PREDICTING OFFSHORE WIND ENERGY RESOURCES (POWER)

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Abstract

In the coming years, exploitation of offshore wind energy is set to play a central role in Europe's overall energy strategy by assisting EU member state governments to achieve their national greenhouse gas emission reduction targets (both now and in the future), whilst continuing to meet the demand for energy. However, development and integration of offshore wind energy is currently handicapped by significant knowledge gaps, including a scarcity of good quality information on the extent, characteristics and distribution of the offshore wind energy resource.

The objective of the Predicting Offshore Wind Energy Resources (POWER) project was to improve the understanding of the nature and distribution of Europe's offshore wind resource. In particular the project team set out to improve upon previous estimates of the European offshore wind energy resource, to consider a number of additional factors that could affect its exploitation on a commercial basis and to present the information in a straightforward, yet useful format.

Within POWER, a novel wind resource assessment methodology was developed which can produce long-term and spatially detailed estimates of the wind conditions at offshore sites covering a wide area. Furthermore, the team applied this methodology to the region 30ºN to 70ºN and 15ºW to 30ºE on a grid of 0.5º resolution, an area which covers the major sea areas bordering EU countries – the North Sea, the Baltic, the Mediterranean and the eastern North Atlantic.

The POWER project has produced state-of-the-art estimates of the extent and distribution of Europe's offshore wind energy resources not only in the coastal zone – the current focus of the offshore wind industry's attention – but also throughout the region's far offshore areas, where there is potential for wind energy to be exploited in the longer-term.

On a local scale, POWER provides detailed first estimates of the long-term environmental conditions at specific offshore locations. This information is useful to the offshore wind energy industry since this is the exact type of data required for initial scoping and feasibility studies for new offshore wind energy developments. It may be possible to base preliminary assessments of the turbine power output as well as other key parameters such as initial values of the design parameters for turbine support structures from the POWER results.

The data on wind and wave parameters for European waters produced by the POWER project has been compiled as a set of Microsoft Excel work books. The data can be accessed using the "POWER tool" - a simple graphical user interface (GUI) that allows the user to display, in both numerical and graphical form, data from the database of wind and wave parameters

The POWER project's techniques should enable the wind energy industry to exploit the offshore wind energy resource with greater confidence, and hence facilitate a future expansion of the wind turbine manufacturing and installation industry – with the consequent employment opportunities.

1 Partnership

The POWER consortium was made up of the following organisations : Co-ordinator : Energy Research Unit, CLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK (contact person : Dr Jim Halliday, Tel : +44-1235-445559, Fax : +44-1235-446863, e-mail : j.a.halliday@rl.ac.uk); Climatic Research Unit, University of East Anglia, Norwich, NR4 7TJ, UK (Contact person : Dr Jean Palutikof, Tel : +44 1603 593647, Fax : +44 1063 507784, e-mail : j.palutikof@uea.ac.uk); Dept of Wind Energy and Atmospheric Physics, Risoe National Laboratory, PO Box 49, DK-4000 Roskilde, Denmark (Contact person : Dr Rebecca Barthelmie, Tel : +45 46 77 5020, Fax : +45 46 77 5970, e-mail : r.barthelmie@risoe.dk); Ecofys bv, P.O. Box 8408, NL-3503 RK Utrecht, The Netherlands (Contact person : Dr Jan Coelingh, Tel +31 30 2808 395, Fax : +31 30 2808 301, e-mail : j.coelingh@ecofys.nl); KEMA Power Generation and Sustainables, P.O. Box 9035, NL-6800 ET Arnhem, The Netherlands (Contact person : Hans Cleijne, Tel : +31 26 3566 393, Fax : +31 26 4458 279, e-mail : j.w.cleijne@kema.nl)

2 Objectives of POWER

In the coming years, offshore wind energy is set to play a central role in Europe's overall energy strategy by assisting EU member state governments to achieve their national greenhouse gas emission reduction targets (both now and in the future), whilst continuing to meet the demand for energy. However, development of offshore wind energy is currently handicapped by significant knowledge gaps, especially good quality information on the extent, characteristics and distribution of the offshore wind energy resource. The Predicting Offshore Wind Energy Resources (POWER) project was an ambitious attempt to improve the understanding of the nature and distribution of this resource.

3 Introduction

Perhaps the most significant obstacle to the assessment of offshore wind resources to date has been the lack of measured offshore wind data on which to base the estimates. Happily, the POWER project methodology does not rely directly on observed anemometer 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 consists 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) has been used to investigate the effects of atmospheric stability on wind predictions in the land/sea transition zone.

The stability routines in the CDM existed as a local (km) scale model. The model was significantly expanded for POWER to a) allow use of geostrophic wind speed , b) to allow land based profiles as input (for comparison with the SODAR data) and c) finally to utilise WAsP input (to attempt to make stability corrections). Within the POWER project, the CDM was "fine-tuned" using both existing offshore mast data and coastal SODAR (SOund Detection And Ranging) data. In addition, the estimates of wind resource were supplemented by assessments of short-term variability and information on regions of extreme environmental loading. Since historical atmospheric pressure data dates back to 1880 and beyond, the methodology allowed the long-term (decade to decade) variability of the offshore wind resource also to be investigated.

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

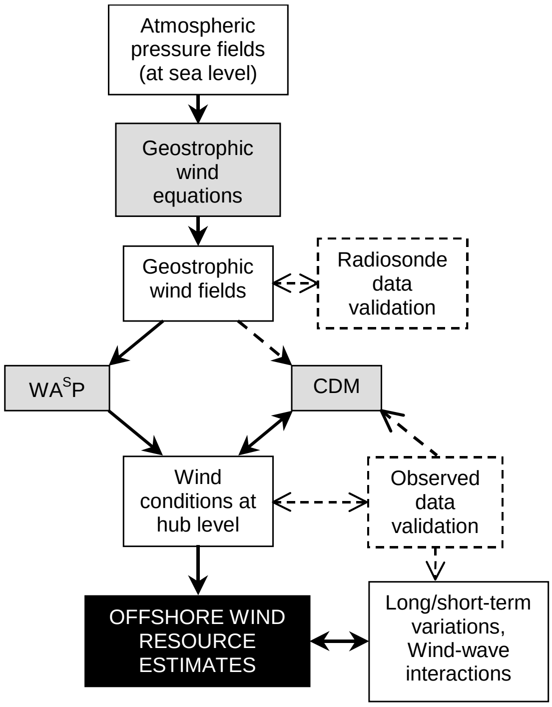


Figure 1 Flow schematic illustrating POWER methodology

4 Calculating geostrophic winds from sea level pressure data

Geostrophic winds are theoretical winds which flow parallel to isobars (contours of equal surface pressure) and which are a good approximation to the actual wind in the free atmosphere. Within the context of the POWER project, geostrophic winds are of particular interest because they can be calculated from surface pressure data. This is significant because while measured wind data at offshore locations are spatially and temporally sparse and often of variable quality, there are several good quality data sets of atmospheric pressure available that cover offshore areas. This means the atmospheric pressure data can be used to construct geostrophic wind conditions, which can then in turn be manipulated using well-established wind resource assessment techniques.

Atmospheric pressure data at mean sea level were obtained from the US National Centers for Environmental Prediction (NCEP) for the period 1985-97, at 6-hourly intervals and on a 2.5º latitude by 2.5º longitude grid. These data were interpolated onto a 0.5º latitude by 0.5º longitude grid using bicubic spline interpolation.

The interpolated atmospheric pressure data were then used to calculate the sea level pressure gradients in the westerly and southerly directions at each point in the 0.5º by 0.5º latitude/longitude grid. Finally, 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:

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

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

where:

U_g and V_g are the westerly and southerly components of the geostrophic wind speed respectively
f_c is the local Coriolis force for the given latitude
ρ is the density of air
$\partial p/\partial y$ is the component of atmospheric pressure gradient from west to east
$\partial p/\partial x$ is the component of atmospheric pressure gradient from south to north

Figure 2 shows the distribution of the mean annual geostrophic winds calculated from the NCEP pressure data in the period 1985 to 1997.

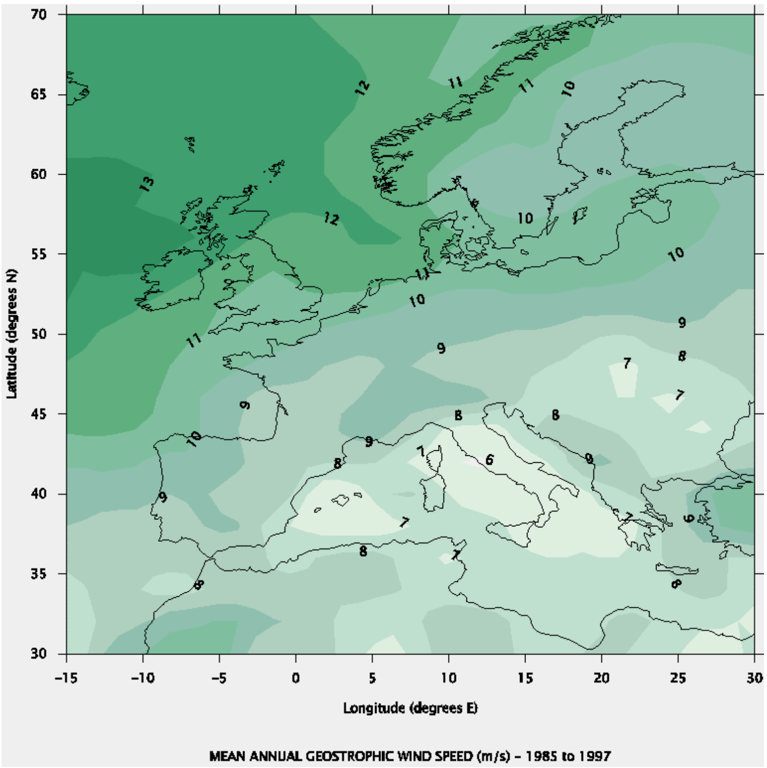


Figure 2 Calculated mean annual geostrophic wind speeds (m s^{-1}) – 1985 to 1997

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. There was an overall good agreement between the data sets.

The calculation of geostrophic winds, and their validation, are discussed in full in [1, Chapter 3].

5 Transforming geostrophic winds to turbine hub heights using WAsP

The Wind Atlas Analysis and Application Programme (WAsP) [2] is a linear flow model that can be used to transform geostrophic winds to the surface layer. WAsP is well-established and commonly used throughout the wind energy community to perform wind resource assessments. The model's calculations are based on the geostrophic drag law combined with models of stability and development of internal boundary layers (IBL). Coastal effects are 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.

Mean wind conditions for the period 1985-97 were estimated using WAsP at eight hub heights at each POWER grid point over the sea. The hub height levels (10m, 30m, 50m, 70m, 90m, 110m, 130m and 150m above mean sea level respectively) were chosen to cover the range of expected hub heights of wind turbines that are likely to be sited offshore in the coming years. In addition, the monthly and inter-annual variability of the wind conditions in European waters were also investigated by performing WAsP model runs estimating the mean monthly and mean yearly wind conditions at all offshore grid points. Finally, some additional WAsP runs were performed to obtain offshore wind predictions at specific locations and heights, which could be compared directly against observed data for validation purposes (see section 10).

An example of the results from the WAsP runs performed are presented in Figure 3 – a plot showing the distribution of mean wind speeds for the period 1985-1997 at 50m above mean sea level throughout the POWER project area.

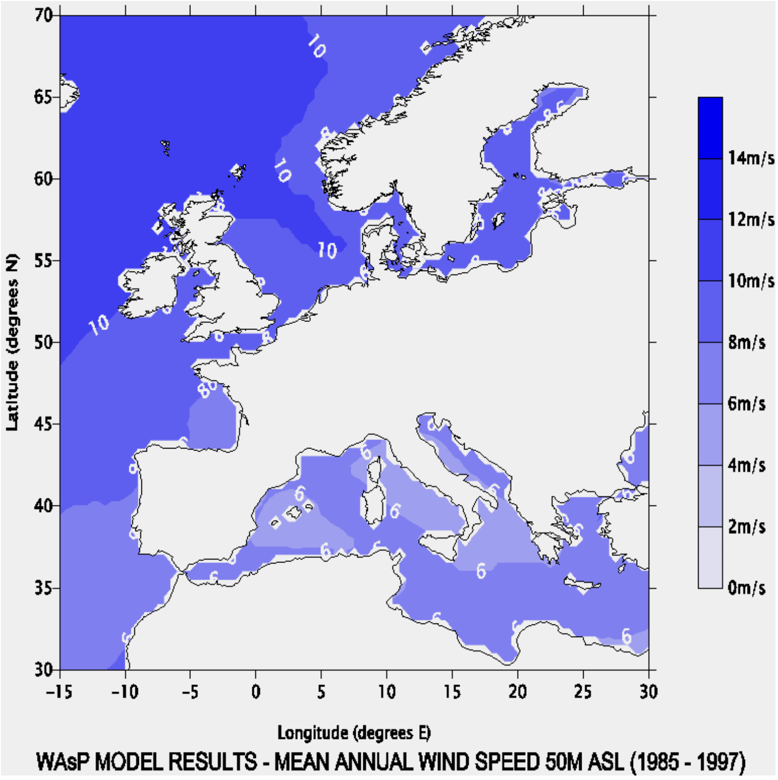


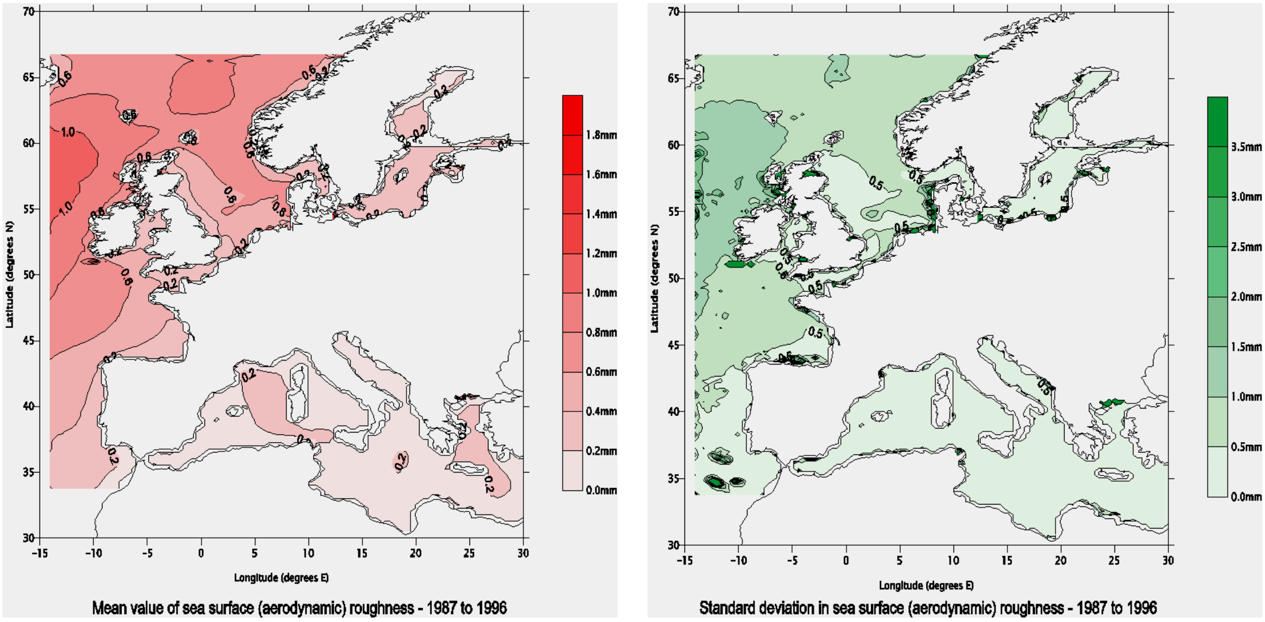
Figure 3 Plot showing the distribution of mean annual wind speeds at 50m a.s.l. throughout EU waters

The results indicate that the highest wind speeds are found in along the Atlantic margin, the North Sea and Baltic regions with mean annual wind speeds at 50m above sea level in excess of 8.0ms^{-1} throughout these areas. The highest wind speeds are experienced north and west of Scotland, where mean annual wind speeds greater than 10.5 ms^{-1} are expected. 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, the most of Mediterranean basin is less windy, with extensive regions experiencing mean annual wind speeds of less than 6ms^{-1}. However, good wind speeds are to be found in parts of the Aegean.

Although there are some slight discrepancies present, overall these results broadly compare with earlier offshore wind resource estimates [6] and [7]. {The discrepancies in the WAsP results mentioned mainly arise from the use of different input data (e.g. Moore [6] used 900 mb data and the European Wind Atlas [7] used surface data).}

WAsP uses a simple approach to modelling aerodynamic roughness, assuming a constant sea surface roughness length z_0=2x10^{-4}m for all sea areas, wind conditions and sea states. However, whereas the roughness of land features can be thought of as essentially constant, the sea surface geometry and roughness alter continuously with varying wind speed.

One of the project's objectives was to assess the effect of variable sea surface roughness on offshore wind speed predictions. The project team investigated this using a new parameterisation for z_0 [3] to calculate aerodynamic roughness values in European waters over the period January 1987 to December 1996. The results suggest that that for the bulk of the time, z_0 values are very small indicating the sea surface is aerodynamically very smooth. However, there are relatively short periods, mostly corresponding to the high wind events, when the sea surface roughness increases significantly with predicted values of z_0 in excess of 4x10^{-3}m. In order to get an indication of the distribution and overall variability of the sea surface roughness, the mean value of z_0, as well as its standard deviation, was calculated. An example of the results obtained are illustrated in Figures 4a and 4b.



(a) **(b)**

Figure 4 Distributions of mean value of sea surface roughness, z_0, and its standard deviation – 1987 to 1996

During the course of the project, the project team became aware of the results of other modelling studies [4] [5] [1, Chapter 5] which indicate that the variability in the z_0 values predicted here would result in only small differences (less than 0.5%) in predicted wind speeds compared to the existing WAsP predictions. Furthermore, [4] suggests that thermal stratification/stability issues have a much greater impact on offshore wind resources than changes in sea surface roughness. However, as discussed below, it proved impossible to assess whether stability-corrected results were an improvement on the close-to-neutral predictions made with WasP. Finally, the tidal range at a site may also impact on the wind speed predictions, particularly as in some areas large expanses of rough foreshore may be exposed at low water. It should be remembered that some parts of the POWER project area are subject to large (>4m) tidal ranges and so this could be a significant effect at these locations. However, for the majority of the POWER assessment area the tidal range is much less than 4m for this effect will not be significant.

Therefore, although it is clear that variable sea surface roughness will modify wind speed predictions slightly, the impact of other contributory factors are expected to dominate and therefore no attempt was made to correct the POWER WAsP results for variations in sea surface roughness.

The WAsP modelling performed within the project, and other related investigations, are discussed in full in [1, Chapter 4].

6 Modelling the coastal discontinuity

In coastal sea areas the wind regime is influenced by the adjoining land surfaces resulting in some complex interactions. In stable atmospheric conditions in particular, the influence of upwind land surfaces on the offshore wind speed profiles can be determined over long distances [8] (up to 50km and potentially beyond in highly stable conditions).

The CDM [9 and 10] is a combined stability and internal boundary layer (IBL) model which was significantly exhanced during the POWER project and based on similar principles to WAsP - the major difference being that on- and off-shore stabilities 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. The CDM determines its stability corrections from data of air and sea temperature data.

During its development, the performance of the stability component of the model was evaluated by comparing the Monin-Obukhov length stability parameter values predicted with observed values measured at a number of sites in Danish waters. In addition, preliminary CDM results were compared with the results of detailed analyses of data from meteorological masts in Danish waters. Further refinement and validation of the CDM was achieved using various data observed at coastal and offshore sites. Some of these data come from existing masts and platforms, however within the POWER project additional data were collected for this purpose using a mini-SODAR device (see Section 6).

Two versions of the CDM were applied to European waters within the POWER project:

1. GEOCDM - configured to take time series of geostrophic wind conditions as input
2. WASPCDM- configured to accept WAsP predicted wind speed distributions for each direction sector as input.

Development of the CDM has so far focused on accounting for roughness and stability changes between land and sea. As such, the representation of some of the other wind transformation processes in the CDM are not as advanced as found in the WAsP model. This means that the predictions made using the GEOCDM are based on a simplified transformation model and on this basis have not been used for the final POWER results.

The advantage of WASPCDM approach is that WAsP can give more accurate predictions of wind speed corrected for local orography, shelter and roughness. However, since the WAsP output is in the form of mean wind speed profile predictions the CDM stability correction must also be a mean value for each sector. Unfortunately, it was found that this does not necessarily improve the average wind speed profile predictions. The reason for this is that individual time series corrections of wind speed profiles for stability can either be positive or negative - hence calculating the average of the corrected wind speed profiles does not give the same result as calculating an average of the stability corrections and then using this to correct the mean wind speed profile.

A further problem highlighted is the spatial resolution of the stability correction. The initial data sets are supplied on 0.5 by 0.5 ° grid whereas it is known that mean offshore wind speeds vary on scales of about 0.5 km in coastal regions. CDM and WAsP applied at the 0.5 by 0.5 ° grid scale are unable to resolve complex coastlines, however, applying the same techniques with an improved coastline resolution would improve the predictions. However, at the time of the project, such data were not readily available.

In addition the use of air temperatures from mixed land/sea grid cells may not provide an accurate determination of stability, particularly when combined with a sea surface temperature data base from different sources. Errors in the source databases are of the same order as the temperature difference which is used to calculate the stability parameter. However to improve the stability correction is more difficult since a) currently sea surface and air temperatures are not available at better than 0.5 by 0.5° grid resolution and b) a more precise estimate of stability requires either direct flux measurements or a measured temperature difference.

Thus overall, it was found that applying the CDM, in its current form at least, to WASP predicted wind speeds does not improve the predictions. Therefore, although it is clear that coastal effects are expected to modify wind speed predictions, no additional CDM corrections have been included in POWER's final output, as at the present time the input data of stability and coastline resolution were not available in the resolution needed. It is suggested that when such data do become available, the effect of applying the CDM corrections should be re-examined.

Development and validation of the CDM and its application to European Union waters is discussed in more depth in [1, Chapter 5].

7 Wind speed profiles using SODAR

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 particular heights. These data can then be used to build vertical profiles of the wind speed and direction at heights well above conventional meteorological masts.

Within the POWER project three sets of SODAR measurements were performed:

1. SODAR trials at Petten (The Netherlands): October 1998 - May 1999

Equipment trials were carried out by staff from Ecofys in collaboration with ECN and gave the project staff valuable experience in setting up the SODAR system and performing the mesurements as well as enabling them to set up quality control and analysis systems for the observations.

2. *Measuring Post Noordwijk (9km off the coast of The Netherlands): January –June 2000*
   In total 4 months of good quality observed data were obtained while the SODAR system was installed at the Measuring Post Noordwijk (MPN) research platform owned and operated by the Public Works Department (Rijkwaterstaat), Directie Noordzee. These measurements were used to help validate the Coastal Discontinuity Model.

3. *Weybourne (UK)*
   SODAR data were measured at a coastal site in eastern England by staff from the UEA.

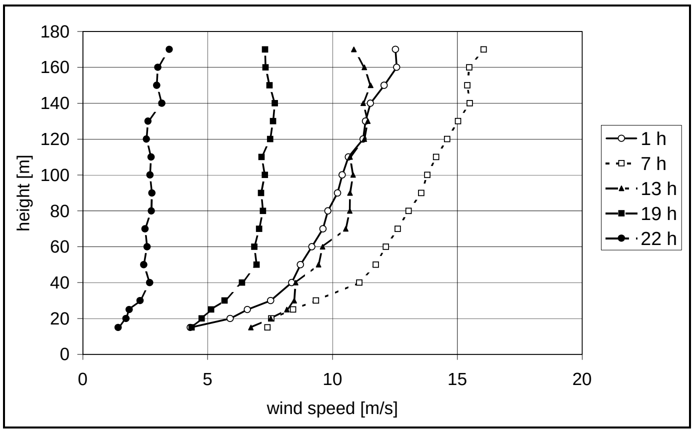


Figure 5 Example of wind speed profiles at MPN as measured with a SODAR on one day. The profiles shown are hourly averages

The SODAR has proved to be a very useful device to measure wind speed profiles and can help to describe boundary layer phenomena. However, it was found that the quality of SODAR measurements tends to be adversely affected by rain and background noise (e.g. from waves, wind whistling through superstructures, diesel generators etc.). Furthermore, SODAR height performance is affected by the stability conditions; the more unstable the atmosphere, the better the height performance.

A more detailed account of the SODAR equipment and a description and analysis of the data obtained can be found in [1, Chapter 6].

8 Time-dependent variability

Offshore wind speeds are known to vary over a wide range of time scales:

long-term – inter-annual, decadal and other long-term trends such as climate change
medium-term - seasonal and diurnal cycles
short-term – e.g. gusts

The scale of these variations is sufficient to have economic implications for both onshore and offshore wind farms. Given this importance, within POWER, the project team sought to extend the current understanding of three types of variability in the offshore wind regime, namely, long-term trends, the diurnal cycle and gusts. The analyses and results are described more fully in [1, Chapter 7].

Long-term trends

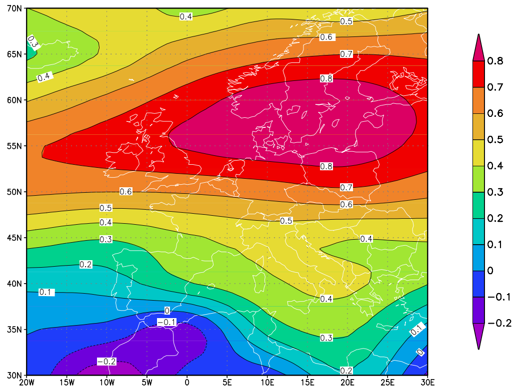
Historical records of sea level pressure in Europe extend back to the 1870s. Happily, this means that the POWER methodology can be used to investigate the long-term (decade to decade) variability of the offshore (and onshore) wind resource.

Monthly mean geostrophic wind speeds were calculated using the technique outlined in Section 3 and based on UK Meteorological Office's daily records of mean sea level pressure dataset throughout Europe for the period 1900 to 1997. The monthly mean geostrophic wind speeds were then organised in space using Principal Components Analysis (PCA) to identify the dominant regional wind regimes over Europe. PCA is a statistical technique which performs two important functions;

1. Reduction of the data set to a new set of components (or modes of variability), representing only major patterns of variance that may be of interest.
2. Objective identification of important modes of variability which are orthogonal, that is, they have no common variations (they are uncorrelated).

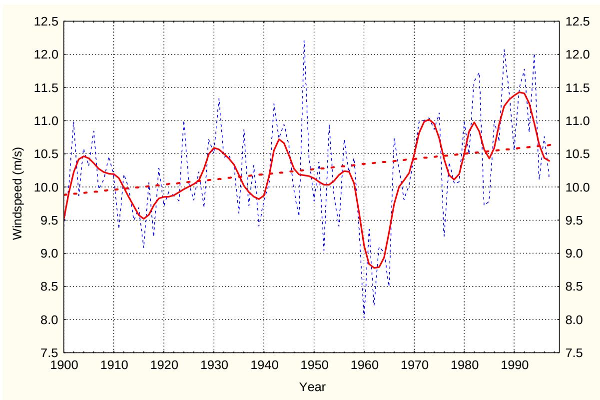
Here, the PCA identified seven important components, each associated with a spatial pattern of windiness and which together explain over 83% of the total variance in the original data. One of the components (designated here as number 3) was found to influence north Africa only, and so was not considered further.

The spatial patterns of the components have regions where the influence of the component is particularly strong. As an example, Figure 6a shows the pattern of loadings associated with the first component of the PCA. This has strong influence over the Baltic and southern Scandinavia. Inspection of the spatial patterns for each component showed that a set of grid squares in the original dataset of geostrophic winds could be identified as being most strongly associated with each component.



(a)

Example of factor loading pattern – Factor 1, explaining 26.37% of the variance



(b)

Example of wind speed trend - Winter (Oct. to Feb.) wind speeds associated with Factor 1

Figure 6 Examples of long-term trend analysis plots

Therefore, for each component, the wind speeds for the associated grid squares were averaged to produce a composite seasonal time series of wind speeds. Only grid squares over the sea were considered in this process. The resulting seasonal time series were examined for trend and periodic behaviour. Figure 6b shows the example time series for the first component, which is strongly associated with a set of grid squares over the Baltic, the North Sea, and the coastal waters of Scandinavia, the UK and Ireland. In Figure 6b we show the wind speed time series together with a smoothed line, to reveal the overall time series features of the data, and the linear trend line over the whole period of record. This particular example shows that winter wind speeds over north western Europe have a long-term rising trend that is largely a function of increasing wind speeds since the 1960s. Prior to this, the record shows no trend. There is no evidence of regular periodicity in these data.

Although there is no indication in the data of any significant periodic activity, there is considerable evidence of stable long-term trends associated with particular factors. This is important since a background of rising trend, for example, in the more northern high wind speed regions, may mean more downtime as turbines cut-out more frequently. Conversely, rising trend in relatively low wind speed regions may mean that a currently inadequate resource may eventually become economically viable.

In terms of assessing offshore wind potential, the regions affected by trends can be determined from Table 1. The final column gives the percentage change in wind speed over the period of trend described in the previous two columns. For example, if we were interested in exploiting the offshore wind resources of Greece we can see from Table 1 that Greece is experiencing a very small falling trend associated with Factor 2. However, the wind field associated with Factor 7 has rising trend over southern Greece with an increase in wind speeds of 30% over 60 years in summer and of 10% over

100 years in winter. Given that wind speeds off Greece are relatively low, the rising trend is encouraging for the development of offshore wind energy, assuming that it persists.

Basin	Country	Factors	Season	Trend	Duration (yrs)	Amount (%)
Atlantic	Belgium	1, 4	winter	rising	40	+15
	Denmark	1	winter	rising	40	+15
	France	1, 4	winter	rising	40	+15
		2	winter	falling	100	Very small
	Germany	1	winter	rising	40	+15
	Holland	1, 4	winter	rising	40	+15
	Ireland	1, 4	winter	rising	40	+15
	Portugal	2	winter	falling	100	Very small
		4	winter	rising	40	+15
		6	summer/winter	none/falling	0/100	0/-8
	Spain	2	winter	falling	100	Very small
		4	winter	rising	40	+15
		6	summer/winter	none/falling	0/100	0/-8
	United Kingdom	1, 5, 4	winter	rising	40, 80, 40	+15, +20, +15
Baltic	Denmark	1	winter	rising	40	+15
	Finland	1, 5	winter	rising	40, 80	+15, +20
	Germany	1	winter	rising	40	+15
	Sweden	1, 5	winter	rising	40, 80	+15, +20
Mediterranean	France	2	winter	falling	100	Very small
	Greece	2	winter	falling	100	Very small
		7	summer/winter	rising	60/100	+30/ Very small
	Italy	2	winter	falling	100	Very small
	Spain	2	winter	falling	100	Very small
		6	summer/winter	none/falling	0/100	0/-8

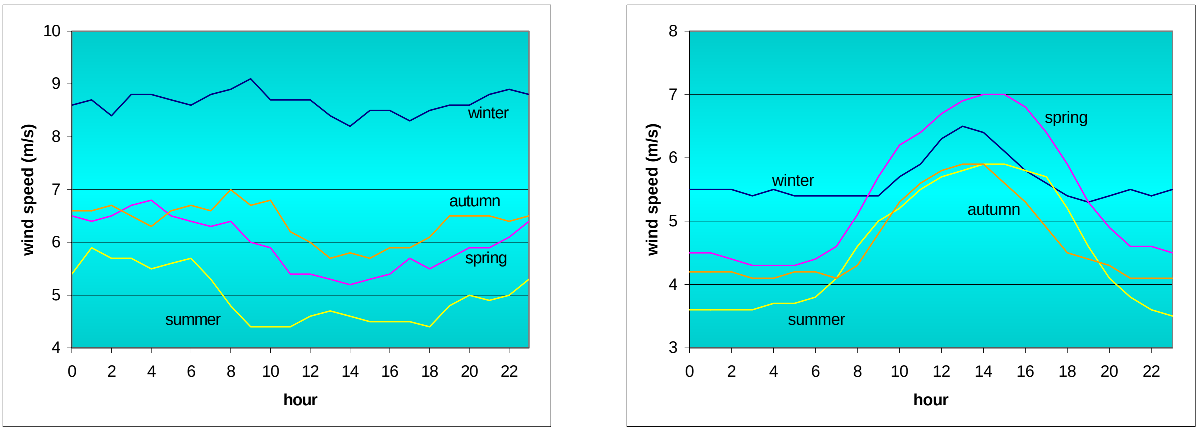
Table 1 *Countries affected by trend in seasonal wind speeds*

Medium-term variability: the diurnal cycle

Wind speed variations related to the diurnal cycle have implications for the sustained productive capacity of a wind farm. The diurnal cycle of coastal wind was examined using example stations around the United Kingdom. Ten coastal stations were selected on the basis of geographical coverage, suitable site exposure, and length of record.

Analysis of these data demonstrate that consideration of the diurnal cycle of wind speed is essential in any assessment of offshore wind potential, especially for the near offshore where early wind farm developments are most likely to be located. For winds with a land fetch (i.e. approaching the anemometer from over a land surface) there is a pronounced diurnal cycle, peaking in the early afternoon, in spring, summer, and autumn. The peak of the cycle can give higher mean hourly wind speeds in summer than in winter. No diurnal cycle, or a weak cycle peaking in the early hours of the morning, is associated with winds having a sea fetch (i.e. approaching the anemometer from over a sea surface). In winter, wind speeds have no diurnal cycle irrespective of fetch. The diurnal cycle appears not to have any relation to the direction of the wind, being purely a function of land fetch. Moreover, any relation with the geographical location of the recording station appears to be weak.

Figure 7 shows an example of these data for one of the selected coastal stations. In this case the plots are based on data recorded at Gorleston on the east coast of England between 1987 and 1993.



(a) *Gorleston: sea fetch diurnal cycle by season*

(b) *Gorleston: land fetch diurnal cycle by season*

Figure 7 Examples of diurnal cycle analysis plots

Overall, the suggestion is that the results should apply equally to other European coasts at similar latitudes, including the whole of the North Sea, the Baltic Sea, central and southern Norway, western France and, probably, the Atlantic coasts of Spain and Portugal. The Mediterranean behaves essentially as an inland sea, with little mixing between warm surface water and cool water advected from polar latitudes. Thus, it is likely that the surface waters have more of a diurnal cycle of temperature than the open ocean and that the difference in wind speeds between land and sea fetches is less pronounced than on the coasts of the North Atlantic. Station data from the Mediterranean would be required to test this hypothesis.

Short-term variability: Gusts

Due to difficulties in obtaining gust data from offshore sites, it was decided to concentrate on exploring techniques for obtaining information on extreme events. The UK coastal station datasets used in the analysis of the diurnal cycle of wind speed also contain information on the maximum gust speed in each hour. In order to best represent patterns of gust behaviour over the open sea, only the four stations with no land fetch were considered. Of these, the most complete record was for Tiree, a small island off the west coast of Scotland, where 15 years of gust data were available (1983-1997).

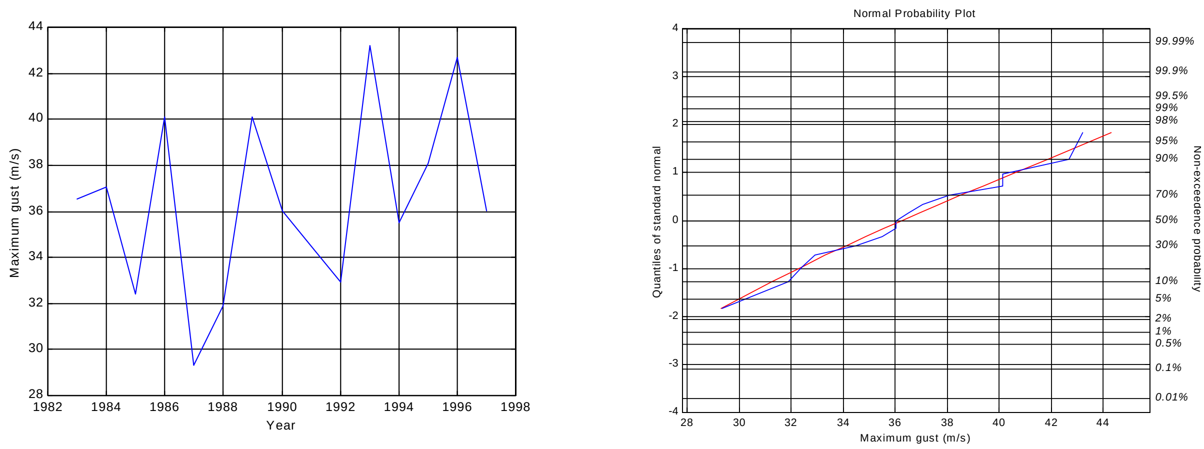
A simple but elegant method of examining the long-term behaviour of maxima involves fitting the Generalised Extreme Value (GEV) Distribution to the data. If a reasonable fit is obtained, various statistics about the return period of maximum gusts over many years can be deduced. Three methods of fitting the GEV to the annual maximum gust were tested:

- ❖ maximum likelihood,
- ❖ method of moments, and
- ❖ probability weighted moments (PWM)

Figure 8a shows the time series of the 15 annual maxima for Tiree. Figure 8b shows the cumulative density functions (CDF) derived empirically from this maximum gust time series together with the

CDF from the GEV, calculated using PWM, that best fits this time series. The match appears to be very good.

Overall, the results indicated that extreme value analysis offers a valuable technique for the evaluation of damaging high wind occurrence at offshore wind speed sites. From a relatively short run of data, here 15 years, it is possible to explore the behaviour of severe winds over 50 years.



(a)

Annual gust maxima for Tiree

(b)

Normal probability plot of empirical (blue line) and GEV (red straight line) functions for Tiree annual maximum gust speeds

Figure 8 Example results from analysis of extreme gusts

9 Waves

Offshore wind turbines are designed to withstand the fatigue loading and extreme loads that are encountered at sea locations. To this end it is important to characterise both the wind loads, the wave loads and the correlations between them. Modern design codes use the wave state as input to generate the corresponding loads. The wave state is characterised by the significant wave height, the wave direction, the wave period and the corresponding wave conditions.

Previous studies (e.g. Opti-OWECS) have shown that the loads that offshore wind turbines have to withstand are generated by wind sea. The time period of these waves corresponds to the dynamic response periods of the structure, whereas swell waves have much longer wave periods and thus are less of a problem to the structure.

The POWER study has concentrated on mapping these parameters for the European seas. In addition, for selected areas more detailed “footprint” data have been compiled. The footprint-data give more insight in the wind and wave pattern, i.e. the annual variations, monthly variations, extreme conditions, and frequency distributions. Moreover, the footprints contain correlations between wind and wave conditions, such as scatter diagrams which can be used for design purposes.

These data have been retrieved from the UK Meteorological Office’s European wave model archive covering the area 30.5°N to 66.75°N and 14.0°W to 35.5°E. This comprises the Baltic Sea, the North Sea, the Atlantic, the Mediterranean Sea and the Black Sea.

Generally, the significant wave height with a 50 year return period is the determining wave load for offshore constructions. Figure 9 depicts the distribution of this load for the European seas. We can conclude that the most severe wave conditions appear in the Atlantic Ocean (Norway, Ireland, France and Spain). The Baltic sea is sheltered for extreme wave conditions. Surprisingly in parts of the Mediterranean quite severe wave conditions might occur.

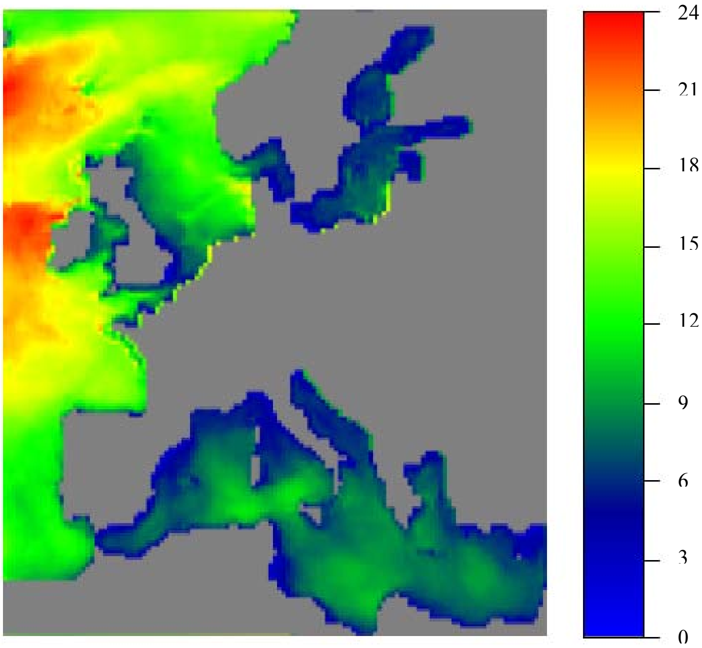


Figure 9 Extreme wave height (m) for a 50 year return period

More details of the analysis of wave data can be found in [1, Chapter 8].

10 Confidence limits

A bootstrapping estimation method was used to gauge the reliability of the final POWER wind speed estimates by calculating 95% confidence limits in the calculated mean monthly wind speeds.

Essentially, bootstrapping uses the available data to create a large number of extra data sets using resampling with replacement. Using the Weibull parameters for each directional bin estimated by WAsP (see Section 4), twelve sets of simulated wind speeds were created, one for each directional bin, with 100 simulated wind speeds per bin. The creation of simulated data fitting a known distribution (in this case the Weibull distribution) is fairly straightforward and the facility is available in many commercial statistics packages including MatLab. The simulated data were then used to calculate the monthly mean wind speed for that grid square for each direction bin. To arrive at an overall mean, the bin means were weighted according to the frequency of wind speeds associated with each direction, and then summed. The 95% confidence limits for the overall mean were derived by applying the frequency weighting procedure to the confidence limits for each directional bin.

Clearly, the method is complex, and the project team found it impractical to perform the analysis for each height and grid point. Therefore, effort was concentrated on six grid squares, each chosen to represent one of the regions identified as important in the analysis of the long-term wind field patterns (see Section 7). Furthermore, 95% confidence limits were produced for a single height (90m a.s.l.) selected to be a typical hub height for offshore wind turbines. Note, however, that the methodology can be readily applied to data for any height at any location.

The use of Monte Carlo simulation to calculate confidence limits was also investigated. The confidence limits were similar to those from bootstrapping but the analysis took 100 times longer, making the use of this method prohibitively slow.

The methodology and results of the analysis of confidence limits are described more fully in [1, Chapter 9].

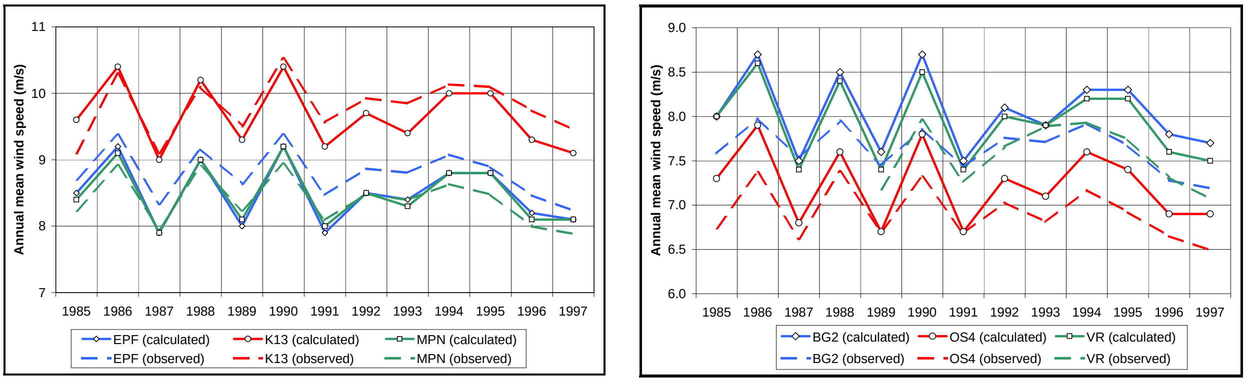
11 Comparisons with measured data

POWER's WAsP model results were compared with measured data from sites off the coasts of The Netherlands (Measuring Network Zeeland (ZEGE) and Measuring Network North Sea (MNZ)), Denmark (meteorological masts at Horns Rev and Læsø Syd) and the Mediterranean. In some cases, the source data had been subjected to inconsistent processing techniques which meant that a significant amount of effort was required to reconstruct the observation data to make them consistent and thus suitable for the comparison.

The comparison results presented here merely provide an overview of the comparisons performed. Full details are given in [1, Chapter 10].

Dutch waters

Figure 10 and Table 2 both compare observed and calculated values of mean annual wind speeds for six stations in Dutch waters - three of the Measuring Network North Sea (K13, Euro platform (EPF) and Measuring Post Noordwijk (MPN)) and three of the ZEGE network (Oosterschelde 4 (OS4), Brouwershavensche gat 2 (BG2) and Vlakte van de Raan (VR)).



(a) *Measuring Network North Sea*

(b) *ZEGE*

Figure 10 Comparison of observed and calculated annual mean wind speeds in Dutch waters

The dashed lines are the results of the averages of the (reconstructed) observations, the solid lines are the POWER WAsP calculations

Table 2: Overview of observed versus calculated mean wind speeds.

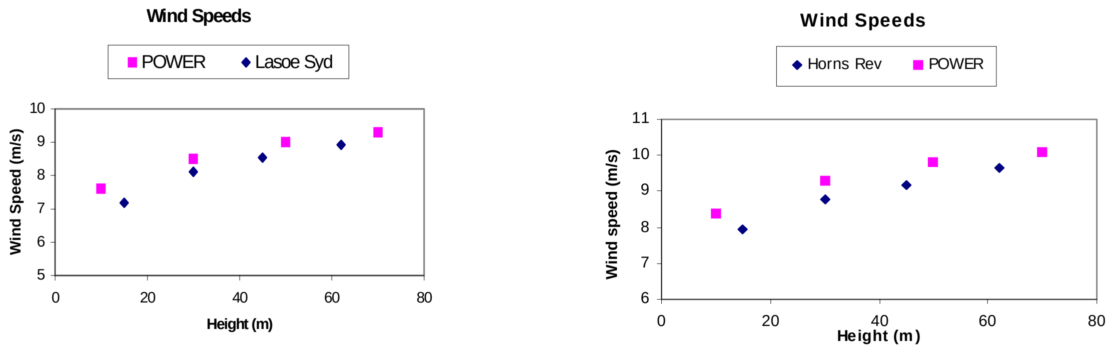
Location	EPF	K13	MPN	BG2	OS4	VR
observed mean wind speed (m/s)	8.80	9.80	8.40	7.64	6.91	7.56
calculated mean wind speed (m/s)	8.50	9.66	8.48	8.05	7.23	7.86
observed/calculated	104%	101%	99%	95%	96%	96%

The results of these comparisons suggest the POWER results show good agreement with the observed data in Dutch waters.

Danish waters

The POWER WasP results were also compared against high quality wind speed profile data collected by ELSAM on purpose-built meteorological masts at two prospective offshore wind farms sites for in Danish waters – Horns Rev and Læsø Syd. These data were gathered over the 12 month period between June 1999 and May 2000.

Figures 11a and 11b compare POWER WAsP model mean annual wind speed estimates with wind speeds observed at Horns Rev and Læsø Syd respectively.



(a) Horns Rev

(b) *Læsø Syd*

Figure 11 Observed and calculated mean vertical wind speed profile in Danish waters

At first sight, these results suggest POWER has overestimated the mean wind speeds at these site by the order of 0.5m/s. However, it must be remembered that the ELSAM Horns Rev/ Læsø Syd observations represent the wind conditions that occurred at these locations during a single 12 month period (June 1999-May 2000), whereas the POWER results represent mean wind speeds over 13 year period (1985-1997). Figure 12 and 13 show POWER estimates of the inter-annual variation in mean wind speed over this 1985-1997 period at Horns Rev and Læsø Syd respectively. It is clear that from year to year there is significant variation in the mean wind speeds at the sites. Furthermore, the ELSAM Horns Rev/ Læsø Syd observed wind speed values lie within the overall range of mean wind speed values estimated for the sites.

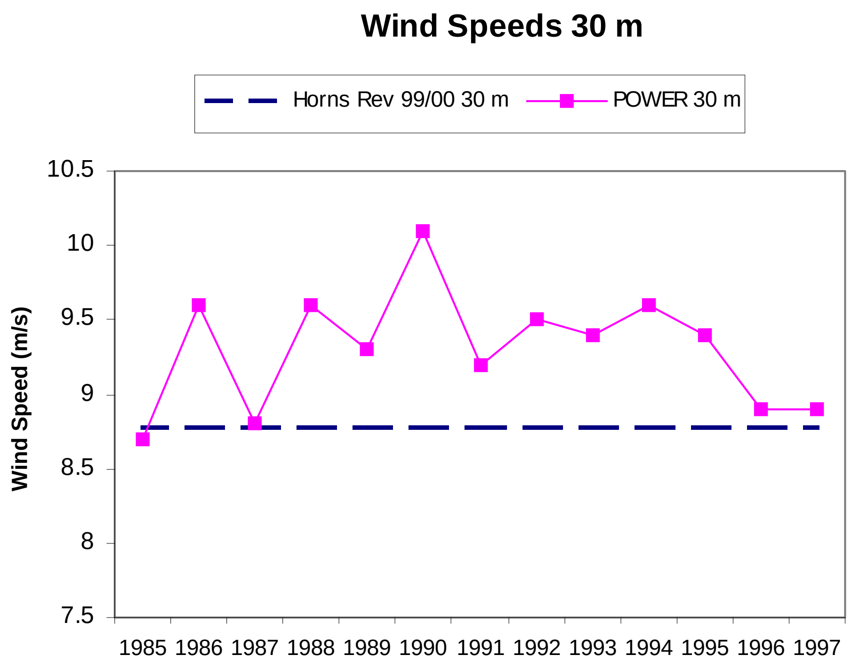


Figure 12 – Predicted variation in mean yearly wind speed at 30 m ASL for Horns Rev 1985-97

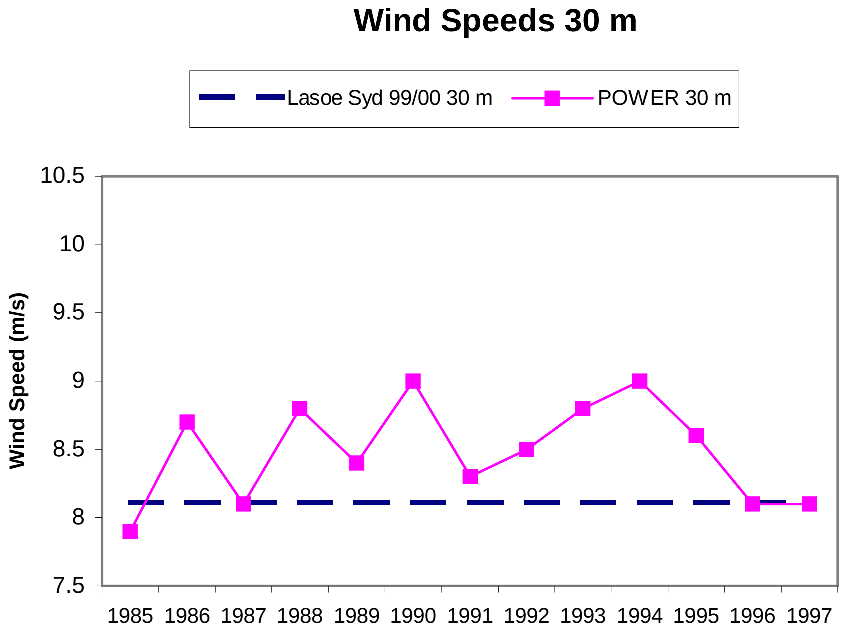


Figure 13 – Predicted variation in mean yearly wind speed at 30 m ASL for Læsø Syd 1985-97

Figures 14 and 15 compare the observed variation in mean monthly wind speed (for June 1999 to May 2000) with the POWER model estimates for Horns Rev and Læsø Syd. The correlation between the observed and calculated values is good.

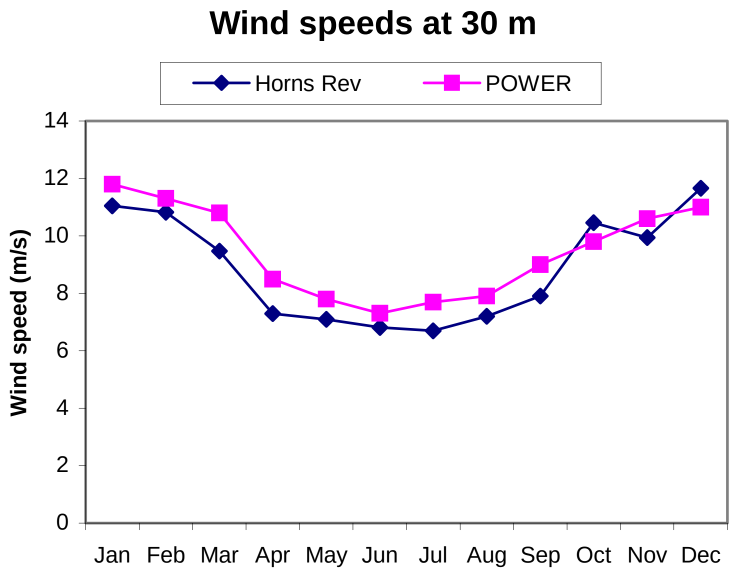


Figure 14 – Comparison of observed and calculated monthly variations in wind speed at Horns Rev

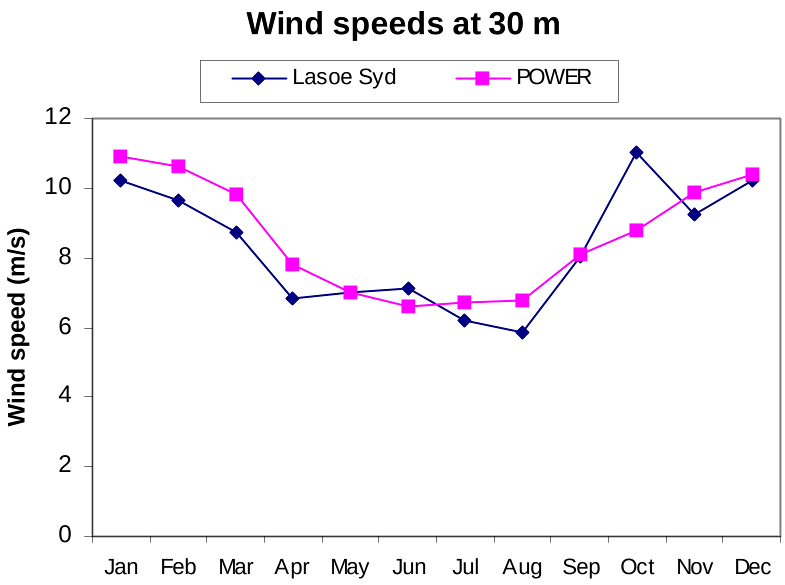


Figure 15 – Comparison of observed and calculated monthly variations in wind speed at Læsø Syd

Figures 16 and 17 show the observed and calculated wind rose at Horns Rev and Læsø Syd respectively.

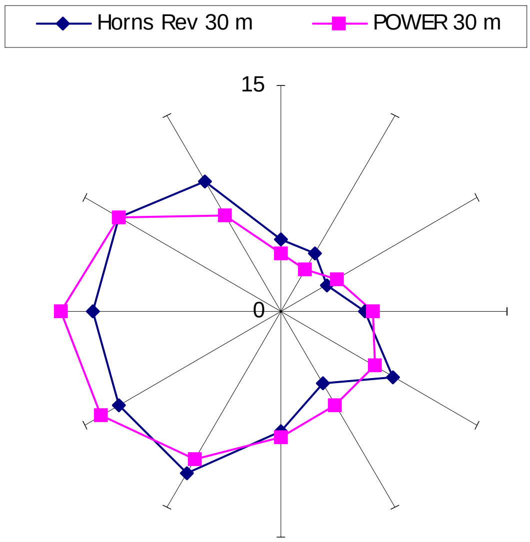


Figure 16 – Comparison of observed and calculated wind rose at Horns Rev

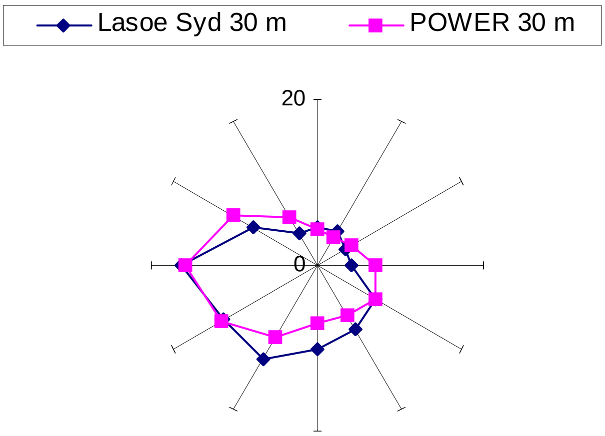


Figure 17 – Comparison of observed and calculated wind rose at Læsø Syd Figure

Finally, Figures 18 and 19 show the observed and calculated wind speed distributions at Horns Rev and Læsø Syd respectively. In both cases, the POWER results seem to have under-estimated the frequency of medium- to low wind speeds, but over-estimated the frequency of high wind speeds

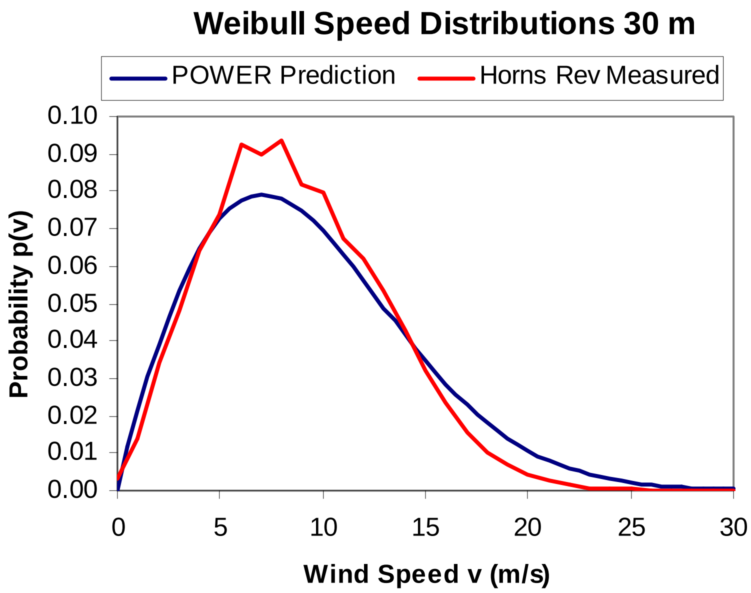


Figure 18– Comparison of observed and calculated wind speed distribution at Horns Rev

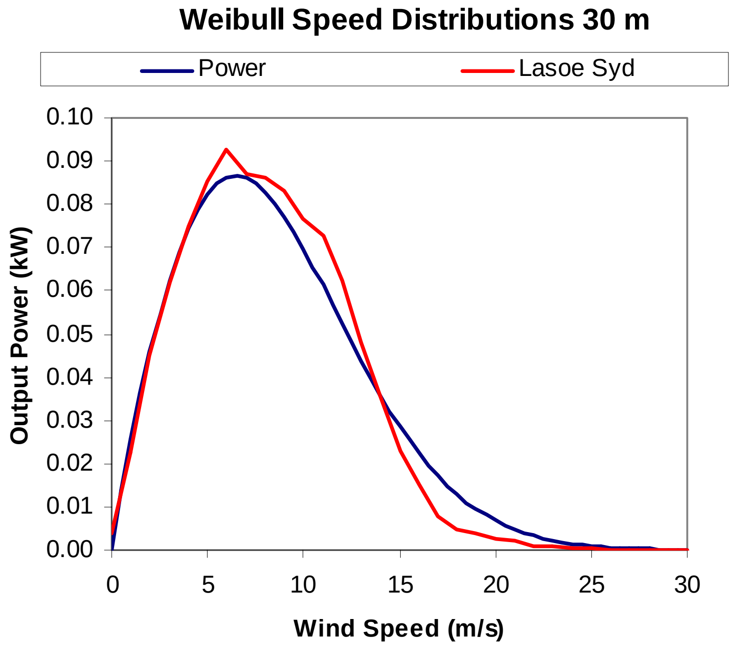


Figure 19 – Comparison of observed and calculated wind speed distribution at Læsø Syd

Overall, comparison of observed and calculated wind conditions at both of these proposed Danish offshore wind farm sites indicate that the POWER results are a good representation of the typical wind regime for these sites.

12 Conclusions

On a regional and national scale, POWER has produced state-of-the-art estimates of the extent and distribution of Europe's offshore wind energy resources not only in the coastal zone – the current focus of the offshore wind industry's attention – but also throughout the region's far offshore areas, where there is potential for wind energy to be exploited in the longer-term by turbines mounted on floating structures. Hence, this information will enable the most appropriate and economically attractive areas for offshore wind energy development to be identified, both now and in future.

On a local scale, POWER provides detailed first estimates of the long-term environmental conditions at specific offshore locations. This information is useful to the offshore wind energy industry since this is the exactly the type of data required for initial scoping and feasibility studies for new offshore wind energy developments. It may be possible to base preliminary assessments of the turbine power output as well as other key parameters such as initial values of the design parameters for turbine support structures etc. on the POWER results. This enables the broad technical and economic feasibility of an offshore wind farm at a particular site to be established without the need to initiate costly and time-consuming an offshore meteorological data gathering campaign. If the site is suitable, more detailed (and short-term) wind and wave monitoring studies can then be performed at the site, which refine the initial POWER estimates for detailed design purposes.

13 The POWER tool

The data on wind and wave parameters for European waters produced by the POWER project has been compiled as a set of Microsoft Excel work books. The data can be accessed using the "POWER tool" - a simple graphical user interface (GUI) that allows the user to display, in both numerical and graphical form, data from the database of wind and wave parameters.

14 Acknowledgements

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