POWER – A METHODOLOGY FOR PREDICTING OFFSHORE WIND ENERGY RESOURCES

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ABSTRACT

An accurate estimate of the long-term wind speed is essential to site an offshore wind farm effectively. Unfortunately measured wind speed data at potential offshore wind farm sites are currently sparse. A major European Commission funded project called 'Predicting Offshore Wind Energy Resources" (POWER) aims to develop a methodology for predicting the long-term wind resource that does not rely directly on offshore anemometry mast data. Work on the POWER project began in August 1998 and is scheduled to finish in July 2001.

This paper presents an overview of POWER and shows how the components of the prediction methodology fit together. Finally, this paper reports on progress in the project to date and presents some preliminary results.

KEYWORDS

Offshore, Wind, Energy, Atlas, Resource

INTRODUCTION

There is an increasing interest in using offshore sites for wind farms, particularly in Europe. However, to site an offshore wind farm effectively, it is necessary to have good estimates of the expected long-term wind speed. Consequently, there is considerable interest in establishing an accurate knowledge of the wind regime in offshore waters.

Unfortunately, compared to sites on land, measured wind data at offshore locations are spatially and temporally sparse and of variable quality. Offshore meteorological masts have been erected in a number of locations. However, such masts are expensive and difficult to erect and also costly to operate – particularly for prolonged periods. Furthermore, to produce a long-term estimate of wind speed based on these measurements requires a correlation with an onshore site where long-term data are available. Such correlation may not be appropriate due to the differing on-and offshore climatologies.

A novel methodology has been developed which can produce long-term and spatially detailed estimates of the wind conditions at offshore sites covering a wide area. Within the POWER project, this methodology is being applied to European Union waters. The resulting wind resource estimates may subsequently be used to identify areas that are favourable for offshore wind power installations. More detailed monitoring studies can then be carried out at a particular site to refine the initial estimates.

THE POWER METHODOLOGY

Overview

The POWER methodology does not rely directly on anemometry mast data to predict wind conditions offshore. Instead, the estimates are based on grids of atmospheric pressure data at mean sea level covering the area of interest.

The methodology is built up of three basic steps:

1. The mean sea level pressure gradient is used to calculate the geostrophic wind.

2. The geostrophic wind is transformed to the sea surface layer by applying the Wind Atlas Analysis and Application Program (WAsP).

3. In nearshore areas, a coastal discontinuity model (CDM) is used to predict wind conditions taking account of atmospheric stability effects experienced in the land/sea transition zone.

Within the POWER project, the CDM is “fine-tuned” using both existing offshore mast data and coastal SODAR (SOund Detection And Ranging) data. The estimates of wind resource will be supplemented by assessments of short-term variability and information on regions of extreme environmental loading. In addition, since historical atmospheric pressure data dates back to 1880 and beyond, the methodology allows the long-term (decade to decade) variability of the offshore wind resource to be investigated.

A schematic flow diagram of the POWER methodology is shown in Figure 1.

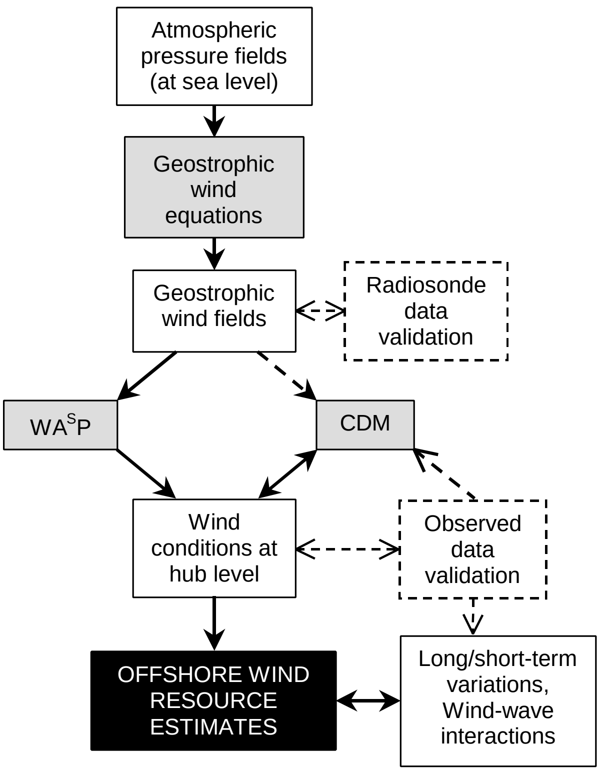

Figure 1 Flow schematic of the POWER methodology

Calculation of geostrophic winds

Geostrophic wind theory is used to convert southerly and westerly components of sea level pressure gradient into their associated geostrophic wind values using equations 1 and 2:

$$U_g = -\frac{1}{f_c \rho}\frac{\partial p}{\partial y} \qquad 1.$$

$$V_g = +\frac{1}{f_c \rho}\frac{\partial p}{\partial x} \qquad 2.$$

Where f_c is the local Coriolis parameter at latitude ϕ given by:

$$f_c = 2\Omega \sin \phi \qquad 3.$$

U_g and V_g are the westerly and southerly components of the geostrophic wind speed respectively, O is the Earth's angular velocity (7.29×10^{-5} rad s^{-1}), ? is the density of air, ?p/?x is the component of the pressure gradient from south to north and ?p/?y is the pressure gradient from west to east.

WAsP transformation

WAsP [1] is a linear flow model that can be used to transform geostrophic winds to wind turbine hub levels in the surface layer. The model calculations are based on the geostrophic drag law combined with models of stability and development of an internal boundary layer (IBL). WAsP makes adjustments to the wind speed profile offshore based on the assumption that the wind speed profile in the surface layer (up to approximately 100m) is slightly stable.

The WAsP model is well-established and commonly used throughout the wind energy community to perform wind resource assessments. The standard version of the software allows coastal effects to be modelled assuming differences in mean onshore and offshore stability and using internal boundary layer theory to modify wind speed profiles over the width of the coastal zone.

Coastal Discontinuity Model (CDM)

In coastal sea areas the wind regime is influenced by the adjoining land surfaces resulting in some complex interactions. In stable conditions in particular, the influence of upwind land surfaces on the offshore wind speed profiles can be determined over long distances [7], (up to 50km and potentially beyond in highly stable conditions).

The CDM [2 and 3] is a combined stability and internal boundary layer (IBL) model that is being developed at Risø. It is based on similar principles to WAsP, the major difference being that on- and off-shore stability are calculated in each time step and used to modify individual offshore wind speed profiles from the logarithmic while accounting for the differential growth of the IBL in varying stability conditions. It is capable of producing advanced estimates of wind conditions in the coastal transition zone as it accounts for stability effects generated by thermal and frictional changes at the coastal discontinuity.

APPLICATION OF THE POWER METHODOLOGY TO EUROPEAN WATERS

Introduction

The POWER methodology outlined above is being applied to the region 30ºN to 70ºN and 15ºW to 30ºE. As Figure 2 shows, this area covers the major sea areas bordering European Union countries – the North Sea, the Baltic, the Mediterranean and the eastern North Atlantic.

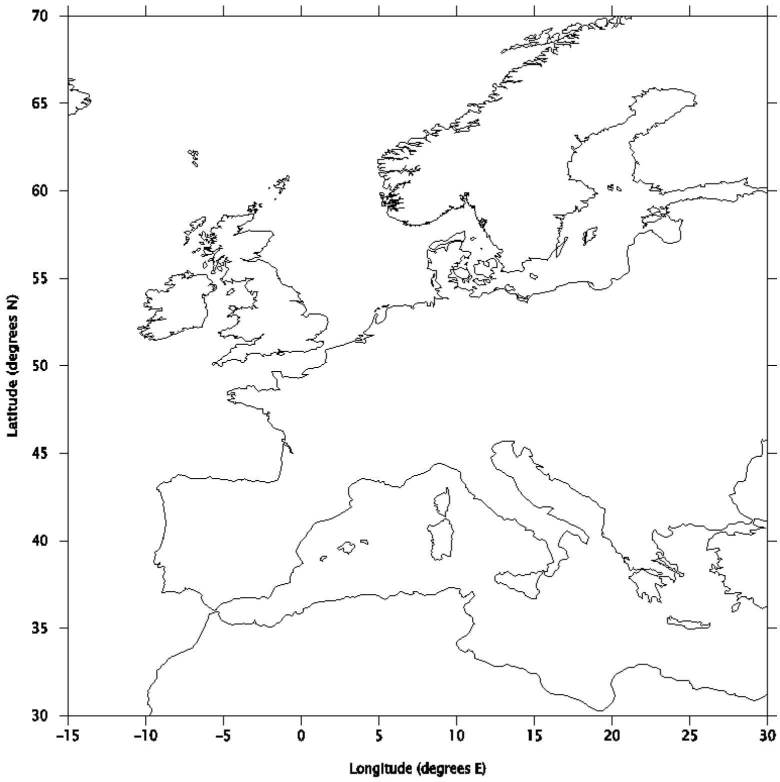

Figure 2 Map showing the European sea area where the POWER methodology is being applied

The following sections report on the overall progress to date with the POWER project, together with some preliminary results.

Calculation of geostrophic winds and validation against radiosonde observations

Six-hourly atmospheric pressure data on a 2.5º x 2.5º latitude/longitude grid were obtained from the US National Centers for Environmental Prediction (NCEP). Data covering the period 1985 to 1997 were interpolated onto a 0.5º latitude by 0.5º longitude grid using bicubic spline interpolation. The pressure gradient at each grid point was then used to calculate the geostrophic wind speed and direction for each grid point and time step using equations 1 and 2.

Figure 3 presents a contour plot showing the distribution of the mean annual geostrophic winds calculated from the NCEP pressure data in the period 1985 to 1997.

Radiosonde data were obtained from the British Atmospheric Data Centre (BADC) for the period 1990 to mid-1998 from an extensive network of European stations. Observations from the radiosonde ascents at selected sites were used to compare the observed wind speeds and directions above the friction layer with the calculated geostrophic winds.

Two types of comparison were undertaken. First, the wind speeds and directions occurring at particular time steps were compared for dates representing severe storm conditions as well as more typical winter and summer days with relatively light winds. The overall correspondence between the observed wind speed and direction and the geostrophic values is good. Second, although comparisons of predicted and observed conditions at particular snapshots in time provide a detailed overview of the relationship between the geostrophic wind and the observed frictionless wind, it is only practicable to consider a small number of time steps in this way. Therefore, a comparison of the long-term summary statistics of the calculated geostrophic wind speeds and the radiosonde observations was also made. Once again there was an overall good agreement between the data sets. The comparisons performed suggest that the geostrophic winds calculated in for the project are an excellent representation of frictionless flow over the POWER study area.

The calculation of geostrophic winds, and their validation, are discussed further in [4].

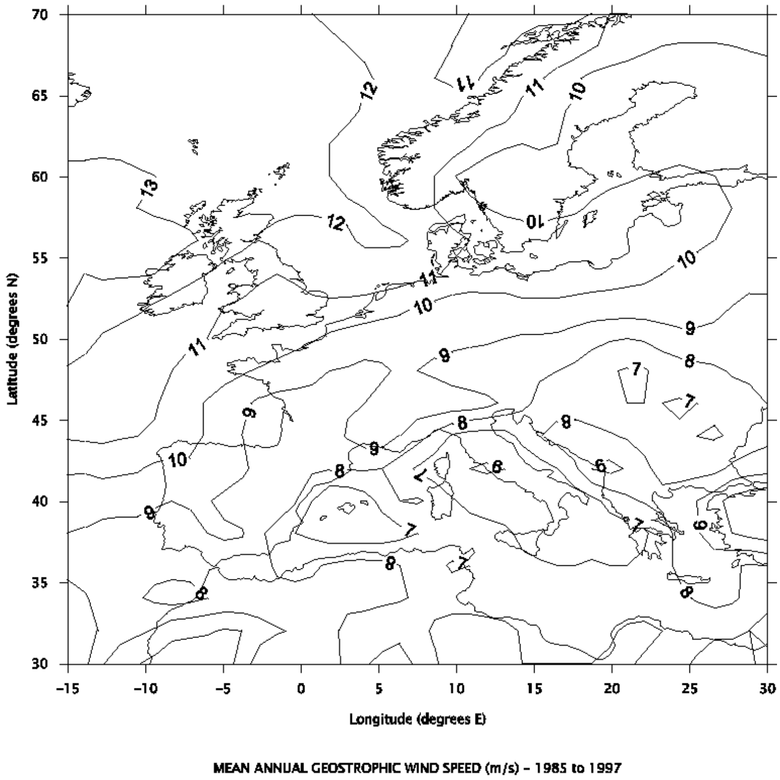

Figure 3 Calculated mean annual geostrophic wind speeds (m s^{-1}) – 1985 to 1997

WAsP modelling

The WAsP model has been used to transform the calculated geostrophic winds to the surface layer, at each point in the 0.5° x 0.5° latitude/longitude grid that lies over the sea. In practice, this means that WAsP analyses have been performed at over 3700 grid locations.

Mean annual and mean monthly wind conditions have been estimated at eight hub heights (10m, 30m, 50m, 70m, 90m, 110m, 130m and 150m above sea level respectively). These levels were chosen to cover the range of expected hub heights for wind turbines that are likely to be sited offshore in the coming years. Where a grid point is situated far offshore (>10km), a constant roughness value of 0.0001m is assumed. Alternatively, where a grid point is close to the coast (<10km) a roughness value of 0.0001m is assumed over the sea area and 0.03m over the land.

The results from the WAsP model runs have been used to estimate the distribution of the mean annual offshore wind energy resource at 50m above sea level in European Union waters. These results are illustrated in Figure 4. **IT MUST BE EMPHASISED THAT FIGURE 4 SHOWS PRELIMINARY RESULTS ONLY.** THE DATA USED TO COMPILE THIS PLOT HAVE BEEN GENERATED BY THE WAsP MODEL USING A SIMPLE REPRESENTATION OF COASTAL EFFECTS AND THE RESULTS HAVE NOT YET BEEN VALIDATED IN DETAIL.

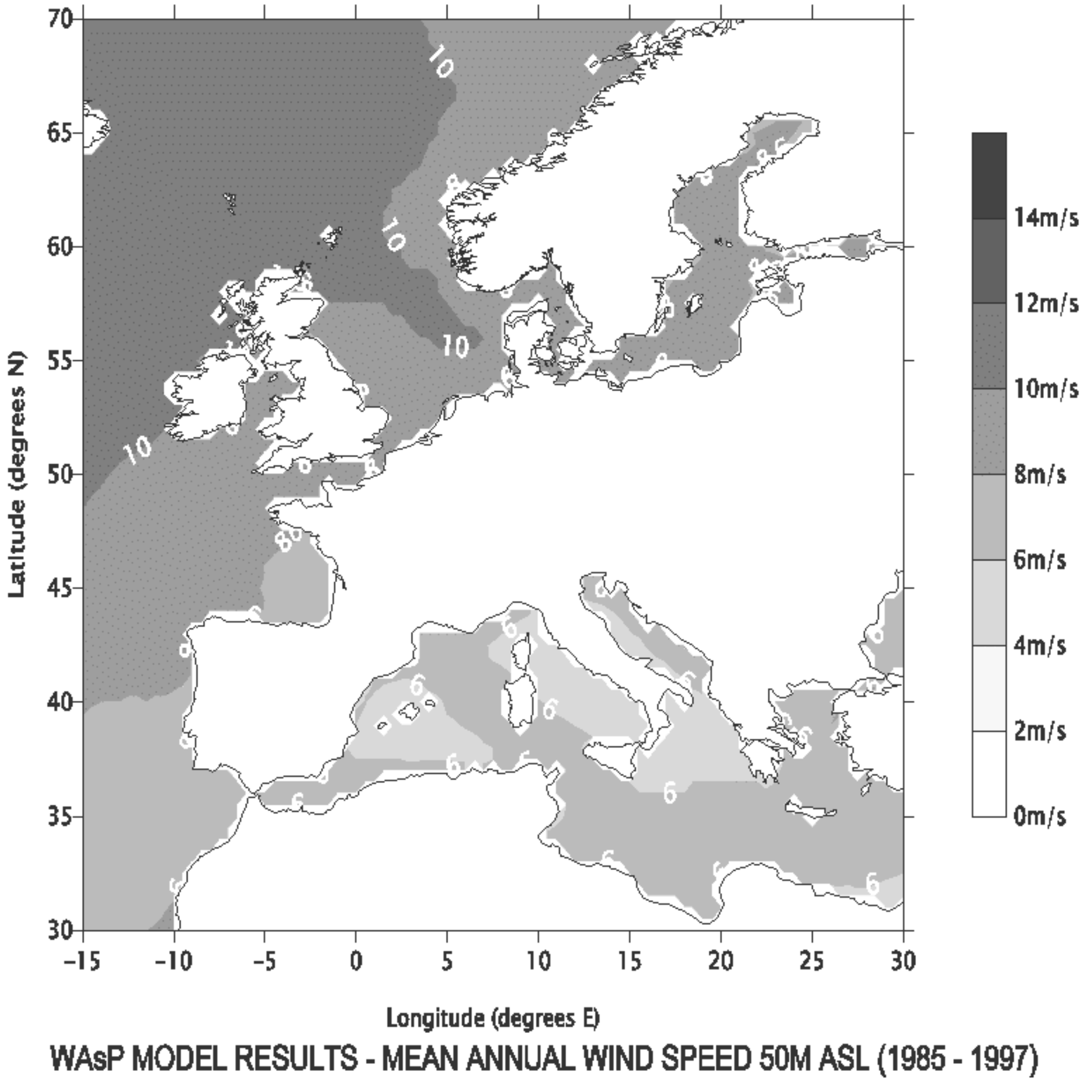

Figure 4 Plot showing the distribution of mean annual wind speeds estimated by WAsP

The POWER project WAsP model results suggest that the highest mean annual wind speeds are found along the Atlantic margin and in the North Sea and Baltic regions. An interesting feature is evident in the North Sea, where a finger of relatively high wind speeds extends into the basin from the north. By contrast, most of Mediterranean basin is shown to be less windy, with extensive regions experiencing mean annual wind speeds of less than $6ms^{-1}$. However, relatively good wind speeds are expected in parts of the Aegean. Although there are some slight discrepancies present, overall these results broadly compare with earlier offshore wind resource estimates [5 and 6].

In addition, Appendix 1 to this paper presents plots of mean monthly wind speeds at 50m above sea level throughout European Union waters. These plots are also based on the POWER project WAsP model results and are subject to the same provisos as Figure 4.

CDM modelling

The basic development work on the CDM is complete. The next task has been to set the model up to perform coastal zone wind corrections throughout the project area and to produce mean annual and mean monthly wind conditions corrected for stability effects at the eight wind turbine hub heights.

The model has been run successfully throughout European Union waters for both the neutral stability case and with stability corrections based on air temperatures and sea surface temperatures although, to date, the model has been applied to data for a single year only. The results obtained so far are very encouraging including some convincing wind speed profile validations. The application of the CDM to European Union waters is discussed further in [2 and 3]

Refinement and validation of the CDM using measured data

Refinement and validation of the CDM is being achieved using various data observed at coastal and offshore sites. Some of this data comes from existing masts and platforms, however within the POWER project additional data are being collected for this purpose using a mini-SODAR device.

The performance of the CDM stability model (MOLLY) has been evaluated by comparing the Monin-Obukhov length values predicted by MOLLY with observed values measured at a number of sites in Danish waters. These comparisons indicate that MOLLY gives very good results. In addition, preliminary CDM results have been compared with the results of detailed analyses of data from meteorological masts in Danish waters [3 and 7].

SODAR (SOund Detection And Ranging) is a remote sensing technique for making wind speed and direction measurements at various heights. The technique is based on the reflection of sound pulses from turbulence in the atmosphere. The time taken for a reflection to be detected is used to determine the range (height) and the Doppler shift in the reflected signal is used to determine the wind speed and direction at that height.

Within the POWER project, SODAR measurements of wind profiles are being made in the coastal transition zone and the resulting data sets are being used to refine the CDM. A set of SODAR measurements from a coastal site in the Netherlands between October 1998 and May 1999 has been completed successfully [8]. The mini-SODAR equipment has now been installed on an offshore research platform located 9km off the Dutch coast, and a further set of measurements are currently being gathered at this site. Finally, a third set of SODAR measurements are planned at a UK coastal site during the summer of 2000. More details of the SODAR measurements are discussed in [9].

Figure 5 View of the mini-SODAR equipment installed at Measuring Post Noordwijk offshore research platform

PLANNED FUTURE WORK

Outline

This paper was written mid-way through POWER project schedule. Once the sections of the project described above have been completed, there are plans to undertake several more associated tasks. These components of the POWER project will be presented in future papers, but in the meantime they are briefly outlined below.

Refinement and validation of the resource estimates

The raw predictions of wind conditions at hub height levels produced by WAsP and CDM will need to be further refined and validated against existing offshore data sets. A series of meteorological data sets from a wide range of sources including the UK Meteorological Office archives and observations from coastal and offshore masts, platforms, light vessels and meteorological stations have been assembled by the project team for this purpose. These data will be used to validate the POWER methodology. Some of the data gathered are discussed in [9].

Wind-wave interactions

Simultaneous wind and wave data will be used to infer the sensitivity of offshore wind speeds to variable sea surface roughness. This will be used to modify the WAsP/CDM model estimates of wind resource. In addition, wind and wave data will be used to identify areas where acute joint wind/wave loading of offshore wind energy structures may be experienced.

Short-term variability

An understanding of the daily variation in wind speed in offshore areas is important for the effective integration of offshore wind power into an onshore power grid. Existing offshore data sets with a high temporal resolution will be used to assess the diurnal variability of offshore wind speed at several locations.

Long-term variability

Wind speeds are known to vary on a range of time scales including seasonal cycles (see Appendix 1), decadal cycles (caused by unforced/internal variations e.g. the North Atlantic Oscillation) and very long-term variations (forced/external variations e.g. greenhouse warming). The scale of these variations is sufficient to have economic implications for both onshore *and* offshore wind farms.

A major advantage of POWER methodology is that historical records of sea level pressure extend back as far as 1880. This means that POWER estimates of offshore wind resource can be used to assess the long-term (decade to decade) variability of the offshore wind resource. This analysis will allow the expected uncertainty on the wind resource values due to long-term variability to be calculated. Similar assessments of long-term variability on land have been made in [10] and [11].

Case study

A final validation of the POWER methodology in European waters will be to perform a case study. The refined wind speed values will be compared with measurements taken at the planned location of a real offshore wind farm.

Dissemination of the results

It is intended that once the implementation of the POWER methodology in European Union waters is completed, the 0.5º x 0.5º latitude/longitude grid point values will be packaged as a database. There will be an interface for easy retrieval of the data by potential offshore wind farm developers.

CONCLUSIONS

- This paper has presented an outline of the newly developed POWER methodology for assessing wind power resources in offshore waters.
- The POWER methodology does not rely directly on offshore wind speed measurements. Instead, offshore wind resource estimates are based on atmospheric pressure data.
- Since historical atmospheric pressure records date back several decades, POWER estimates of wind resources may have a truly long-term basis.
- The POWER methodology is being applied throughout European Union waters on a 0.5º x 0.5º latitude/longitude grid.
- Preliminary results from early stages of the application of the methodology have been presented.
- The project results indicate that the geostrophic wind speeds and directions calculated from interpolated pressure data are an excellent representation of frictionless flow in the coastal regions of Europe.
- Preliminary wind speed distribution plots for European Union waters have been presented. These plots are based on the results of WAsP model runs performed for the POWER project.
- Progress with development and subsequent application of a Coastal Discontinuity Model (CDM) has been discussed.
- The use of a SOund Detection And Ranging (SODAR) equipment to measure coastal and offshore wind profiles has been outlined.
- Finally, this paper has also highlighted future work that will be carried out within the POWER project.

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