UpWind

SIXTH FRAMEWORK PROGRAMME

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- Centre for Renewable Energy Sources (CRES)
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- Renewable Energy National Centre of Spain (CENER)
- Garrad Hassan and Partners Limited

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Flow

THE CHALLENGE

The challenge is to develop wind farm models that can be used to accurately predict power losses and loads in wind farms and used to optimise wind turbine spacing whether in flat or complex terrain, onshore or offshore.

When wind turbines are placed together in a wind farm, the flow from one turbine impacts the flow of the next turbine downwind. Because the first turbine has extracted energy from the wind, the second (downwind) and subsequent turbines experience lower wind speeds and hence have lower power output. Each turbine also creates turbulence as it rotor rotates so the downwind turbine experiences higher turbulence levels causing increased loads.

The volume of higher turbulence level and lower wind speed behind a wind turbine is called the wind turbine wake. Wakes are a serious problem in wind energy technology because the deficit of energy production can be as high as 20% of the energy produced by a singe turbine at the same site, depending on the size of the wind farm, its location and the type of wind turbine. This work package aims to improve wake models used in wind farm design so that power losses can be accurately predicted.

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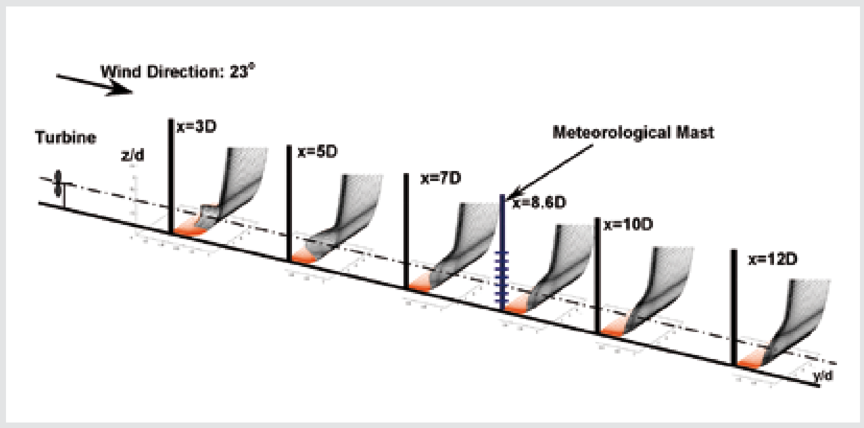


THE RESEARCH ACTIVITIES

R&D is focused on understanding how wind turbine wakes behave in complex terrain and offshore. Many wind farms are now being developed in complex terrain. We know that wakes behave differently in non-flat terrain and it is necessary to understand how wakes change as they move over hills. The strategy is to use more complex Computational Fluid Dynamics (CFD) codes because these are expected to gain a better description of the general flow in complex terrain. These models are computationally intensive and we need new strategies for depicting large numbers of turbines within these codes.

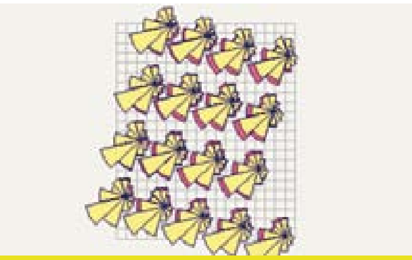
Three model simulation types are being carried out to compare the performance of the CFD models with wind farm models where appropriate:

- Simple terrain (Gaussian Hill);
- Five turbines in flat terrain;
- The complex terrain wind farm.

Very large wind farms are being developed offshore and the first indication from wind farm measurements are that standard wind farm models under-predict power losses due to wakes. We have been able to develop 'engineering solutions' to bring model predictions in line with observations but now R&D activities are focusing on understanding why wind farm models which work well over land or for small wind farms offshore do not work well for large offshore wind farms. There are a number of processes which need to be evaluated including changes in the structure of the boundary layer over the wind farm due to wind turbines wakes, how multiple wakes are combined in wind farm models and the behaviour of wakes at the edges of the wind farm.

Due to the time and expense of taking long-term measurements, research relies on the wind farm developer's willingness to share data with the WP team so that the data can be used (confidentially, if required) to evaluate the performance of the different model formulations. The work is a mix of analysis, building physical models, analysing data sets for specific situations and evaluating and verifying whether the accuracy of the prediction of power losses from wakes has become more accurate.

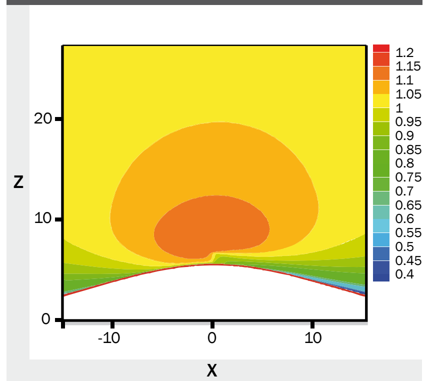
The comparison between wake models and measurements is based on the full spectrum of models from wind farm codes which use moderately simple wake models to full CFD models. The most straightforward models are those using



Wakes losses predicted in a large wind farm.

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 axis symmetric. One example is the WAsP model. There is a whole group of models which are based on a semi-empirical model, developed by John Ainslie. These include GH WindFarmer. ECN's WAKEFARM model is based on the UPMWAKE code which originally was developed by the Universidad Politécnica de Madrid. By using these models and the simpler models described above, it is not possible to model the near-wake physics explicitly. Hence these models are not valid at less than approximately 3 rotor diameters from the turbine. The remaining models are CFD codes including the CENER model based on the commercial CFD code Fluent. The CRES–flow NS model integrates the governing equations by means of an implicit pressure correction scheme, where wind turbines are modeled 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.

Symmetry plane - Vx velocity



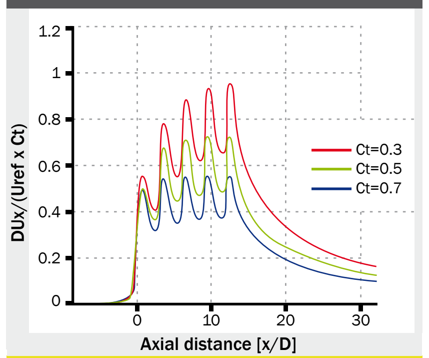
Simulations of the velocity field over an ideal three dimensional hill.

RESULTS AND APPLICATIONS

Evaluation of the CFD codes shows that the axial variation of the velocity deficit at hub height is represented well for the case of five wind turbines with the distance between the machines varying from 3D to 7D. For high values the thrust coefficient, the increase of the velocity deficit at the downwind wind turbines is not significant even when the distance between the machines is small (3D). However, for lower values of the thrust coefficient there is a significant increase in the velocity deficit of the second wind turbine which is larger if the wind turbines are more closely spaced. In general, there is no significant increase in the velocity deficit after the third wind turbine. High values of the turbulence intensity for the five wind turbines case are observed. Compared to the single wind turbine case, the level of maximum turbulence intensity is almost doubled.

In complex terrain, the wind speed deficit remains significant, even 20 rotor diameters downstream from the wind turbine, and the wind speed deficit at hub height does not decrease smoothly with distance. If the turbulence intensity is high this results in a faster flow recovery at long distances and the flow recovery is slower in complex terrain.

TI=13%, Distance=3D



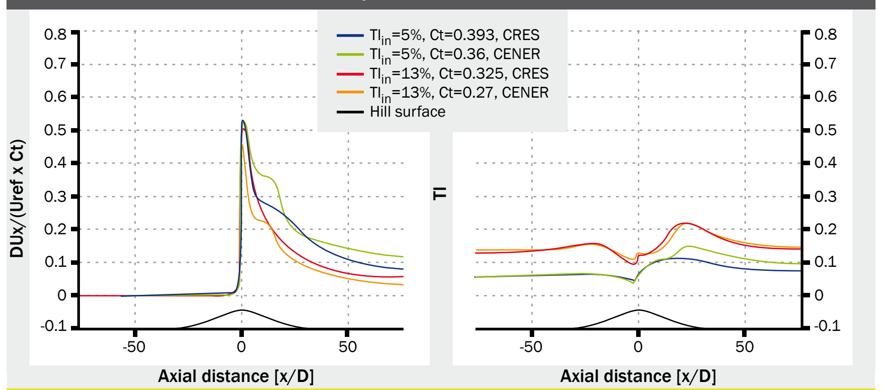
CFD simulations of five wind turbines in flat terrain.

Evaluation of the models in large offshore wind farms indicates that the performance of the models is somewhat variable. For very small wake widths models tend to over-predict wake losses, potentially because they 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.

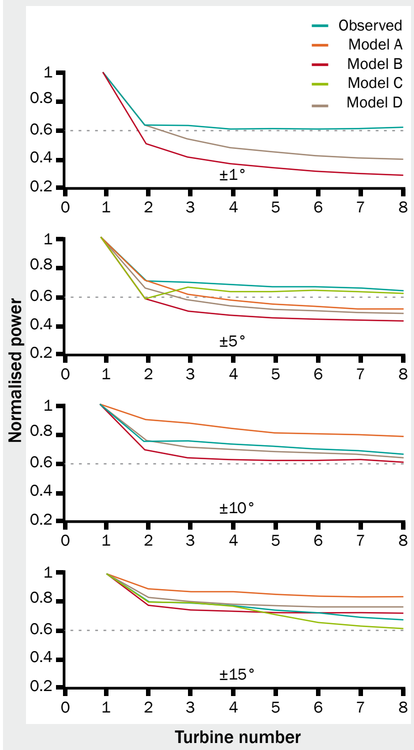
The observations show that as the equivalent wake spacing increases, the initial power loss (at the second turbine) decreases but the power loss in the row increases moving down the row. By the fifth turbine all three wake spacing have a similar power output compared to the free stream. The models all predict closer to the observed power output for the larger wake spacing.

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.

3D axisymmetric hill, L=1750 m



CFD simulations of the velocity deficit and turbulence intensity over an ideal Gaussian hill with a wind turbine placed on the summit.



Comparison of models and measurements for Horns Rev (direction 270°) for 8±0.5 m/s for different widths of wake sectors.

Comparisons of wind and turbulence downwind of very large wind farms have 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) took place, show good agreement with measurements. The wind speed determined from power output within the wind farm can drop to less than 80% of its free stream value (according to the initial wind speed and direction angles considered). Recovery to approximately 90% of the free stream 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.

The development of new codes and modifying existing models for more accurate representation of power losses due to wind turbine wakes is foreseen. These new codes can be used by developers to optimise wind farm layouts.