Estimation of offshore wind resources - the influence of the sea fetch

Bernhard Lange
Wind Energy and Atmospheric Physics, RISØ National Laboratory, P.O. Box 49, DK-4000 Roskilde

Jørgen Højstrup
NEG Micon A/S, Alsvej 21, DK-8900 Randers

ABSTRACT: The increasing interest in harvesting offshore wind energy 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 correspond with the length of the sea fetch: 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. An analysis of the vertical wind speed profiles at three sites indicates that a combination of different effects is responsible for the correlation between sea fetch and model behaviour.

1 INTRODUCTION

Suitable sites for wind farms on land are scarce in some regions in Europe, while potential areas for offshore sites 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 and 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 (Mortensen 1993) of the European Wind Atlas (Troen & Petersen 1993) 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 (Petersen 1993). No significant deviation was found. Only very few measurements are available for a validation of WAsP for offshore sites. A comparison with Vindeby data showed reasonable agreement with a slight overprediction of the wind speed at Vindeby (Barthelmie et al. 1996a).

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 in distances of about 10 km from the coast. They are used to investigate wind characteristics and estimate wind speeds and power productions for planned wind farms (Barthelmie et al., in press).

The data presently available from these measurements are used in this study together with data from the Vindeby offshore wind farm which is located about 2 km from the coast. Thus the measurements cover the distances most likely encountered in the planning of offshore wind farms.

2 WASP FOR OFFSHORE CONDITIONS

Compared to land conditions the modelling of the wind resource in coastal waters is complicated by a combination of several effects:

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

For fully developed wind waves the dependence on wind speed can be modelled with the Charnock model (Charnock 1955). It describes the sea surface roughness as a function of wind speed, but independent of fetch. In the confined waters around the measurement sites the waves are mainly fetch limited and the length of the upwind sea fetch might also be important for the sea surface roughness (Frandsen et al. 1996, Johnson et al. 1997).

WAsP assumes an average value of 0.2 mm for the sea surface roughness. No dependency on wind speed or fetch is taken into account.

The atmospheric stability is the second parameter, which differs greatly between land and water areas. Its main influence is on the vertical momentum transport, which is reflected in the vertical wind speed profile. It also influences the growth of the internal boundary layer after the land-sea roughness change.

In the WAsP model the atmospheric stability is taken into account as a perturbation of the logarithmic wind speed profile. The mean vertical heat flux and its variability is used to characterise the atmospheric stability. 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 described by an internal

Figure 1: Locations of the measurement sites in the Baltic Sea in the southern part of Denmark

boundary layer (IBL) approach. The IBL model does not depend on the atmospheric stability, i.e. no difference is made between an IBL over land and over water.

A detailed analysis of the influence of the atmospheric stability in the coastal zone has been performed in (Barthelmie 1997) with the Vindeby data. A comparison with WAsP and a discussion of the performance of the atmospheric stability models of WAsP can be found in (Barthelmie et al. 1996b). Modifications of the model parameters of WAsP only lead to small improvements in the prediction accuracy.

The focus of the investigation here is laid on the question if the length of the upstream sea fetch has an influence on the prediction accuracy of the WAsP model. With the new measurements now available, a wide range of sea fetch distances are available for this investigation.

3 MEASUREMENT SITES

Measurements have been performed at six meteorological masts on and around the islands of Lolland and Falster in Denmark. The locations are shown in figure 1. The measurements at Vindeby sea mast west (SMW), Vindeby sea mast south (SMS), Omø and Rødsand are measurements from offshore meteorological masts. The measurements at Vindeby and Gedser Land Masts (LM) are accompanying coastal measurements. All collected data are half hourly averages. Long term meteorological measurements from the station Tystofte are also used.

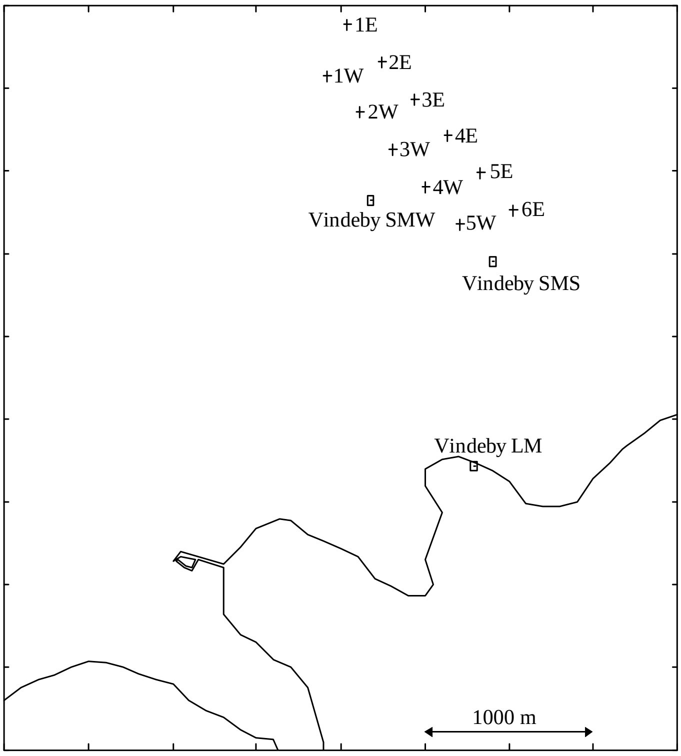

Figure 2: Layout of the Vindeby offshore wind farm and the measurement masts Vindeby SMW, SMS and LM.

The Vindeby masts SMW, SMS and LM are situated near the Vindeby offshore wind farm about 1.5 to 2 km off the north coast of Lolland (Fig. 2). The wind farm consists of 11 Bonus 450 kW turbines. For a detailed description of the wind farm see (Barthelmie et al. 1994).

Wind speed measurements at the Vindeby masts are disturbed for some wind direction sectors by wakes of the wind turbines. The measured wind speeds are therefore corrected for the shading effect of the turbines when they are bin-averaged for 30º wind direction sectors. Correction factors for the mean wind speeds are estimated with the wind farm modelling program FCalc (FCalc 1996). Reductions of up to 7% for the SMW and 2% for the LM are predicted.

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 (Fig. 1).

The meteorological station Tystofte is a land measurement located in the southern part of Sealand, in about 5 km distance to the coast and 25 km to the Omø measurement site (Fig. 1).

4 WIND RESOURCES

The wind resource, 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 correlation with a 14 year long time series from the station Tystofte.

It has to be kept in mind, however, that the measurement periods at Omø and Rødsand are only about 9 and 13 months, respectively. Even though they were corrected, this leaves some uncertainty of the estimated mean wind speeds.

The estimation of the long term mean wind speeds from the measurements was done by a combination of different methods using all available measurements (see Barthelmie et al., in press).

WAsP estimations were calculated using two different measurement stations as input:

- The Vindeby land mast, which is a coastal measurement at the Vindeby site. The predictions made with these measurements were corrected for deviations from the long term average.
- The Tystofte station, which is a long term land measurement.

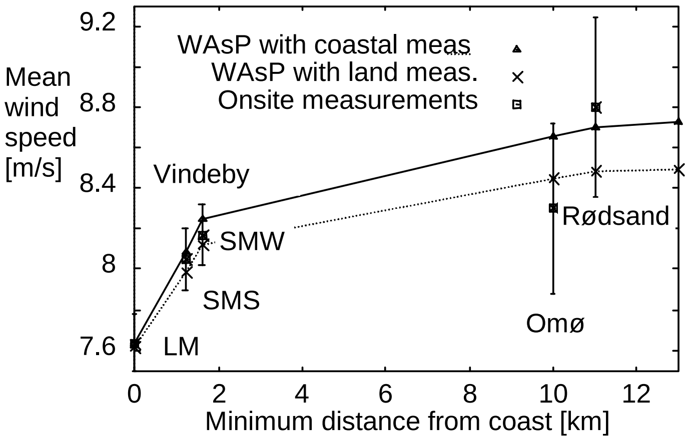

Figure 3: Long term mean wind speeds for a coastal and 4 offshore sites estimated from onsite measurements and predicted by WAsP on the basis of a coastal and a land measurement

Figure 3 shows the mean wind speeds of the sites versus their distances to the nearest coast, i.e. their minimum sea fetch. The points connected with lines are WAsP predictions, the squares are the estimations from the onsite measurements. The error bars indicate the estimated maximum uncertainties of the wind resource estimated from the measurements.

Deviations of the WAsP predictions from the estimations based on the onsite measurements are generally small, up to 5%. They are in the same range as the uncertainties in the wind speed estimations based on the onsite data. As expected, the mean wind speed rises with increasing distance to the coast. The increase in wind speed between the coastal station (Vindeby LM) and the offshore sites in 10 km distance is about 10-15%. The largest increase in wind speed when going offshore from the coast is found for the first kilometres. For the WAsP predictions an additional point is shown which gives the results for the open sea, i.e. the maximum possible value. It can bee 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.

The WAsP predictions based on the coastal and the land measurements coincide at the site of the coastal station. For stations further away from the coast the predictions differ up to about 3% with the prediction based on the land measurement being lower than that based on the coastal measurement. For the sites near the shore both predictions are very close to the measurement. Differences are only 1-2% and lie within the uncertainty range of the measured data. For the sites Omø and Rødsand, which have larger distances to the shore, the differences are still small (1-5%). However, a considerable difference is found in the measurements of this two sites while WAsP estimates almost equal values.

A possible reason for this is the difference in the fetch situations. Omø is surrounded by land in 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 (Fig. 1).

5 INFLUENCE OF THE SEA FETCH

5.1 Methodology

Ratios of measured wind speeds from two different stations are built for 12 wind directional sectors. These are compared with the respective ratios from WAsP estimated wind speeds. With different fetches for the two stations the influence of the sea fetch can be investigated in its measured and modelled influence on the wind speed.

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 avoid this error the comparison is made for wind speed ratios rather then wind speeds.

An example of the directional dependence of the wind speed ratio is given in figure 4. The ratio is obtained by dividing the measured mean wind speed of Vindeby SMW by that measured at Vindeby LM. It is plotted versus the wind direction measured at Vindeby SMW. No corrections for wind farm shading have been applied here and the directional resolution is 3º.

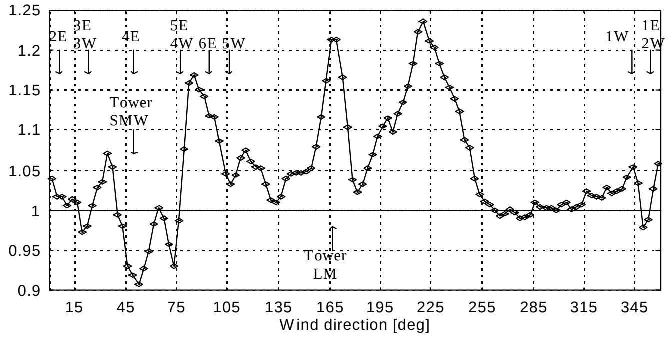

Figure 4: Measured ratios of mean wind speed Vindeby SMW / Vindeby LM; directional resolution 3º; directions of the turbines and measurement masts are shown with arrows

The directions with mast shading are shown and the disturbance can clearly be seen. Also indicated are the directions of the 11 turbines from the Vindeby wind farm. The reduction of the wind speed due to the influence of the wakes is obvious.

For the WAsP estimations of the wind speed ratios, 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 of the station itself and of the second measurement station. 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.

5.2 Direction dependent wind speed ratios

Examples for measured and WAsP estimated direction dependent wind speed ratios are shown in figures 5, 6 and 7 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.

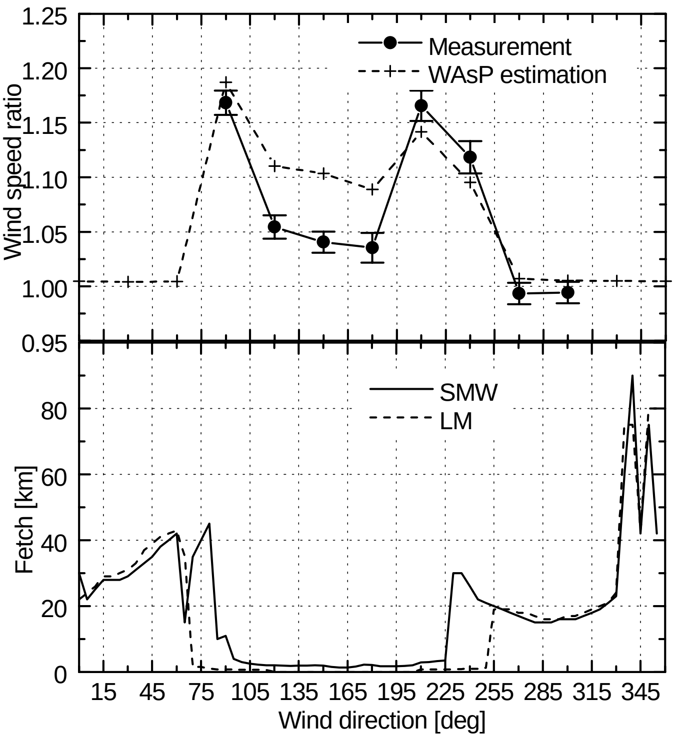

Figure 5: Vindeby SMW / Vindeby LM: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

Figure 5 shows the ratios of Vindeby SMW and LM. Vindeby SMW is located 1.6 km off the north coast of Lolland (Fig. 2). 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 this 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.

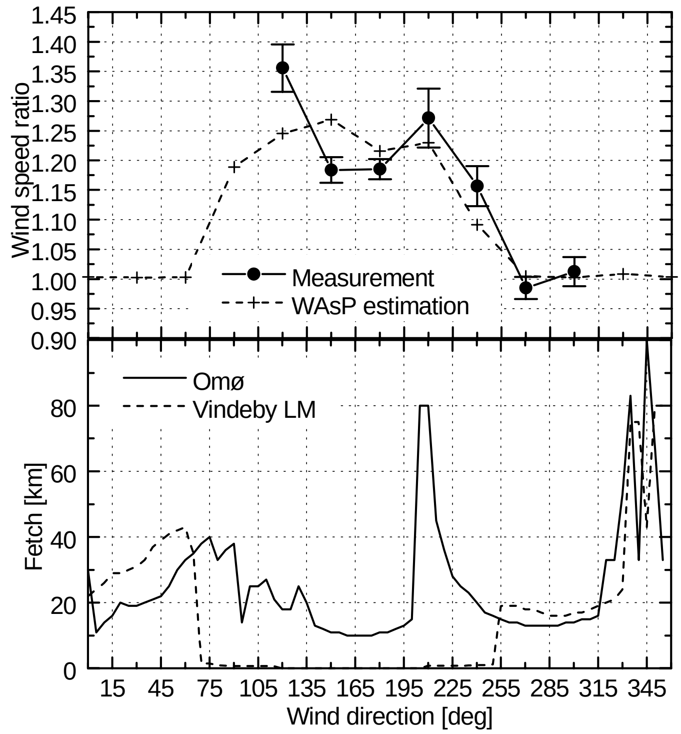

Figure 6: Measured and WAsP-predicted wind speed ratios versus wind direction from Omø / Vindeby LM (top) and sea fetches of Omø and Vindeby LM versus wind direction

Figure 6 show the results for the ratio between Omø and Vindeby LM. The overall situation at these sites is quite similar to the one for Vindeby SMW and LM, only that Omø is located about 10 km further offshore (Fig. 1). 150° and 180° are the sectors with wind from Lolland and a sea fetch of about 10-15 km. Here WAsP again overpredicts the difference between sea and land. The very rapid change of sea fetch length from 15 to more than 80 km at 200º seems to have an influence also on the wind direction sector 180º.

For the very long fetches at Omø at 120º and to a lesser extent at 210º and 240º WAsP underpredicts the difference.

In figure 7 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 (Fig. 1). A comparison of these sites gives the opportunity to study the measured and predicted differences for two offshore stations with very 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.

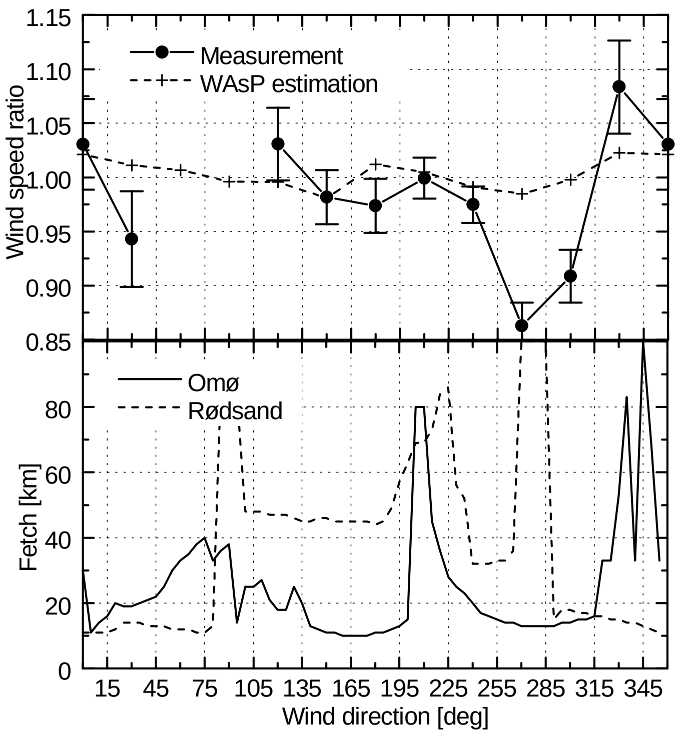

Figure 7: Omø / Rødsand: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

The WAsP-predictions show only very small deviations 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 can be seen which can not easily 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 there compared to Omø. Since WAsP does not take these long fetches into account it underpredicts the wind resource at Rødsand.

6 WIND SPEED PROFILES

To investigate possible causes for deviations of WAsP results, measured and modelled vertical wind speed profiles are compared. Two pairs of stations have been used for this: Vindeby LM and SMW as well as Vindeby LM and Omø. Measurements are available at three heights: 10m, 30m and 48m (46 m at LM). The wind speed measurements have been corrected for the effect of the flow distortion caused by the measurement tower, except for wind directions where the tower was upwind of the anemometer. The correction factors have been estimated after (Højstrup, in press).

WAsP calculations are made using the measured time series at Vindeby SMW and Omø at 48 m height as input. Estimations are made for both sites at all heights.

In most cases the WAsP calculations of the mean wind speeds as well as the estimations of the vertical wind speed profiles agree well with the measurements. Some examples of measured and modelled profiles are shown in figures 8 and 9.

Figure 8 shows the case with wind blowing from land, i.e. Vindeby LM has land fetch, Vindeby SMW has about 1.6 km sea fetch and Omø has about 10 km sea fetch.

The effect of different land and sea roughnesses can clearly be seen as the profiles for the offshore stations are steeper than for the LM. A comparison of the profiles from Vindeby SMW and LM clearly shows a wind speed difference, which decreases with height. At the highest anemometer the difference is only about 3%. This shows that at 1.6 km distance the influence of the land is still dominant at the height of 48 m.

This tendency is also present in the profiles of Vindeby LM and Omø, though to a lesser extent. Here the wind speed difference at the highest anemometer is also much larger. This shows that the influence of the land roughness is much weaker and the internal boundary layer from the land-sea transition is higher.

All measured profiles are to some extent curved towards higher wind speeds at greater heights compared to the logarithmic profile which would be a straight line in the graphs. This is believed to be mainly caused by influences of the atmospheric stability. The large curvature of the profile of the SMW is probably due to the additional influence of the internal boundary layer from the land sea roughness change.

The earlier comparison of the wind speed ratios showed that WAsP overpredicts the difference between LM and the offshore masts at 48 m height (Figs 5, 6). This can also be seen from the profiles in figure 8. However, it also shows that the steepnesses of the predicted and measured profiles do not deviate much. This indicates together with the deviations of the curvatures of the profiles that the simplifications WAsP makes in the description of the sea surface roughness are not the only reason for the deviations. It should be kept in mind, however, that the measurement at Omø / Vindeby LM stems from a relatively short time series. Therefore the atmospheric stability which occurred during the measurement differs from the yearly distribution WAsP assumes.

Figure 9 shows the situation of land fetch for the LM and long sea fetches for both of the offshore masts (240º sector). From the wind speed ratios a slight underprediction of the wind speed difference at 48 m is known, especially for the ratio of Vindeby LM / Omø (Figs 5, 6). This is repeated in the profiles. Again it can be seen that the steepnesses of the offshore profiles compare well between modelled and measured values. For the LM the modelled steepness is slightly too small, which points towards a slight overestimation of the land roughness. As before, the curvatures indicate an influence of the atmospheric stability which is not accurately modelled.

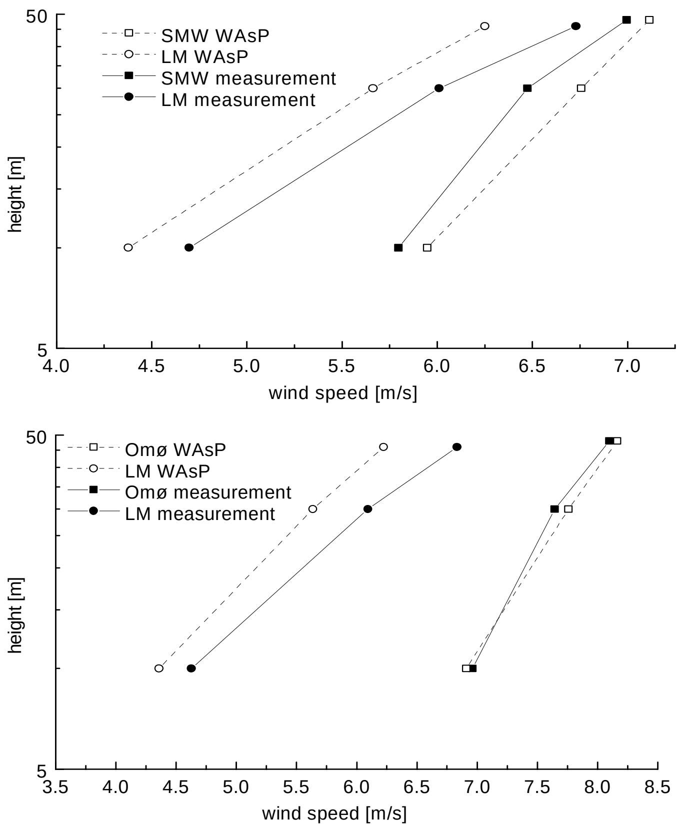

Figure 8: Measured and WAsP-predicted mean wind speeds for wind directions with land fetch situations (150° and 180° sectors) versus measurement heights for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph)

In the examples both over- and underestimation of the difference between land and offshore wind speed are present. In both cases modelled and measured profiles show deviations in curvature and only small differences of steepness. This indicates that a combination of different reasons is responsible for the deviations found from the analysis of the wind speed ratios. It seems likely that the deviations found are not solely caused by a problem of the modelled sea surface roughness. Additionally, the growth of the internal boundary layer and the influence of the atmospheric stability play an important role.

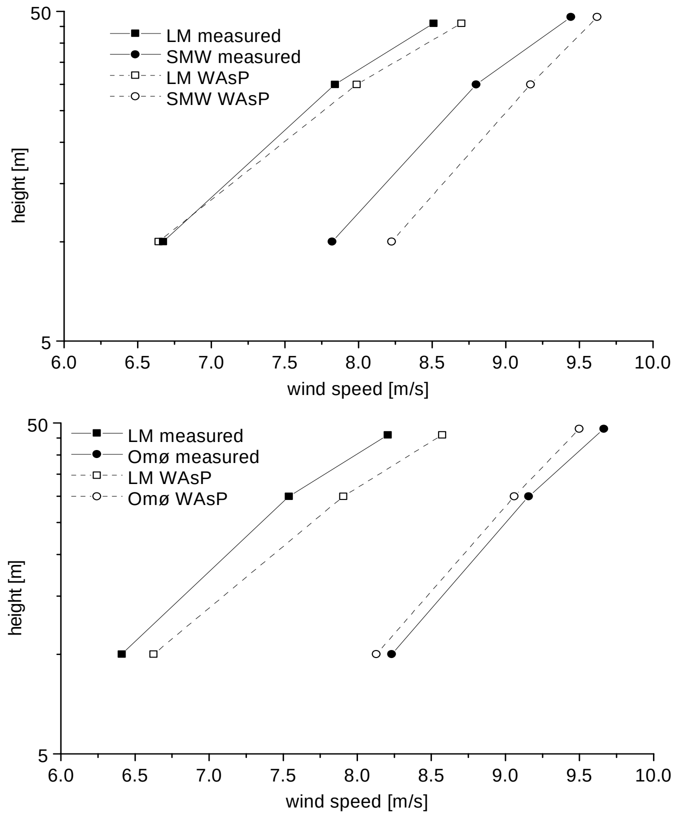

Figure 9: Measured and WAsP-predicted mean wind speeds for wind directions with different fetch situations (240° sector) versus measurement heights for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph)

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.

The measurement indicates 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. However, 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.

The comparison of measured and predicted height profiles indicates that a combination of different reasons is responsible for the deviations found for some wind directions. The modelled sea surface roughness can not solely be held responsible for the deviations. The growth of the internal boundary layer and the influence of the atmospheric stability also seem to play an important role

A detailed model is needed to find an explanation for these findings. It might have to include several effects like the dependence of the sea surface roughness on wind speed and fetch (see e.g. Johnson et al. 1997) as well as the influence of the atmospheric stability on the height profile of the wind speed and on internal boundary layers due to roughness changes (see e.g. Barthelmie et al. 1996a).

ACKNOWLEDGEMENTS

The measurements at Omø, Rødsand, Gedser Rev, Gedser and Vindeby were funded by the Danish Energistyrelsen in the project 'Kortlægning af Offshore Vindressourcer' and of the European Commission in the JOULE-programs. The work of one of the authors (B. Lange) is funded by the European Commission through a Marie Curie Research Training Grant.

REFERENCES

Barthelmie, R.J., M.S. Courtney, J. Højstrup and P. Sanderhoff 1994. *The Vindeby Project: A Description.* Risø Report R-741(EN). Risø National Laboratory, Roskilde, Denmark

Barthelmie, R.J., M.S. Courtney, J. Højstrup & S.E. Larsen 1996a. Meteorological aspects of offshore wind energy: Observations from the Vindeby wind farm. *Journal of Wind Engineering and Industrial Aerodynamics* Vol. 62: 191-211

Barthelmie, R.J., N.G. Mortensen, L. Landberg & J. Højstrup 1996b. Application of the WAsP Model to Determine the Wind Resource in Non-neutral Conditions in Coastal Areas. *Proceedings of the European Union Wind Energy Conference, Göteborg, Sweden*

Barthelmie, R.J. 1997. The Effect of Atmospheric Stability on the Temporal and Spatial Variability of Offshore Wind Resources. *Proceedings of the OWEMES European Seminar: Offshore Wind Energy in Mediterranean and other European Seas*

Barthelmie, R.J., M.S. Courtney, B. Lange, M. Nielsen, A.M. Sempreviva, J. Svenson, F. Olsen & T. Christensen, in press. Offshore wind resources at Danish measurement sites. *Proceedings of the European Wind Energy Conference and Exhibition 1999, Nice*

Charnock, H. 1955. Wind stress over a water surface. *Quarterly Journal of the Royal Meteorological Society,* Vol. 81: 639-640

FCalc 1996. *Farm Calculation program*. University of Oldenburg, Germany

Frandsen, S. (ed.), L. Chacón, P. Enevoldsen, R. Gómez-Elvira, J. Hernández, J. Højstrup, F. Manuel, K. Thomsen & P. Sørensen 1996. *Measurements on and Modelling of Offshore Wind Farms*. Risø Report R-903 (EN)

Højstrup, J., in press: Vertical Extrapolation of Offshore Windprofiles. *Proceedings of the European Wind Energy Conference and Exhibition 1999, Nice*

Johnson, H.K., H.J. Vested, J. Højstrup, S.E. Larsen & H. Hersbach 1998. On the Dependence of Sea Surface Roughness on Wind Waves. *Journal of Physical Oceanography.* Vol.28: 1702-1716

Mortensen, N.G., L. Landberg, I. Troen & E.L. Petersen 1993. *Wind Atlas Analysis and Application Program (WAsP)*. Risø National Laboratory, Roskilde, Denmark

Petersen, E.L. 1993. Wind Resources Part I, The European Wind Climatology. *Proceedings of the European Wind Energy Conference, Lübeck-Travemünde; 1993*: 663-668

Troen, I. & E.L. Petersen 1989. *European Wind Atlas.* Risø National Laboratory, Roskilde, Denmark