WASP FOR OFFSHORE SITES IN CONFINED COASTAL WATERS - THE INFLUENCE OF THE SEA FETCH

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The increasing interest in harvesting wind energy offshore requires reliable tools for the wind resource estimation at these sites. Most commonly used for wind resource predictions on land as well as offshore is the WAsP program. This program has been validated extensively for sites on land and at the coast. However, due to the lack of suitable measurements there is still a need for further validation for offshore sites. New data from ongoing measurements in the Danish Baltic Sea region are available now. The wind resources estimated from these measurements are compared to WAsP-predictions. They are found to agree well. The only deviation found is for two sites with comparable distance to the coast but with a different distribution of land. Here the measurements show slightly different wind resources which are not predicted by WAsP. Wind speed ratios of several pairs of stations are modelled with WAsP for 12 directional sectors and compared with the measurements. Deviations in the directional wind speed predictions were found to be dependent on the corresponding sea fetches: For smaller sea fetches WAsP seems to slightly overpredict the wind speed, while for long fetches of more than 30 km an underprediction is found.
Keywords: Wind resource assessment, Off-shore, WAsP, Coastal sea areas

1. INTRODUCTION

Suitable sites for wind farms on land are scarce in some regions in Europe, while the potential areas for offshore installations are huge. Additionally, the wind resource offshore is much better than on land. Therefore the interest in developing offshore sites for wind energy utilisation has been growing in recent years. It is expected that an important part of the future expansion of wind energy utilisation at least in Europe will come from offshore sites.

However, compared to land sites the economic viability of offshore wind farms depends on the compensation of the additional installation cost by a higher energy production. A reliable prediction of the wind resource at offshore sites is therefore crucial for project planning and siting.

The wind resource prediction model WAsP [1] is the standard method for wind resource predictions on land as well as offshore. It has been validated extensively for land conditions. A validation study for coastal stations was performed by intercomparisons of wind measurements at different heights from high meteorological masts close to the sea [2]. No significant deviation was found. Only very few measurements are available for a validation of WAsP for offshore sites. Some comparisons with offshore measurements from measurement platforms have been made and also showed a good agreement [2]. A comparison with Vindeby data showed reasonable agreement with a slight overprediction of the wind speed at Vindeby [3].

In Denmark plans are going ahead to install 4000 MW offshore wind turbines until the year 2030. In the current planing phase offshore wind measurements are being made at three prospective wind farm sites. The measurements are located in the confined Danish waters of the Baltic Sea near the islands of Lolland and Falster at distances of about 10 km from the coast. The data presently available from these measurements are analysed together with data from the Vindeby offshore wind farm which is located about 2 km from the coast.

2. OFFSHORE WIND CONDITIONS

Modelling wind resources over coastal waters is different to land conditions due to a combination of several effects:

The favourable wind resource offshore is mainly caused by the low surface roughness of the sea. Contrary to land conditions, the sea surface roughness is not constant but depends on the waves present. These are in turn governed by the momentum exchange process between wind and waves which depends on wind speed, water depths and distance from the shore.

The atmospheric stability is the second parameter which differs greatly between land and water areas. This is caused by the different heat fluxes and heat flux variances between land and water. It might also depend on the length of the sea fetch in a transition zone when the wind blows from land to water. The wind speed is influenced by atmospheric stability in two ways:

The vertical wind speed profile is directly dependent on the atmospheric stability.

The internal boundary layer (IBL) which develops at the coastal discontinuity influences the wind speed offshore for wind from land. The growth of this IBL depends on the atmospheric stability.

3. WASP FOR OFFSHORE WIND CONDITIONS

The above mentioned effects influencing the wind speed in coastal waters are treated by WAsP with simplified empirical models:

- The atmospheric stability is treated as a perturbation of the logarithmic vertical wind speed profile. It is calculated with an empirical formula taking into account the mean and the variability of the heat flux from the surface to the air. Land and water surfaces are distinguished by different values for these quantities.

An interpolation between land and sea areas is used in a transition zone on both sides of the coastal discontinuity.
- Roughness changes are treated with an empirical formula using an internal boundary layer (IBL) approach. The IBL model does not depend on the atmospheric stability.
- WAsP assumes a constant value of 0.2 mm for the sea surface roughness. No dependency on wind speed or fetch is taken into account.

4. MEASUREMENT SITES

Measurements are being performed at several meteorological masts on and around the islands of Lolland and Falster in Denmark. The locations of the stations used here are shown in figure 1. The measurements at Vindeby sea mast west (SMW), Omø and Rødsand are measurements from offshore meteorological masts. The measurement at Vindeby Land Mast (LM) is an accompanying coastal measurement.
The Vindeby SMW is situated 300 m west of the Vindeby farm 1.6 km from the coast. The Vindeby LM is erected at the coast close to the wind farm. Measurements started in November 1993 and almost 60000 records of half hourly averages are available. For a detailed description of the measurements see [3].
Wind speed measurements at the Sea Mast West are disturbed for some wind direction sectors (330º-120º) by wakes from the wind turbines. This influence has been corrected for by an estimation of the wake effects with the wind farm modelling program FCalc [4].
The sites Omø and Rødsand are offshore sites located in the south-eastern part of Denmark near the island of Lolland. Both sites have a distance of about 10 km to the nearest land. Omø is located to the north of Lolland near the Vindeby site, while Rødsand is situated south-east of Lolland (see Figure 1).
Half hourly averages of wind speeds and directions in different heights, temperatures and temperature differences are collected. Measurements started in August 1996 and currently 6200 records are available at the station Omø and 13200 at Rødsand.

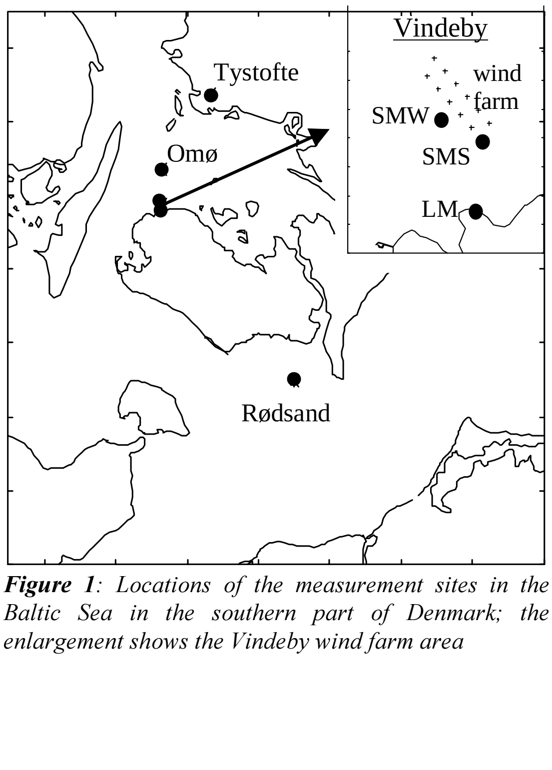

Figure 1*: Locations of the measurement sites in the Baltic Sea in the southern part of Denmark; the enlargement shows the Vindeby wind farm area*

5. WIND RESOURCES

The wind resources, i.e. the long term mean wind speed, is estimated from the onsite measurements and compared to WAsP-predictions. Deviations between the wind resource during the measurement period and the long term average were corrected by using a 14 year time series from the station Tystofte. This station is a land measurement located in the southern part of Sealand, about 5 km from the coast.
WAsP predictions were calculated using two different measurement stations as input: The Vindeby land mast and the Tystofte meteorological station.
Figure 2 shows the mean wind speeds of the sites at 48 m height (46 m at Vindeby LM) versus their distances to the coast, i.e. their minimum sea fetch. The points connected with lines are WAsP predictions, the squares are the estimations from the onsite measurements.

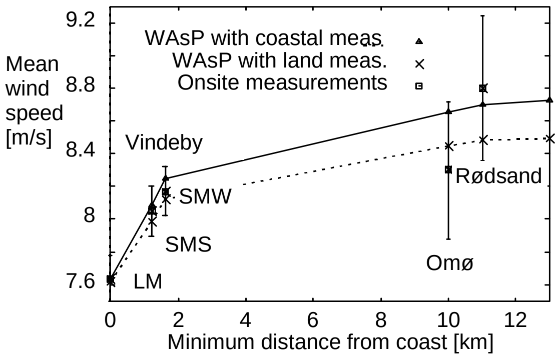

Figure 2: *Long term mean wind speeds for a coastal and four offshore sites estimated from onsite measurements (with estimated maximum uncertainties) and predicted by WAsP on the basis of coastal and land measurements*

As expected, the mean wind speed rises with increasing distance to the coast. The increase in wind speed with distance is large for the first kilometres but decreases quickly thereafter. Deviations of the WAsP predictions are generally small, up to 5%, and are in the same range as the uncertainties in the wind speed estimations based on the onsite data.
For the WAsP predictions an additional point is shown which gives the results for the open sea. It can be seen that the two sites Rødsand and Omø almost reach that limit. WAsP assumes only a very small influence of the land for distances larger that about 10 km.
Contrary to this prediction the estimations for Omø and Rødsand on the basis of the onsite measurements indicate a difference in the mean wind speed. A possible reason for this is the difference in the fetch situations. Omø is surrounded by land at about 10 km distance in the south, west and north-east directions, while Rødsand has land in this distance only in the northern and north-eastern directions, where the wind speed probability is low. It also has long sea fetches in the most frequent westerly wind directions (see fig.1).

6. FETCH INFLUENCE ON THE WIND RESOURCE

6.1 Methodology

The measured and WAsP predicted wind speed ratios between a number of sites are compared for 12 wind direction sectors. Since the sea fetch for the sectors differ greatly, a possible dependency can be investigated.
The WAsP method uses measurements from one site (predictor) to estimate the wind resource at the predicted site. Within the model the measured directional wind speed distributions are described by Weibull functions. For short time series this procedure introduces an error due to deviations of the measured distribution from Weibull curves. To compensate for this error the comparison is made for wind speed ratios rather then wind speeds.
First a common time series of wind speeds and directions is compiled for both stations. The measured data of one site are taken as input to WAsP to derive a wind climatology. This is used to predict the sectorwise mean wind speeds for both sites.
Subsequently the predictor and predicted station are exchanged and a new ratio calculated. The average ratio is used for comparison with the measurement.
The ratios of the measured data are derived from the same time series as used for the WAsP predictions. The wind speeds of both stations are bin averaged in 30° bins with respect to the wind speed of one station. This is repeated with the wind direction of the other station and the average ratio is used for comparison. Wind direction sectors where the measurement is disturbed by mast interference are omitted. Uncertainties of the measured ratios are estimated as the average standard deviation of the means plus half of the difference of the two ratios calculated.

6.2 Direction dependent wind speed ratios

Examples for measured and WAsP estimated direction dependent wind speed ratios are shown in figures 3 and 4 along with the lengths of the sea fetches of the respective stations. The solid lines show the measured ratios and the dashed lines are WAsP predictions. Measured data with possible mast interference have been omitted.
Figure 3 shows the ratios of Vindeby SMW and LM. Vindeby SMW is located 1.6 km off the north coast of Lolland (see figure 1). Here the behaviour of WAsP for small fetches can be investigated.
The measurements show two distinct maxima of the ratio which are roughly in the direction of the coastline. This situation leads to a large fetch difference since the SMW has long sea fetches while the LM has mainly land fetch. In between these maxima (sectors 120º-180º) SMW has a short sea fetch of 1.6 to 3 km only. For the other directions both stations have similar long sea fetches and the ratio is close to one.
The WAsP-predictions show generally the same directional pattern as the measurements. In most cases the deviations between measurements and WAsP-predictions are small and the general behaviour of the directional wind speed difference between two stations is modelled well. Significant deviations are found only for the case with land fetch for LM and short sea fetch for SMW where WAsP seems to overpredict the difference between the wind speeds on land and at sea.
In figure 4 the ratios of the two offshore stations Omø and Rødsand are shown. Rødsand is located 11 km off the south coast of Lolland and the two sites are about 60 km apart from each other (see figure 1). A comparison of these sites gives the opportunity to study the measured and predicted differences for two offshore stations with different fetches situations.
The measurements show a minimum in the ratios at wind direction sectors 270º and 300º and a maximum at 330º. This corresponds closely to the very large sea fetches at Rødsand in directions 260º to 290º and at Omø at 330º to 350º. For the other directions the ratio does not deviate much from one.
The WAsP-predictions show only very small deviations

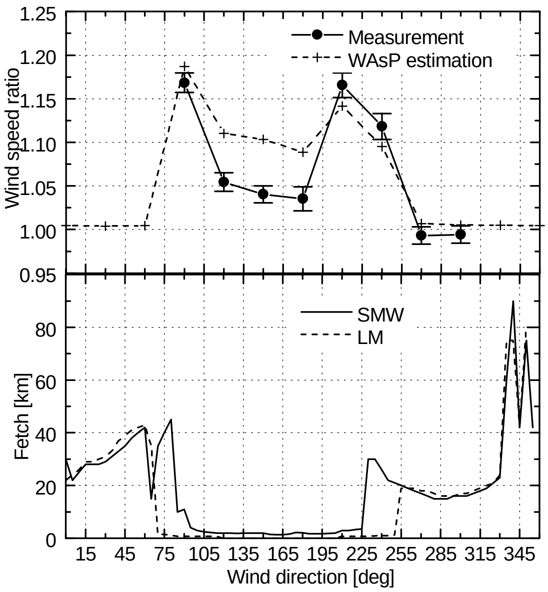

Figure 3: *Vindeby SMW / Vindeby LM: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction*

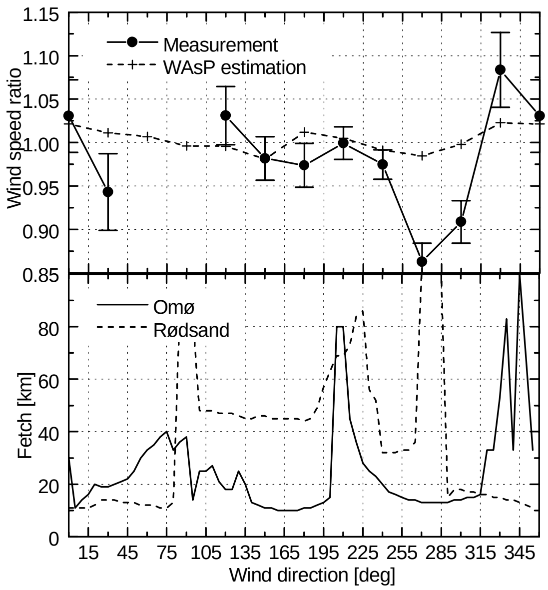

Figure 4: *Omø / Rødsand: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction*

from unity. This leads to significant deviations of 6-12% from the measurements for the two cases mentioned. For the 30º sector a smaller deviation is visible which can not be assigned to a fetch difference. For all other wind directions the deviations are in the order of the measurement uncertainty.

This result explains the measured differences between wind resources at Omø and Rødsand. The very long fetches at Rødsand which also occur in the prevailing wind directions lead to higher wind speeds compared to Omø. Since WAsP does not take these long fetches into account it underpredicts the wind resource at Rødsand.

7. CONCLUSION

The data presently available from ongoing measurements in the Danish Baltic Sea have been analysed and compared with predictions made with the wind resource estimation program WAsP. Measurements of a coastal and an inland station have been used for the predictions. It was found that the predictions of the long term average wind resource are in good agreement with measurements. However, the measurements indicate a small difference in wind resources between the stations Rødsand and Omø, which is not predicted by WAsP.

The investigation of the direction dependent wind speed also shows a generally good agreement between WAsP-predictions and measurements. Only for some wind directions significant deviations were found. These deviations show a correlation with the length of the upwind sea fetch. WAsP tends to overpredict the wind speed for situations with short sea fetches and underpredict it for long fetches. This effect explains the measured differences between the Omø and Rødsand sites since at Rødsand the wind comes more frequently from directions with long fetches.

A detailed model is needed to find an explanation for these findings. It might have to include several effects like the dependency of the sea surface roughness on wind speed and fetch (see e.g. [5]) as well as the influence of the atmospheric stability on the height profile of the wind speed and on internal boundary layers (see e.g.[3]).

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