system:	MSEPS - Multi-Scheme Ensemble Prediction System
Web reference:	www.weprog.com / www.mseps.net
Group operating:	WEPROG - Weather & Wind Energy Prognoses
Method of wake prediction:	We model wake effects in most places only in form of statistical corrections to the power curve of the entire wind farm in the training phase of the wind farm with measurement data. In specific cases, e.g. large single wind farms, we model wake effects with so called "wake indices" at each turbine, for each of our 75 ensemble members and different weather classes. Such wake indices require detailed turbine based observational data and relatively high resolution forecasts
References:	AESO - Alberta Electric System Operator's Wind Power Pilot Project http://www.aeso.ca/gridoperations/13825.html, Pahlow, M., Möhrlen, C., Jørgensen, J.U., Application of cost functions for large-scale integration of wind power using a multi-scheme ensemble prediction technique, Optimization Advances in Electric Power Systems, Ed. Edgardo D. Castronuovo, NOVA Publisher NY, (in print, 2008). Bernhard Ernst, Brett Oakleaf, Mark L. Ahlstrom, Matthias Lange, Corinna Moehrlen, Bernhard Lange, Ulrich Focken, and Kurt Rohrig, Predicting the Wind, Models and Methods of Wind Forecasting for Utility Operations Planning, IEEE Power & Energy, Vol.5 No.6, November/December 2007. Möhrlen, Corinna, Jess U. Jørgensen, Pierre Pinson, Henrik Madsen, Jesper Runge Kristoffern, HRENSEMBLEHR - HIGH RESOLUTION ENSEMBLE FOR HORNS REV, European Offshore Wind Energy Conference, Berlin, 2007. Pahlow, M., L.-E. Langhans, C. Möhrlen, J. Jørgensen, On the Potential of coupling Renewabs into Energy Pools, Zeitschrift f. Energiewirtschaft, No. 1/2007, Vol.31, pp 35-46, 2007

8. Conclusions

In short-term forecasting, once a wind farm is established, the operational data can be used to construct a wind farm power curve which avoids the need to directly model wake losses.

This still leaves the issue of predicting wake losses before the wind farm is constructed and within the first year or so of operation when insufficient data are present. Therefore there is still a need for good quality data from wind farms to assist in the process of improving and validating wind farm/wake models particularly for larger wind farms in complex terrain and offshore. To assist in this process data have been provided in the Wake ViLab (where permission was granted from the data owners) and/or processed into case studies for use by modeling groups. Having shown through this pilot project that there is a need for such a facility, there is considerable scope to broaden the Wake ViLab and to encourage further data owners to contribute.

9. Acknowledgements

With thanks to the companies that responded to the request for information regarding methods used to predict power losses due to wakes in short-term forecasting software and to the companies who supplied data for the Wake ViLab or wake evaluation.

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