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Efficient development of offshore windfarms (ENDOW): Final report to the European Commission

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Risø-R-1407(EN)

Efficient Development of Offshore Windfarms (ENDOW)

Final report to the European Commission: Executive summary (ERK6-1999- 00001)

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April 2003

Abstract Europe has large offshore wind energy potential that is poised for exploitation to make a significant contribution to the objective of providing a clean, renewable and secure energy supply. Offshore wind energy developments are underway in many European countries with planned projects of several thousand megawatts to be installed in addition to the 250 MW installed by the end of 2002. While experience gained through the demonstration projects currently operating is valuable, a major uncertainty in estimating power production lies in the prediction of the dynamic links between the atmosphere and wind turbines in offshore regimes.

The objective of the ENDOW project was to evaluate, enhance and interface wake and boundary-layer models for utilisation offshore. The project resulted in a significant advance in the state of the art in both wake and marine boundary layer models leading to improved prediction of wind speed and turbulence profiles within large offshore wind farms. Use of new databases from existing offshore wind farms and detailed wake profiles collected using a sodar provided a unique opportunity to undertake the first comprehensive evaluation of offshore wake model performances. The wake models evaluated vary in complexity from empirical solutions to the most advanced models based on solutions of the Navier-Stokes equations using eddy viscosity combined with a k-epsilon turbulence closure. Results of wake model performance in different wind speed, stability and roughness conditions provided criteria for their improvement. Mesoscale model simulations were used to evaluate the impact of thermal flows, roughness and orography on offshore wind speeds.

The model hierarchy developed under ENDOW forms the basis of design tools for use by wind energy developers and turbine manufacturers to optimise power output from offshore wind farms through minimised wake effects and optimal grid connections. The design tools are being built onto existing regional scale models and wind farm design software which was developed with EU funding and is in use currently by wind energy developers. This maximises the expected impact of this project through efficient use of existing resources and ease of upgrade for end-users.

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Contents

1 Databases

Databases were compiled from two offshore wind farms at which both meteorological observations and power output were available. The selected sites are Vindeby (sheltered location, shallow water) (Barthelmie et al. 1996), Bockstigen (Baltic, deeper water) (Lange et al. 1999) and Horns Rev (deeper water, near-neutral conditions on average). These are the locations of offshore wind farms with associated meteorological monitoring.

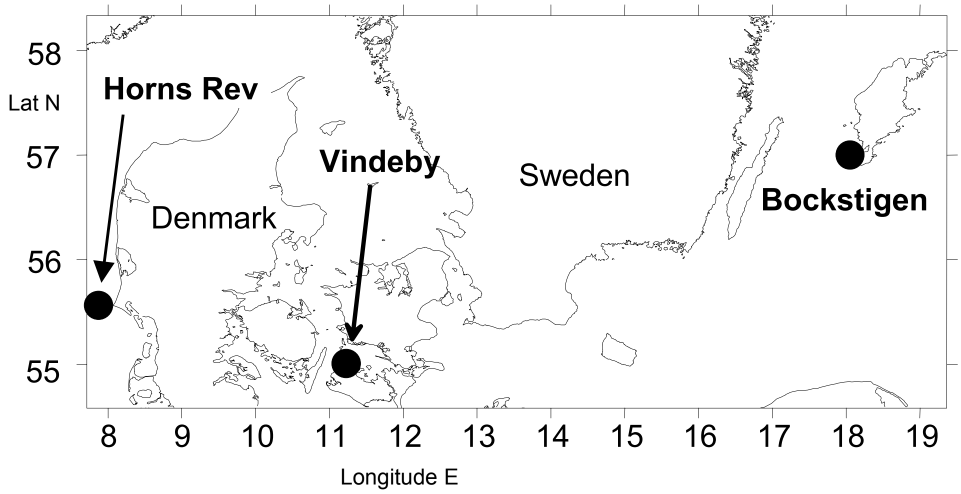

Figure 1. Location of offshore wind farms at Vindeby and Bockstigen and the wind farm at Horns Rev (installed in 2002/2003).

1.1 Site details

1.1.1 Vindeby

The Vindeby wind farm is located to the north of the island of Lolland at a minimum distance of 2 km from the coast. The site is impacted by the land surface to the south but this is mainly flat (< 20 m) and agricultural with a roughness of approximately 0.05 m. A complete description of the site and meteorological monitoring is given in (Barthelmie *et al.*, 1994) Description of the turbines and wake evaluation is given in (Frandsen *et al.*, 1996). Figure 2 shows the layout of the site including the masts and wind farm.

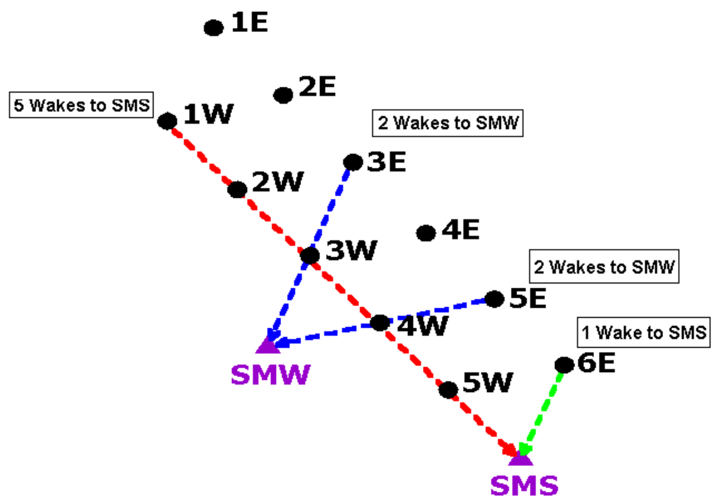

Figure 2. Layout of the wind turbines and masts at Vindeby (distance between the turbines is 300 m along and between rows).

1.1.2 Bockstigen

Bockstigen is located to the south-west of the island of Gotland (Figure 1). There is an offshore mast of 40 m, a 60 m coastal mast and a 120 m inland mast. The maximum variation in the water level is 1.5 m Wind speed profiles are measured. Wind speeds are measured at four heights with the top anemometer being free of mast shadow effects and two anemometers being available on either side of the mast at the remaining heights. Only single wake cases are available at >5D. Power measurements from the turbines are available. The sampling rate is 1 Hz. Figure 3 shows the wind farm layout with distances in rotor diameters. The first results from the project are described in (Lange *et al.*, 1999).

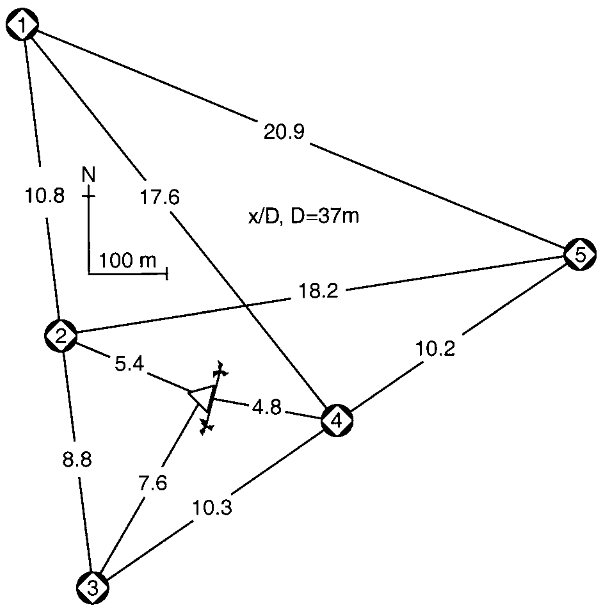

Figure 3. Distances between the turbines in rotor diameters at Bockstigen

1.1.3 Horns Rev

The wind farm at Horns Rev was erected approx. 14 km west of the Jutland coast in the harsh environment of the North Sea. The water depths at the erection site for the wind farm vary between 6 and 12 m. The site is characterised by a large undisturbed over water fetch in the western sectors towards the North Sea. The geographical layout of the Horns Rev wind farm is shown in Figure 4. A complete description of the measurements can be found in (Neckelmann and Petersen, 2000).

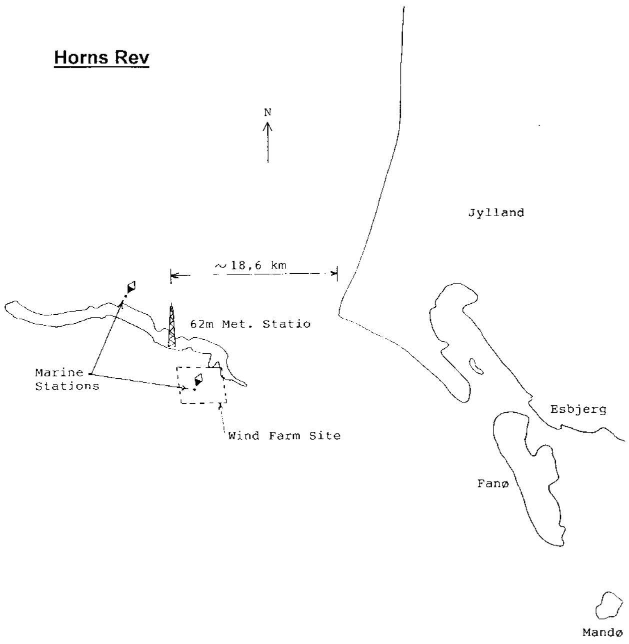

Figure 4. Geographical layout of the wind farm and the measurement systems at Horns Rev.

1.2 Scenarios

Scenarios were defined for Vindeby based on the one minute data set for different wind speeds, turbulence and stability. Data from 1994 and 1995 from LM, SMW and SMS were selected giving a total of 468,110 observations at the three masts simultaneously. An example for the single wake calculations is shown in Table 1. At SMS for directions 18-26 ° the number of observations is 2830. Adding simultaneous observations at SMW the number of observations is reduced to 1034. These are divided into 416 near-neutral, stable or very stable 217, unstable or very unstable 400.

Table 1. Numbers of observations for the single wake scenarios (18-26°)

		U(m/s)		6	8	10	15
TI (%)		#	<5	5-7	7-9	9-11	>11
Cate-gory	Range	1034	161	159	219	283	212
	<4	404	95	94	81	89	45
5	4-6	276	25	27	60	92	72
7.5	6-9	254	40	31	41	69	73
10	9-11	48					
15	>11	51					

2 Wake model evaluation

The objective of the wake model evaluation was to compare the performance of wake models of varying complexity in the offshore environment (Rados *et al.*, 2002). Criteria for improvements of the model were developed and the performance of enhanced models evaluated.

2.1 Wake models

Six different wake models were evaluated:

- Partner ECN: Wakefarm
- Partner RGU: 3D-NS
- Partner UOL: FlaP
- Partner MIUU: Transportation time model
- Partner GH: WindFarmer (Eddy Viscosity model)
- Partner RISO: Engineering model/CFD Model/WAsP

All models, with exception of the model used by MIUU, are based on the approximate solution of the Navier Stokes Equations. The model used by MIUU is significantly different as it uses an empirical approach that is based on the time needed to transport the wake to the point of interest. The differences between the other models are to be found in one or several of the following points:

- the degree of approximations used
- representation of the turbine
- the modelling of the near wake and initial profile
- the turbulence closure used
- the parameterisation of the turbulence
- the description of the boundary layer
- the wake superposition

An unexpectedly large difference in the predictions of the six models between each other and between most of the models and the observational data became apparent in the first evaluation undertaken. This prompted the wake modelling groups to investigate the causes for these differences, and to undertake model modifications.

Model improvements were made by the wake modelling groups mainly with regards to:

- The modelling of the near wake and the initial profile
- The turbulence parameterisation
- The description of the boundary layer
- The wake superposition
- Turbulence representation

Details of these improvements can be found in [Schlez, 2002 #1711]. Subsequently, the models were employed in the same simulations as before to evaluate their performance in comparison with each other and with the measurements.

2.2 Model simulations

The meteorological masts at Vindeby were located such that their positions relative to the wind turbines correspond to the same distances between the rows and the turbines. The four wake cases analysed were one single wake, two double wake and one quintuple wake case that are presented in Figure 1 and Table 2. Note, the MIUU transport time model was not modified and changes in the Risoe model were not included in these evaluations.

Table 2. Wake cases from Vindeby

Wake Type	Wind Direction range	Wake Mast	Free Mast
Single	18° to 28°	LM	SMS
Double	18° to 28°	LM	SMW
Double	70° to 78°	SMS	SMW
Quintuple	314° to 323°	SMW	SMS

LM: Land Mast; SMS: Sea Mast South; SMW: Sea Mast West

2.3 Single wake case

The cases presented here are single, double, quintuple wake at three different velocities (5, 7.5 and 10 m/s), different turbulence intensities and for neutral atmospheric stability. In the following figures the crosses represent the free measurements, the continuous line with symbols represents the free wind speed at LM and other the continuous lines represent the predictions of each of the different wake models. The single wake case was examined in detail in (Rados et al. 2002) and so only one single wake case is presented showing the improved wake model results. The six predicted curves for the single wake case are plotted in Figure 5 together with experimental data for three different turbulence intensities. All graphs are normalized with the free wind speed measured at 38 meters height at LM.

The comparison showed initially a surprisingly wide variation of the predictions between each other on the one hand and the experimental results on the other hand. The differences were highest for low turbulence cases that are of special interest in offshore wind farms and at low wind speeds where wake effects are most pronounced. The predicted curves follow the experimental data very well for high turbulence intensities, although some predictions still differ significantly for lower turbulence intensity (6%). When looking at the measurement it has to be taken into account that the data is normalised with the wind speed from the LM that is located on land about 1.4 km south. The model predictions were much improved by the new parameterisations, particularly in the case of the ECN and UO models. The variability between the predictions was reduced and the model simulations show better agreement with the experimental results.

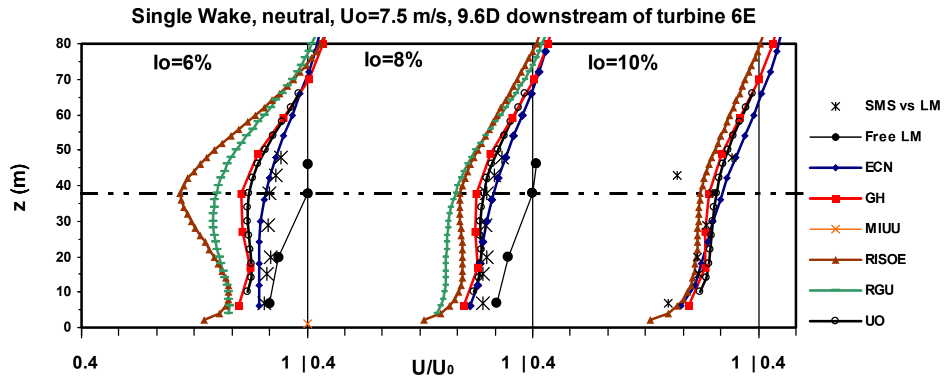

*Figure 5. Experimental data and improved wake models for the single wake case. Observations are indicated by *.*

2.4 Double wake cases

Double wakes of turbines 3E to 3W and 5E to 4W were measured at SMW at Vindeby. This gives two options for the double wake case and both are measured at mast SMW. The free wind speed for the 3E-3W option was taken from the Mast LM. For the 5E-4W option, the measurements at SMS provide information about the free wind speed. The original and improved wake model predictions are plotted in Figure 6, together with the experimental data. The experimental data measured at SMW was normalised with the free wind speed. The ambient turbulence (I_0) is 6% while three wind speed cases 5, 7.5 and 10 m/s are presented.

Most models predict a higher wake effect than was observed in the double wake situations at Vindeby. The improved models show better results with the predictions being closer to each other and closer to the experimental results although they continue over-predicting the wake effect. Possible reasons for this over-prediction include wake meandering or differences in the wake model superposition of multiple wakes in a wind farm situation. The measurements include a degree of uncertainty since the wake wind speeds are averaged over 5-10° direction variations from the centre of the wake and this is not reflected in the model simulations which use an exact wake direction only.

2.5 Quintuple wake case

For the quintuple wake case the 5 turbines wakes that contribute to the wake-effected wind speed at mast SMS are: 1W-2W-3W-4W-5W. The predicted curves for quintuple wake in Figure 7 are plotted together with the experimental data as before. The data was normalized with the free wind speed at Mast LM. The wind speed is increased from left to right at a fixed turbulence intensity of 8%.

Note that not all models can treat multiple wakes. The improved models show better performance than the original models but the model predictions are systematically biased relative to the experimental results (Schlez et al. 2002). A likely cause for this mismatch is the wake superposition methods applied. As in the single and double wake cases wake meandering may also contribute to the discrepancy between the models and the data.

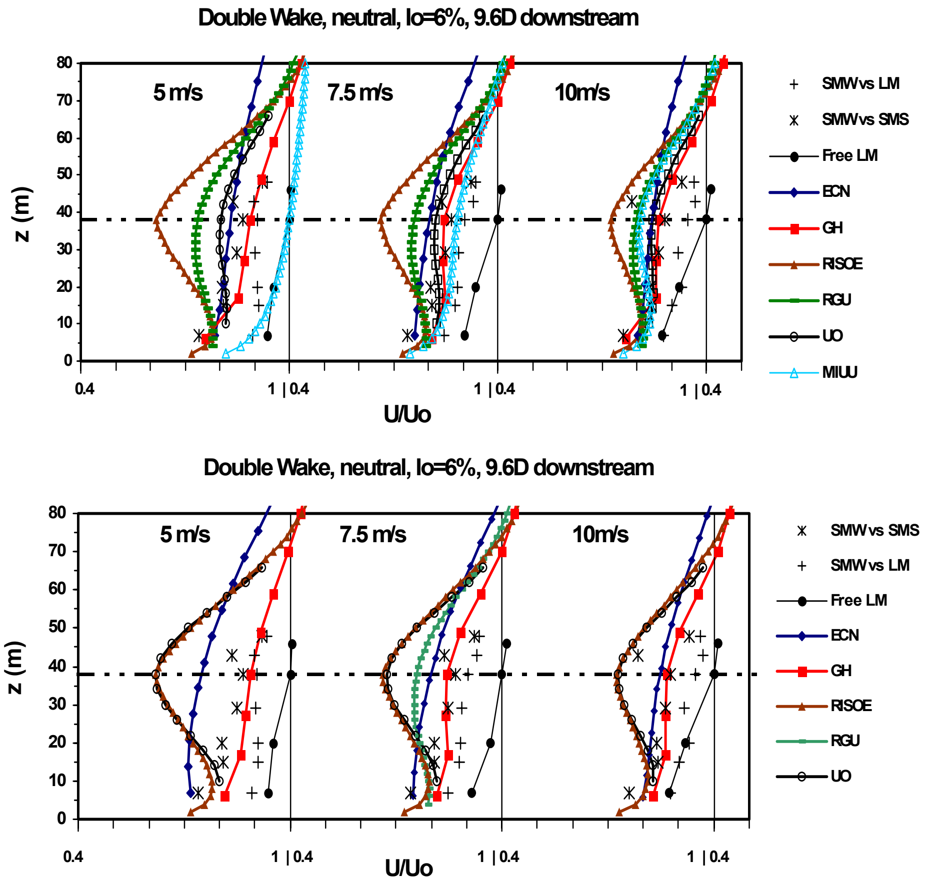

Figure 6. Double wake cases showing experimental data, original (lower) and improved (upper) wake model simulations.

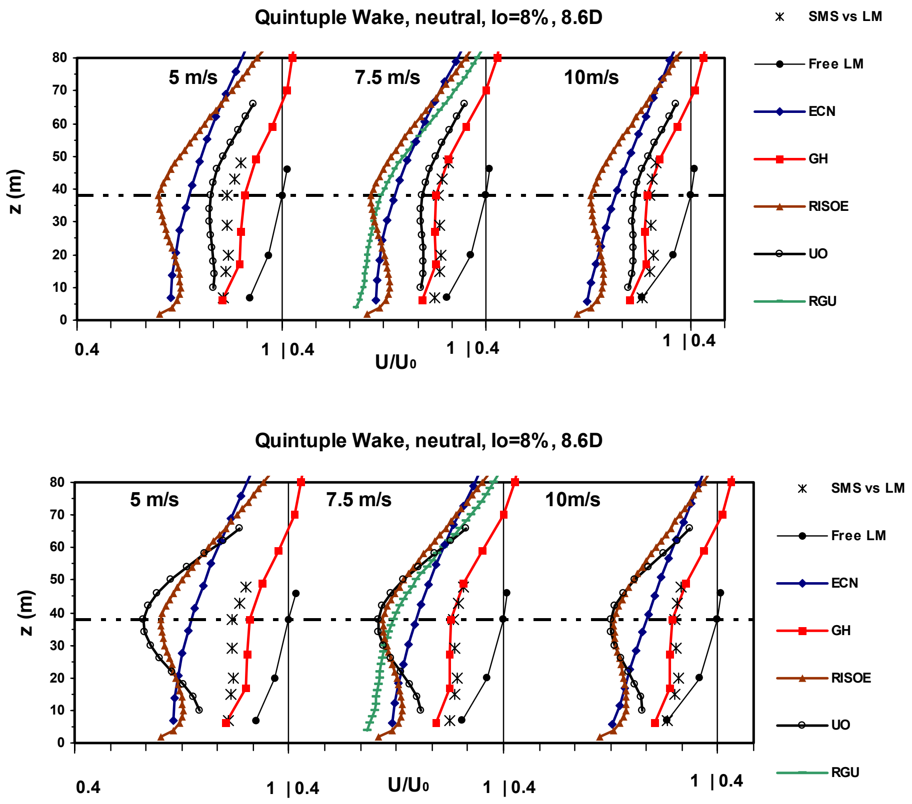

Figure 7. The quintuple wake case showing experimental data, original (lower) and improved (upper) wake model simulations.

The partners have undertaken various improvements to their wake models (see e.g. (Lange et al. 2002), (Schepers *et al.*, 2002). The most important modifications focus on the parameterisation of the near wake, the modelling of wind profile and most critically the treatment of turbulence. Different approaches for wake superposition have been used by the partners, advantages and disadvantages of the approaches became apparent in the quintuple wake comparisons. For further investigation it is recommended to focus on the understanding and modelling of the near wake, the wake superposition and effects related to the statistics, dynamics and magnitude of wind direction changes and associated effects like wake meandering.

Subsequent to this analysis, comparison of the wake model incorporated within WAsP (Mortensen et al. 1993) with the Vindeby scenarios has been conducted. Results are summarized in Table 3. Predicted wind speeds at hub-height are close to those observed (root mean square (RMS) error of 0.37 m/s) in the three lowest wind speed scenarios (up to 10 m/s) at a distance of 9.6 D but the WAsP wake algorithms under-predict the wake magnitude at high wind speeds, possibly indicating the wake recovery as manifest in the algorithms is too rapid, although this discrepancy may also reflect the influence of stability on turbulence profiles and hence wake decay and the influence of wake meandering on the observations.

Table 3. Wake calculation using (1) and (2) of Vindeby scenario using WAsP. The wake wind speeds represent the hub-height (m/s). Also shown are the observed wake wind speeds at 9.6D.

Distance as rotor diameters	3	5	7	9.6	9.6 observed	U_{WAsP}-$U_{freestream}$ (%)	10
Distance (m)	106.5	177.5	248.5	340.8			355
$U_{freestream}$ (m/s)							
5.02	2.89	3.42	3.77	4.08	4.33	-0.25	4.12
7.27	5.03	5.59	5.96	6.29	6.42	-0.13	6.32
9.75	7.40	8.02	8.40	8.73	8.80	-0.07	8.78
13.70	11.50	11.96	12.23	12.46	11.74	0.69	12.49

3 Boundary-layer modelling

Two kinds of boundary–layer models have been evaluated. Mesoscale models give the best representation of atmospheric physics – however they are computationally intensive. Linearised models are simpler and faster to run, however they are typically local scale (~50 km) and do not contain parameterisations of thermal mesoscale flows such as the sea breeze.

3.1 MIUU mesoscale simulations

The offshore wind climate over the Baltic Sea area has been investigated using the three-dimensional higher-order closure MIUU-model from Uppsala University. A technique for modelling the wind climate with this type of model is presented. Following the good agreement between model estimates and observations, it was judged that the model output may be used to analyse different aspects of the offshore winds in detail. For example, the influence from land/sea temperature differences on the wind climate and the effects of the related thermally driven flows were investigated and an attempt was made to quantify these effects on the offshore wind power potential over the Baltic Sea.
Since stability effects tend to average out over the course of the year, the RMS-error of the monthly wind speed differences between model simulations with and without effects from thermally driven flows give an alternative and to some extent more relevant estimate of the true influence from land/sea temperature differences. The RMS error for all offshore grid points was estimated to be 6-11% on a monthly basis. Such errors are about five times larger than the ±2% errors determined for the annual average wind speed. The most extreme RMS errors found offshore were –52% and +75%. Figure 8 shows the seasonal differences and Figure 9 the annual differences between winds simulated with and without temperature differences between land and sea. These results indicate significant spatial variability with largest differences in spring and summer. Without temperature variations wind speeds tend to be lower in the northern Baltic during spring and higher in the southern Baltic during summer. This might be expected in near-surface wind speeds if stable conditions in the northern Baltic during spring were producing wind speed profiles which were more stable than logarithmic. Conversely warmer seas in the southern Baltic might

produce slightly unstable conditions giving an unstable wind speed profile (so slightly lower wind speeds than predicted by the logarithmic profile at the same height). Further details of this work are presented in (Bergström 2002).

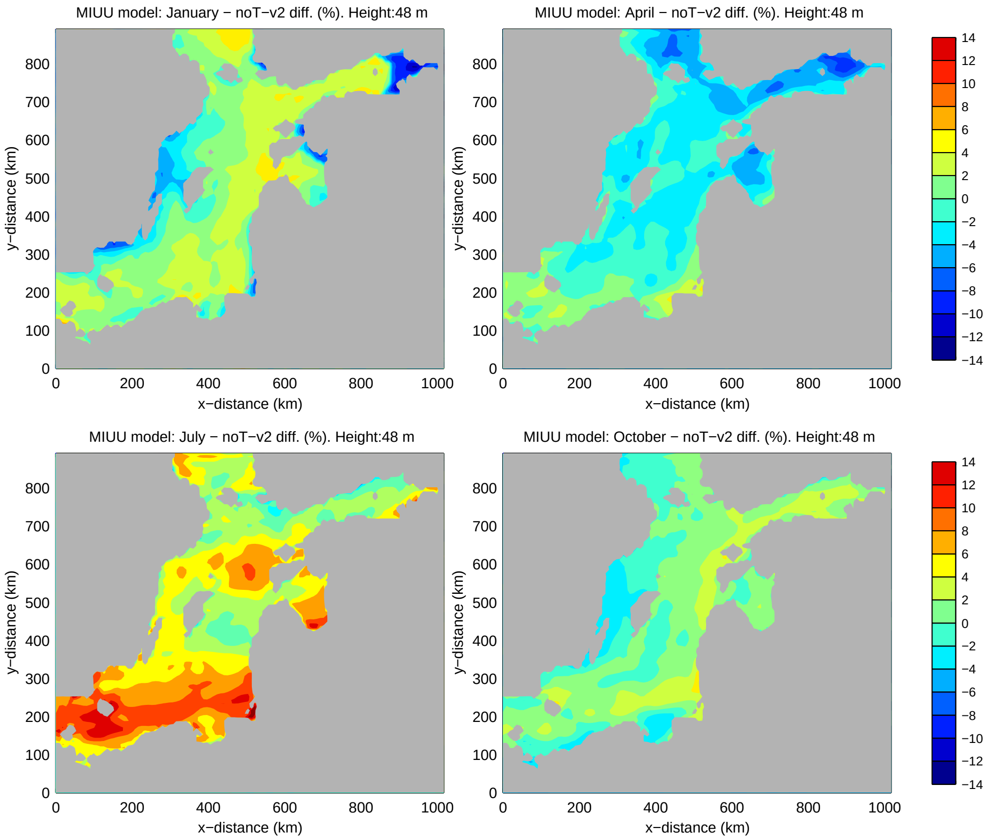

Figure 8. Average wind speed differences (%) between the model runs made with no land/sea temperature differences, and the full climatological runs. Monthly averages for January, April, July, and October

A statistical analysis of the wind fields generated by the MIUU-model reveal the existence of low level jets (LLJ) and suggest that the gain to the wind potential is largest in the western and northern part of the Baltic Sea and may also affect some coastal areas. The influence from a LLJ increases with height with important consequences for modelling wind speed profiles. Model tests without topography (Figure 10) and with no roughness differences between land and sea (Figure 11) reveal that those factors are about equally important to the offshore wind climate as the thermally driven flows.

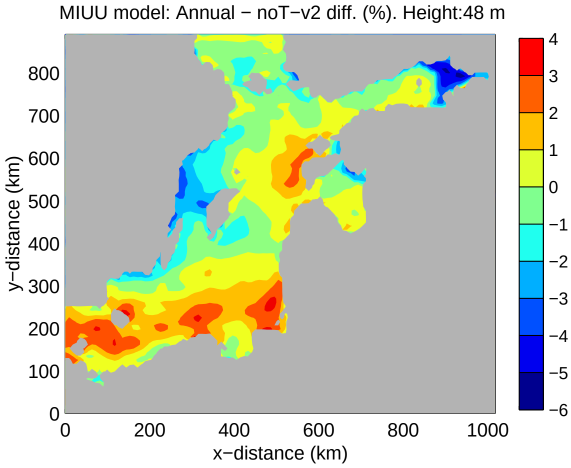

Figure 9. Annual average of difference (%) in mean wind speed between the model runs made with no land/sea temperature differences and the full climate runs.

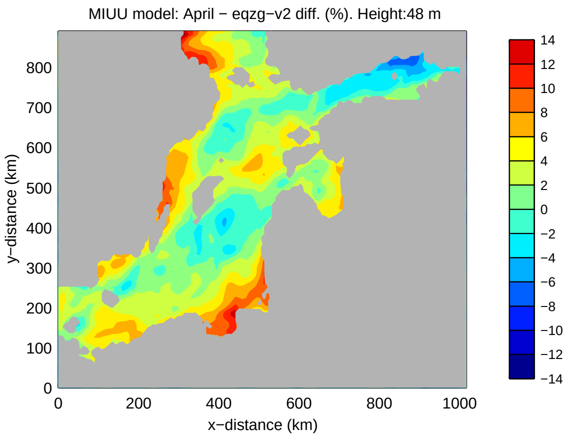

Figure 10. April average of difference (%) in mean wind speed between model runs made without topography and the full climate runs.

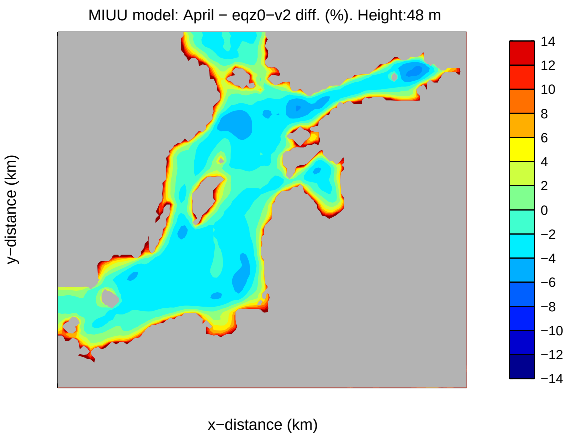

Figure 11. April average of difference (%) in mean wind speed between model runs made without roughness differences and the full climate runs.

The MIUU-model has also been used to study the thermal stability offshore over the Baltic Sea (Figure 12). Unstable conditions were most common in the southern and south-eastern parts, estimated to occur more than 50% of the time in this area. Stable conditions were most common along the coasts and in the northern part of the Baltic Sea, estimated to occur 30-50% of the time here.

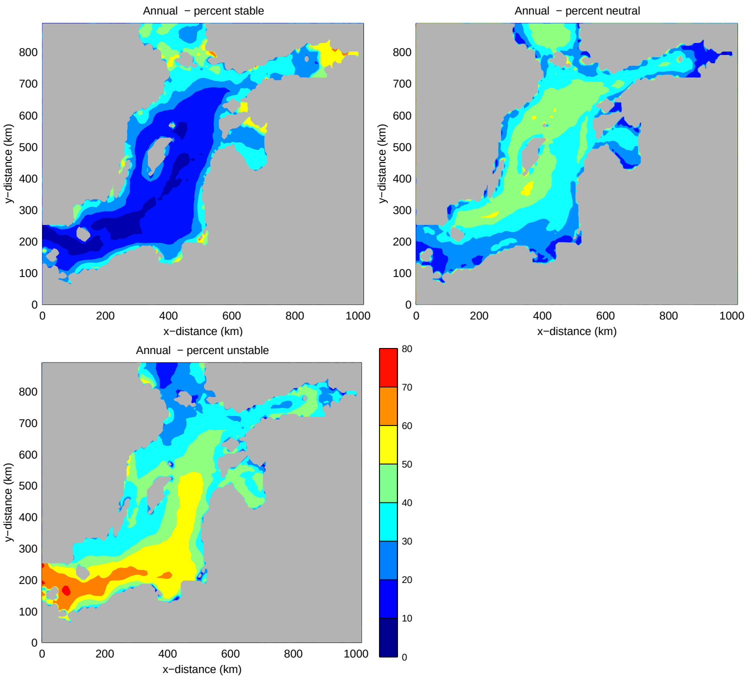

Figure 12. Percentage of stable, neutral (|Ri|<0.05), and unstable stratification conditions. Annual average estimated from climate runs with the MIUU-model.

In synthesis these results indicate:

- The critical importance of boundary conditions for the correct treatment of stability and in situ turbulence which are as important to wind resource predictions as roughness and topography
- That conditions offshore are frequently non-neutral which will impact the dissipation of wind turbine wakes
- That wind speed/stability/turbulence appear to vary on scales which are comparable to those of proposed large offshore wind farms and therefore should be taken into account.

3.2 Comparing the MIUU-model and WAsP/CDM

Thermal stratification of the offshore boundary layer thus deviates from neutral for an appreciable part of the year. There are also large differences between different parts of the Baltic Sea. It is thus important to take the non-neutral temperature conditions into account when estimating the wind potential, both because it affects the vertical wind profile, and because the internal boundary layer growth is highly dependent on thermal stability. Often the thermal stability is not taken into account in each observation by the commonly used simplified analytical models, rather a simplified stability-corrected profile is applied to the statistics, e.g. the WA^{S}P model from Risø in Denmark.

To understand the differences given in the offshore wind potential using simplified models, the annual mean wind climate over the Baltic Sea, estimated with the MIUU-model and with WA^{S}P, have been compared. The result is shown in Fig. 13. The MIUU-model was used on a 9 km resolution as presented in Section 3.1. The WA^{S}P estimates, taken from the POWER project (Halliday *et al.*, 2001) were not made using measured winds at coastal sites as reference, which is usually the case, but instead WASP was used to estimate the boundary layer winds from geostrophic wind data (Bergström and Barthelmie, 2001).
Using WA^{S}P in this way, the differences between the two models are typically rather small ±3% as regards the far offshore areas, while in coastal areas WA^{S}P tends to predict 10-15% higher winds. Figure 14 shows a sample of results from the CDM which is a one column model accounting for stability differences offshore. As shown the model is able to capture the spatial variability of stability variations and their impact on wind resources.

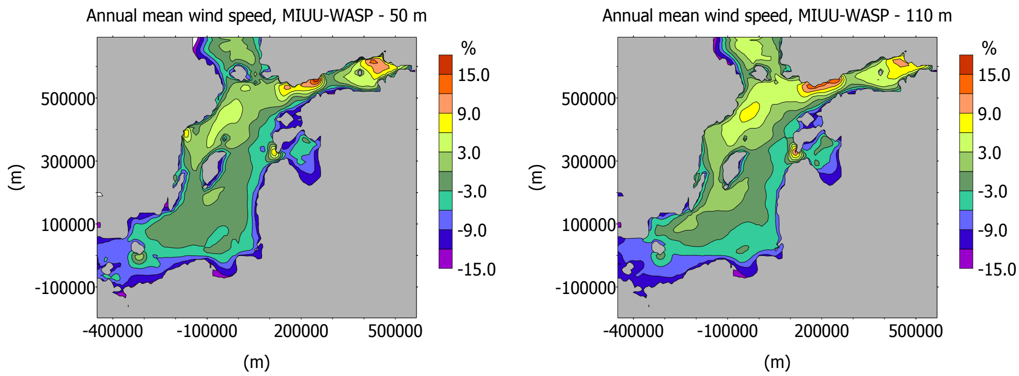

Figure 13. Annual average wind speed difference between the MIUU-model and WAsP at 50 m and 110 m heights. Numbers given in percent.

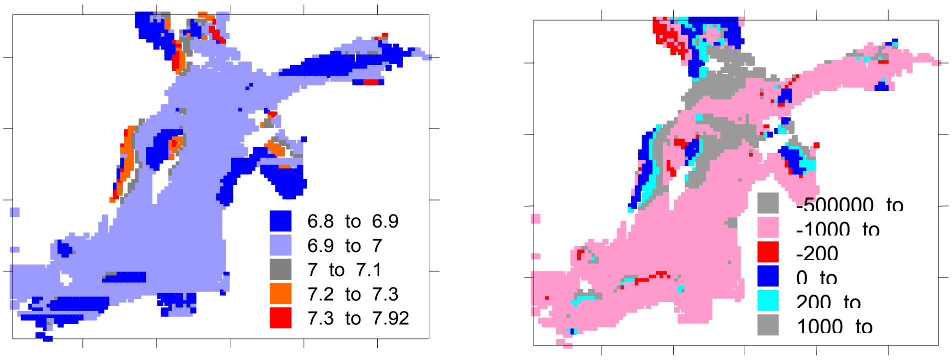

Figure 14. Sample model runs from the CDM for geotsrophic wind of 10m/s and 270°.

4 Sodar measurements

4.1 Experimental data

A ship-mounted sodar was used to measure wind turbine wakes at the Vindeby offshore wind farm in Denmark (Figure 15) The wake magnitude and vertical extent were determined by measuring the wind speed profile behind an operating turbine, then shutting down the turbine and measuring the free-stream wind profile (Figure 16). These measurements were compared with meteorological measurements on two offshore and one coastal mast at the same site. The main purposes of the experiment were to evaluate the utility of sodar for determining wind speed profiles offshore and to provide the first offshore wake measurements with varying distance from a wind turbine. Over the course of a week 36 experiments were conducted in total. The results are presented here in the context of wake measurements at other coastal locations.

April was chosen for the experiment to avoid periods of very high wind speeds (which mainly occur in winter). However, to measure wakes, wind speeds also have to be above turbine cut-in wind speeds of 4 m s^{-1} making summer months less attractive. Mean wind speeds measured at 10 m above mean sea level at SMW in April for the period 1996-1999 inclusive are 7.4 m s^{-1} with mean air temperatures of 5.9°C and a mean water temperature of 5.8°C. The positions of the ship and turbines were measured using a GPS to an accuracy of ± 4 m. As in (Fairall et al. 1997) recording of the tilt and yaw were made. Data were discarded if the tilt angle exceeded ± 4°.

Figure 15. Setting up the sodar (left) and the sodar in position behind a wind turbine at Vindeby (right)

Figure 16. A perfect double wake (left) and quintuple wake (right). Despite the occurrence of these situations, it proved almost impossible to make measurements in these wake conditions due to the directional variability of the wind.

After quality control of the data (mainly to exclude rain periods), 13 turbine-on, turbine-off pairs were analysed to provide the velocity deficit at hub-height as a function of the distance from the turbine. Details are given in Table 4.

Table 4. Details of single wake experiments. # refers to the designation of the experiment (also shown in Figure 10). Relative velocity deficit is calculated from sodar wind speed profiles using a height of 40 m. Free stream wind (U) at 48 m and direction (dir.) are measurements from the meteorological mast, and D the distance to the turbine expressed as number of rotor diameters. Max. disp. is the largest distance from the centre of the wake due to the directional variability of the wind during each experiment (expressed as a fraction of rotor diameter). Ambient turbulence is designated I_0 (%).

#	ΔU/U	U (m s^{-1}) at 48 m	Dir (°)	D	Max. disp.	I_0 (%)
1	0.36	10.54±0.30	336.4±0.9	3.8	0.3	5.8
2	0.13	8.76±0.43	341.2±2.3	6.5	0.75	8.0
3	0.53	8.76±0.43	342.8±1.9	4.1	0.3	7.6
4	0.37	5.74±0.20	226.6±1.1	2.8	0.3	4.2
5	0.30	5.74±0.20	226.6±1.1	3.6	0.5	4.2
6	0.21	5.74±0.20	226.6±1.1	4.5	0.5	4.2
7	0.24	6.37±0.25	152.2±3.1	3.4	0.5	7.7
8	0.32	3.76±0.33	133.1±4.8	4.1	0.5	5.3
9	0.44	6.90±0.59	219.6±2.3	1.7	0.3	7.7
A	0.35	7.54±0.45	205.8±3.3	2.9	0.5	9.0
B	0.11	6.12±0.74	207.8±3.2	7.4	0.5	15.1
C	0.27	8.19±0.46	221.9±3.0	3.4	0.3	8.7
D	0.22	8.19±0.46	221.9±3.0	5.0	0.5	8.7

In Figure 17 the velocity deficit profiles have been grouped according to distance from the turbine (expressed as number of rotor diameters D). Out of the three near-wake experiments, (#4 and 9) two show a distinct minimum at the height of the turbine nacelle and maximum at the mid-points of the blades (29 and 48 m). This is not so evident in the third experiment (#A) which was also at less than 3 D. Of the 5 experiments between 3.3 and 3.9 D all except #5 show a similarly shaped profile with a maximum velocity deficit close to 40 m height. However, there is quite a large variation in the velocity deficits and the two experiments conducted in near-neutral conditions (# 1 and 3) have the highest velocity deficits. Theory predicts that wake recovery should be faster in near-neutral conditions. Three experiments were conducted at distances of 4.1-5.0 D and these show a fairly flat profile. There are two 'far wake' experiments (D>6) which show good agreement in the velocity deficit profile. More details of the experiment can be found in (Barthelmie et al. 2003).

Figure 18 shows the summarised wake data from a number of coastal (onshore) and inland sites (Magnusson and Smedman, 1996). Figure 18 also shows the relative velocity deficit against D from the SODAR experiment with a regression line estimated from the data in (Magnusson and Smedman, 1996) as:

$$\frac{\Delta U}{U} = 1.03 * D^{-0.97} \quad (1)$$

Relative velocity deficits from the SODAR experiment (Table 4) are also shown. Regression of these data give the following fit:

$$\frac{\Delta U}{U} = 1.07 * D^{-1.11} \quad (2)$$

Correlation coefficient for this fit (velocity deficit versus distance in rotor diameters) is 0.91 if the two points outside of the data ellipse are neglected. Although the velocity deficits from the SODAR experiment are smaller than those from (Magnusson and Smedman, 1996) (for the same distance), the difference is small compared to the uncertainty in the measurements. The agreement between the distance decay of the velocity deficit from the offshore Vindeby experiment and the onshore data may also partly reflect the coastal location of many of the measurement sites used in that study which have similar turbulence intensity levels to the Vindeby site.

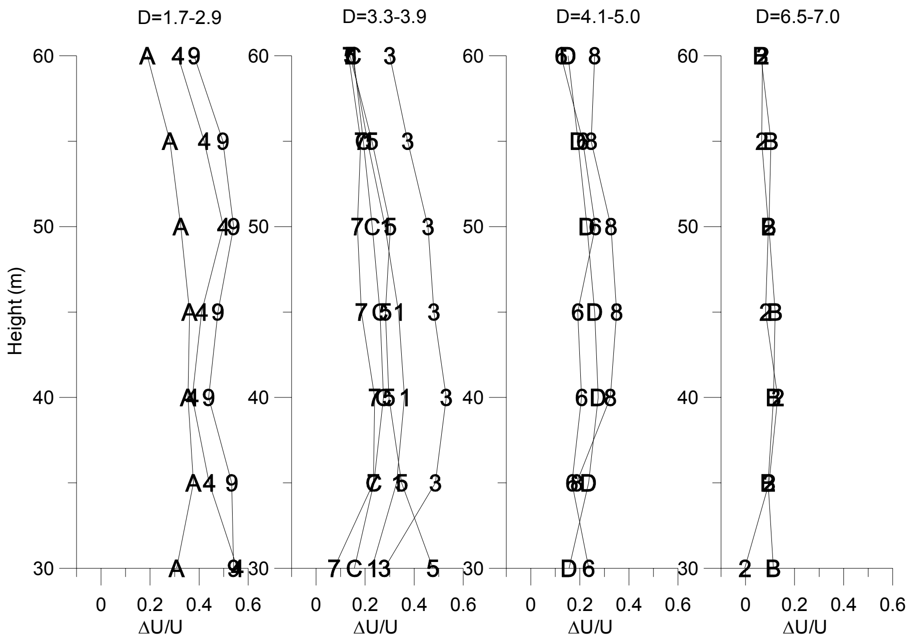

Figure 17. Velocity deficit profiles determined by sodar for single wakes

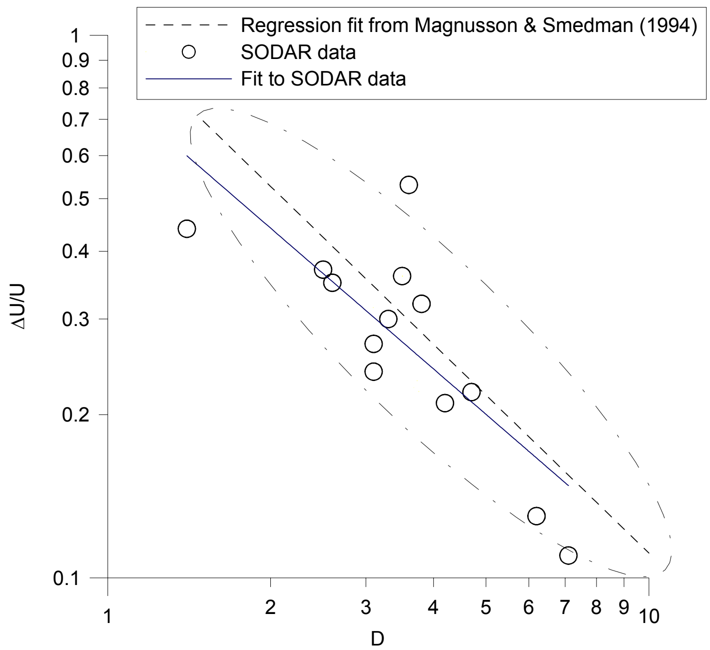

Figure 18. Relative velocity deficit by distance (shown here as number of rotor diameters D). The ellipse shows results from Magnusson and Smedman (1994).

The velocity deficit profile depends on a number of factors including wind speed profile, the wind speed related thrust coefficient of the wind turbine, ambient (mechanical and thermal) and turbine generated turbulence, the possible presence of an internal boundary layer or non-equilibrium conditions as flow adjusts in the coastal area. Hence it is difficult to analyse the data further without use of wake/meteorological models. The next phase of this work involves a comparison of the wake models with this data set.

4.2 Comparison of sodar results with wake model simulations

Figure 18 shows the results of the wake model comparisons with the sodar data. While there is some variability between the results and the measurements, discussions with the wake modellers revealed that not all the simulations were made on an equal basis using the same free-stream wind profile. Hence, the model simulations are now being re-evaluated using three sets of pre-agreed simulations which assume different free-stream conditions according to whether the sodar or the meteorological masts are used and with fixed or Charnock roughness length. The sodar measurements show that the load distribution on the rotor is visible in the initial near wake profile (i.e. the near wake profile is a 'double dip' profile with a local minimum in the rotor plane). As such, the 'Gaussian like' shape for the initial near wake profile as applied by most participants is a too crude approximation. Most operational wake models are not designed for use at less than 3-4 D.

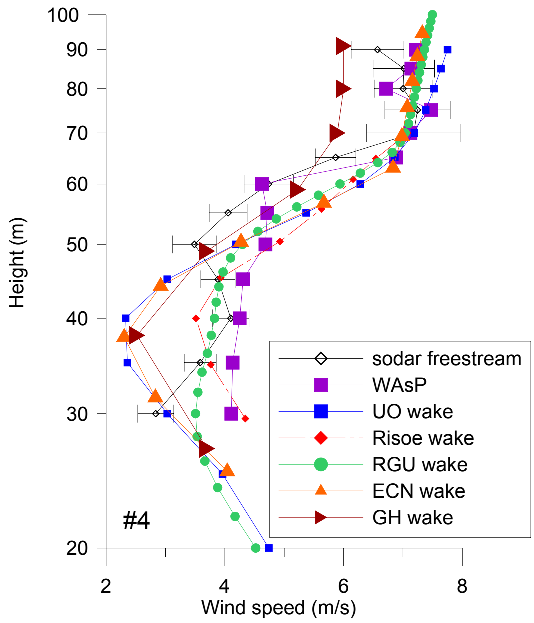

Figure 18. Comparison of sodar measurements with wake model simulations

5 Design tool development

The final objective of the project is to produce a design tool which can be used to improve the layout of offshore wind farms (Schepers et al. 2002). The design tool has been implemented with a modular concept linked by a series of interfaces so that data can be exchanged between the various modules. This has a major advantage for the user who is free to select any of the available software. The concept of the design tool with the links in place is shown in Figure 19.

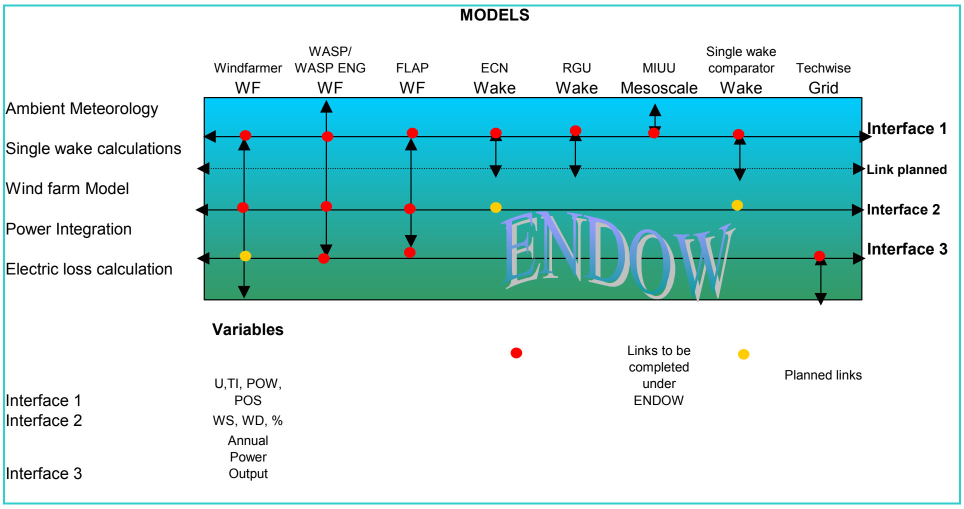

Figure 19. Overview of the ENDOW design tool

The design tool comprises a number of wind farm modules together with the following:
1) Meteorological interface
2) Improved wake model (as described in section 2)
3) Grid connections

1. The meteorological interface
The meteorological interface uses a combination of models to predict wind speed and turbulence which can be used as input to one of the wake models implemented. To date, the transport time model (Magnusson and Smedman 1996), a semi-analytical model based on Prandtl's turbulence boundary equations (Larsen et al. 1996) and the PARK model (Sanderhoff 1993) have been implemented allowing comparison of the reduced wind speeds in wind turbine wakes predicted by the different models (Figure 12).
Further work involves implementing the more comprehensive multiple wake models in the tool.
2. Improved wake models
As described in section 2 most of the wake models have undergone significant enhancements under ENDOW focusing on the near-wake parameterisation and the treatment of turbulence intensity.
3. Grid tools
Two grid tools have also been developed, one comprehensive model implemented in the Windfarmer program and a simpler grid tool developed by Techwise which can be used to calculate cable lengths for different turbine positions.

6 Evaluation

The evaluation consists of:

- Comparison of wake models within the ENDOW single wake generator. Models implemented include the transport time model based on the MIUU model, Risø's Engineering model and a version of the WAsP PARK code. An example of the GUI is shown in Figure 20.

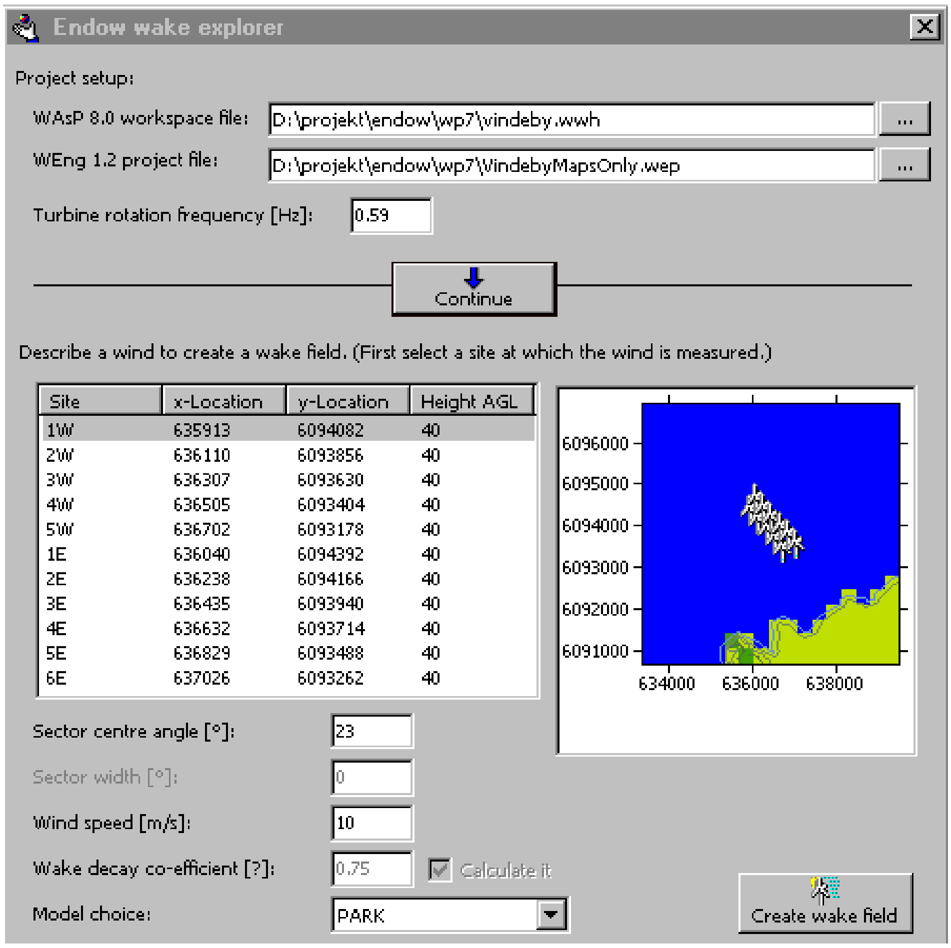

Figure 20. Example GUI from the ENDOW single wake generator

- As described in (Barthelmie *et al.*, 2003) a number of sodar wake profiles are available for comparison with wake models. The advantage with using the sodar data is that near-wake measurements are available as are wake measurements at varying distances from 1.4-7.1D. The main difficulties in making the comparison are to ensure that the wake models are initialised using the same (free-stream) wind speed profile and that most of the models did not consider the averaging of the wake within the volume covered by the sodar, an effect which reduces the measured wake effect. Figure 21 shows an example of the wake profiles simulated for a wake case (3.1D) and the sodar free-stream and wake profiles.

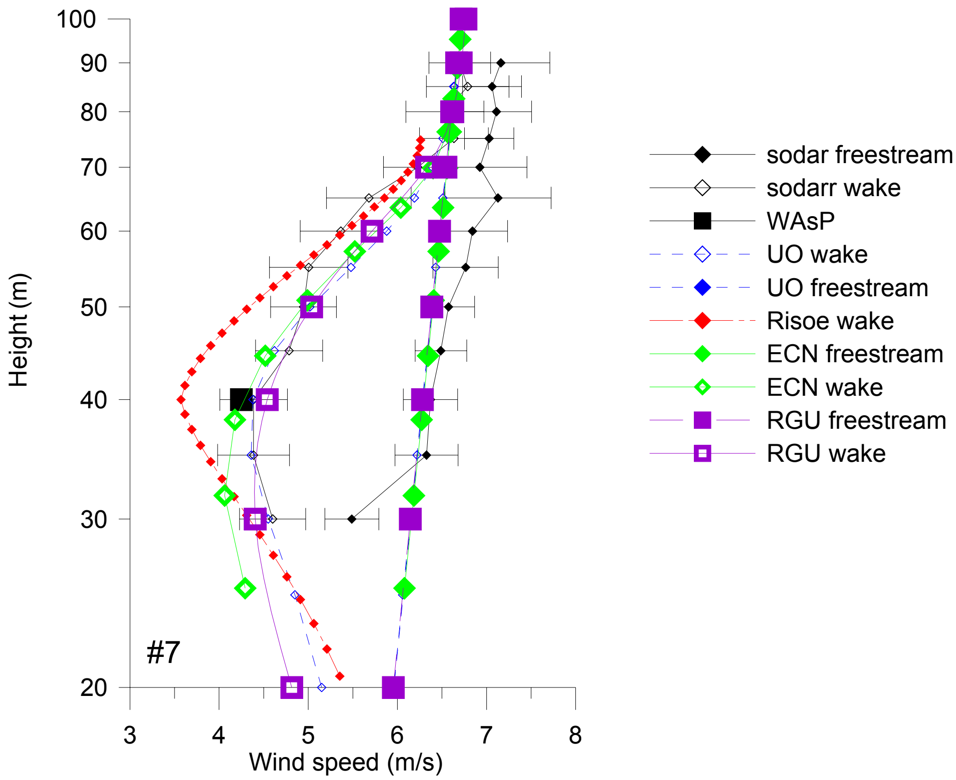

Figure 21. Wake model simulations compared with sodar measurements of wakes at the Vindeby wind farm. The distance from the wind turbine is 3.1D.

- The third part of the evaluation compares power output predictions with measured values and examines wind farm layouts and is described in the next section.

7 Wind farm layouts

The three test cases are Vindeby, Middelgrunden and Horns Rev (Figure 22).. The three windfarm models used are WASP 8, Windfarmer Version 3.1.4 and FlaP

At Vindeby, power output was compared with observed values for the same period at two turbines 4W and 5E (see Figure 2). Figure 23 shows the WAsP predicted power output by sector with the observed values. As shown in Table 5, the modelled wake deficit is similar using the 3 models.

The site at Middelgrunden is rather complex being only 2km from the shore with a bow shaped wind farm with turbine spacing 2.4 D which is beyond the prescribed limits of the models (Figure 24). Nevertheless all three models are able to predict the turbine power output with reasonable agreement (Figure 25). The two major problems with the evaluation are first that the wind observations used in the model simulations are from 97-99 while the power observations from the turbines are from 2002. During 2002 flow had a more easterly component than is typically observed at this site. During 1997-99 flow was predominately westerly/south-westerly. Second, no information on turbine outages has been included in the analysis.

An optimised layout produced by Windfarmer puts the turbines into rows taking advantage of the slightly higher wind speeds predicted by WAsP at slightly larger distances from the coast and increases the turbine spacing. (Figure 26).

The wind farm models can also deal with relatively large wind farms like Horns Rev. Predicted wake losses are 6.7-10.1% depending on assumptions about the wake decay constant and turbulence level. Figure 27 shows the wake loss predictions from FlaP.

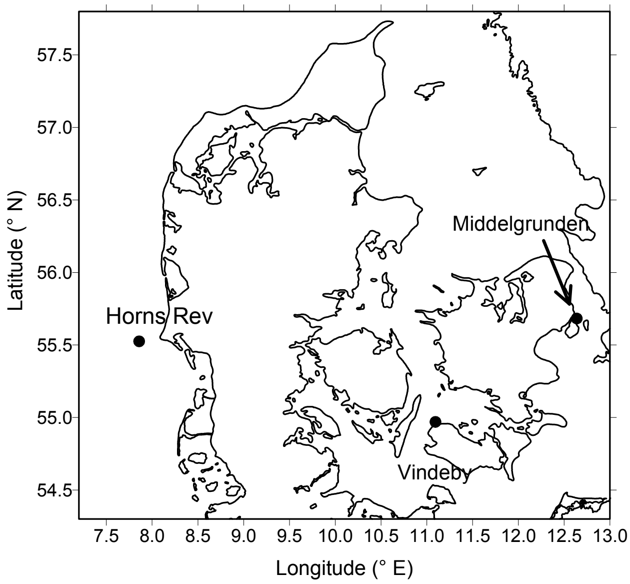

Figure 22. Locations of the evaluation sites.

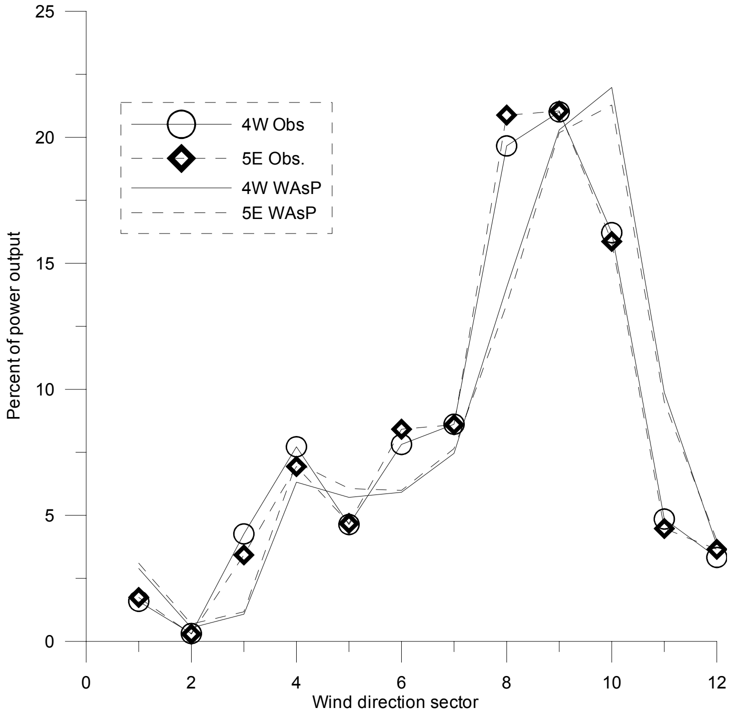

Figure 23. WAsP predicted power output compared with the observed at two turbines (4W and 5E) at Vindeby by 30° directional sector.

Table 5. Comparison of Windfarmer, WAsP and FLAp results at Vindeby

	Predicted wake loss 4W (%)	Predicted wake loss 5E (%)
Windfarmer	2.2	4.4
WAsP	2.43	4.89
FLaP	2.33	4.51

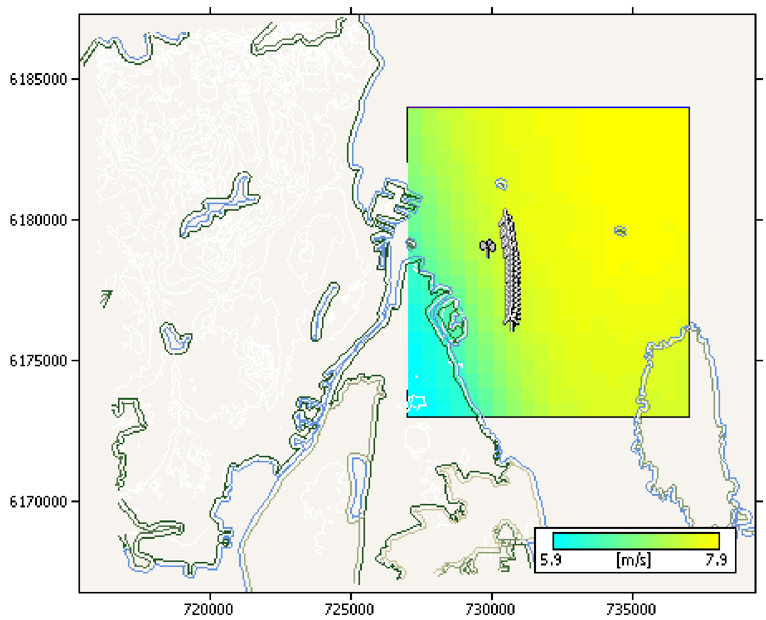

Figure 24. Middelgrunden wind farm and the WAsP predicted wind resource

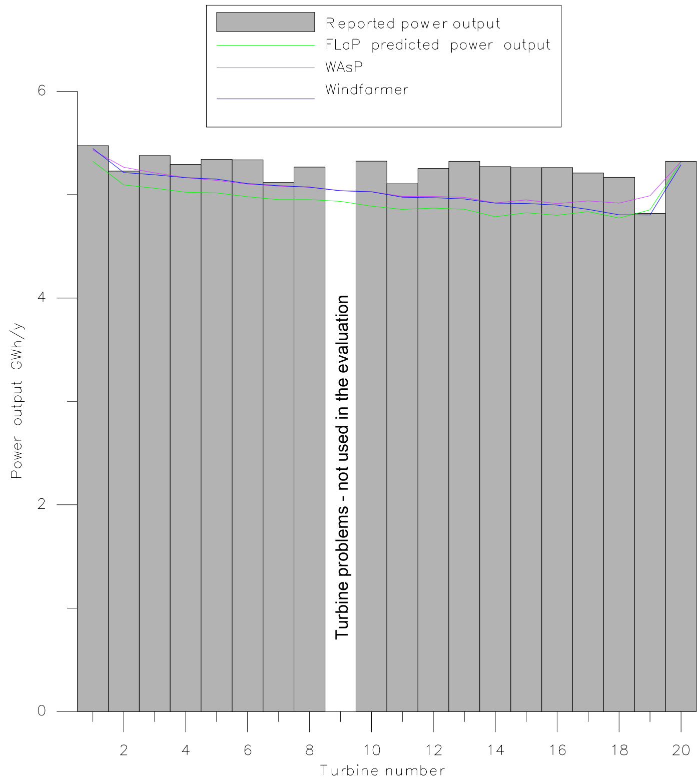

Figure 25. Comparison of Windfarmer, WAsP and Flap predicted power output with observed by turbine. The two major problems with the evaluation are first that the wind observations used in the model simulations are from 97-99 while the power observations from the turbines are from 2002. Second, no information on turbine outages has been included in the analysis.

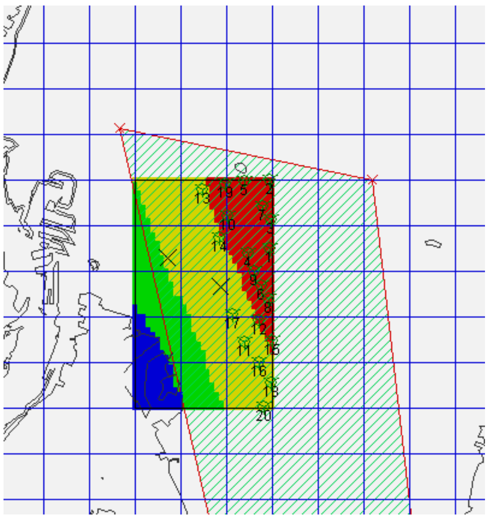

Figure 26. Optimised wind farm layout produced by Windfarmer for Middelgrunden. The area was constrained using the rectangle for which resource calculations were made (shown with blue, green, yellow and orange shading).

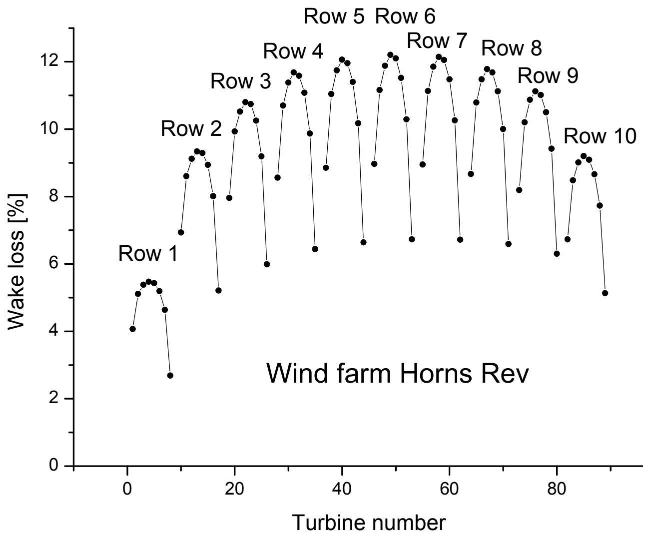

Figure 27. Wake losses by turbine for wind farm Horns Rev calculated with FLaP

8 Conclusions

The products and primary results of the ENDOW project can be summarised as:

- New databases have been constructed containing one minute data from Vindeby which are suitable for examining wake case studies or creating scenarios
- Six wake models were evaluated in a number of scenarios at different wind speeds, turbulence and stability
- A sodar experiment was conducted offshore. The data were used for further wake model evaluation and to provide important insights on the shape of the near wake profile
- The parameterizations of the wake models have been improved mainly in relation to turbulence treatment but also with regard to wake profiles
- Boundary-layer models have been utilised to illustrate the importance of thermal and other effects on predicted wind resources
- A design tool has been assembled in which free-stream wind and turbulence are predicted and a number of wake models can be compared
- A workshop was held to discuss power prediction of offshore wind farms focused on wake effects (Barthelmie et al. 2002)

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Abstract (Max. 2000 characters)

The objective of the ENDOW project was to evaluate, enhance and interface wake and boundary-layer models for utilisation offshore. The project resulted in a significant advance in the state of the art in both wake and marine boundary layer models leading to improved prediction of wind speed and turbulence profiles within large offshore wind farms. Use of new databases from existing offshore wind farms and detailed wake profiles collected using a sodar provided a unique opportunity to undertake the first comprehensive evaluation of offshore wake model performances. The wake models evaluated vary in complexity from empirical solutions to the most advanced models based on solutions of the Navier-Stokes equations using eddy viscosity combined with a k-epsilon turbulence closure. Results of wake model performance in different wind speed, stability and roughness conditions provided criteria for their improvement. Mesoscale model simulations were used to evaluate the impact of thermal flows, roughness and orography on offshore wind speeds.
The model hierarchy developed under ENDOW forms the basis of design tools for use by wind energy developers and turbine manufacturers to optimise power output from offshore wind farms through minimised wake effects and optimal grid connections. The design tools are being built onto existing regional scale models and wind farm design software which was developed with EU funding and is in use currently by wind energy developers. This maximises the expected impact of this project through efficient use of existing resources and ease of upgrade for end-users.