Tidal influence on offshore wind fields and resource predictions

Demian Khan

Entec UK Ltd., Doherty Innovation Centre, Pentlands Science Park,
Bush Loan, Penicuik, EH26 0PZ, UK
E-mail: khand@entecuk.co.uk

David Infield

Centre for Renewable Energy Systems Technology (CREST),
Loughborough University, Loughborough, UK
E-mail: d.g.infield@lboro.ac.uk

Abstract: The rise and fall of the sea surface due to tides effectively moves an offshore wind turbine hub through the wind shear profile. This effect is quantified using measured data from three offshore UK sites. Statistical evidence of the influence of tide on mean wind speed and turbulence is presented. The implications of this effect for predicting offshore wind resource are outlined.

Keywords: Tidal; tide; offshore; wind; resource; MCP.

Reference to this paper should be made as follows: Khan, D. and Infield, D. (2002) 'Tidal influence on offshore wind fields and resource predictions', *Int. J. Environment and Sustainable Development*, Vol. 1, No. 4, pp.312-326.

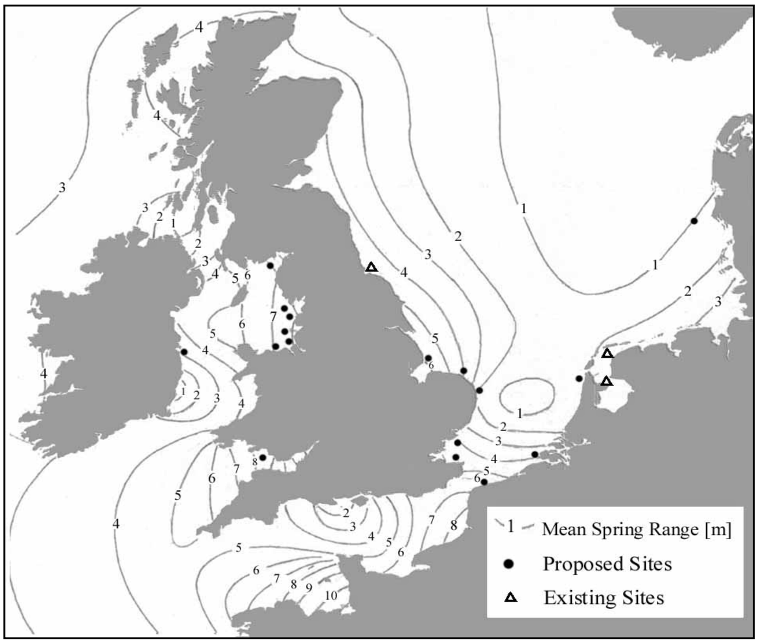
Biographical notes: Demian Khan joined Entec UK in 2002 to become a member of the Renewable Energy Project team. Previously he worked at Garrad Hassan on wind resource assessment and energy yield calculations for a variety of wind farm sites. He received an MSc from CREST on Renewable Energy Systems. The research of his degree is presented in this paper. His dissertations for both undergraduate and postgraduate degrees focused on modelling wind resources, onshore and offshore. He has also performed wave energy resource calculations for the Scottish coast, forming part of the Scottish Executive Renewable Energy study. He now has the responsibility for various projects relating to wind farm development.

David Infield is CREST's director with overall responsibility for managing the operation of it and also principle responsibility for research within it. He first worked on solar thermal systems engineering at the Building Services Research Industry Association (BSRIA) and then on wind energy at the EPSRC Rutherford Appleton Laboratory (RAL) in Oxfordshire. At RAL David was the manager of Energy Research Unit's Wind Test Site. His current research interests involve wind energy and photovoltaics and in particular their integration into electricity systems.

1 Introduction

As wind developers move offshore, new issues arise in estimating the long-term wind resource at prospective sites. One such issue is the influence of a fluctuating hub height above sea level, due to the rise and fall of the tides. The North Sea and Atlantic have considerably higher tidal ranges than the Baltic [1] and the UK coastline experiences higher tidal ranges than Germany, Holland and Denmark, as illustrated in Figure 1. This issue may therefore have most pertinence for developers around the UK coastline.

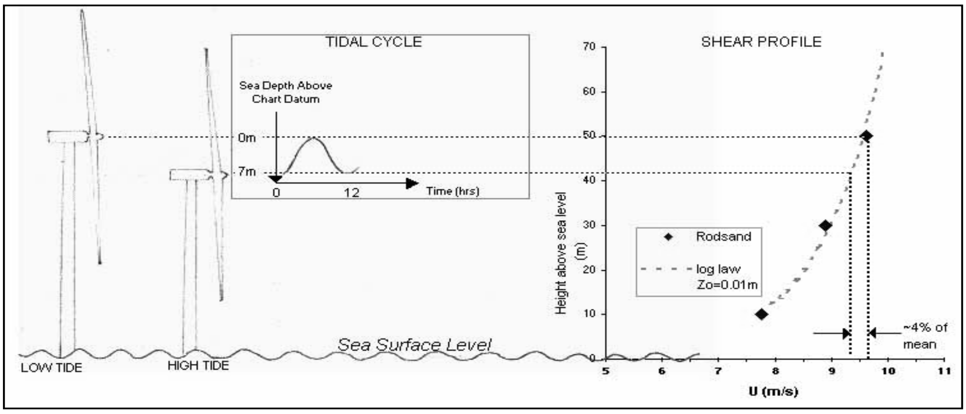
Figure 1 Map of mean spring tidal range with offshore wind farm locations [2–4]



Note: The average tidal range is about 75% of the spring range, or halfway between mean neap and mean spring

As the tide rises and falls, the offshore wind turbine effectively moves through the wind shear profile. Although shear profiles are commonly assumed to be less pronounced offshore, the mean wind speed nevertheless increases significantly with height above the surface, as shown by data from Rodsand, for example [5]. Thus we can expect on average to find higher wind speeds at low tide and lower wind speeds at high tide, shown in Figure 2. Tide is measured in metres above chart datum.

Figure 2 Offshore wind turbine moving through the shear profile during a tidal cycle



Note: Representative values are used, with a measured offshore shear profile [5]

Two scenarios are considered for their implications for offshore wind resource predictions: firstly, where wind records are available from both the offshore development site plus an onshore reference site and, secondly, where only wind records from an onshore reference site are available, i.e. no suitable offshore data exists.

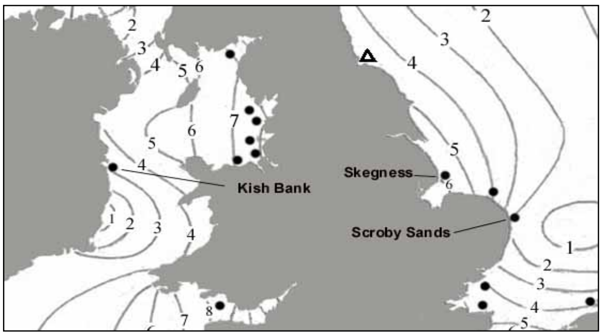
The aims of this study are to identify any tide-induced fluctuation in wind speed, to quantify this fluctuation and to assess how this knowledge may influence offshore wind resource predictions.

2 Analysis of offshore data

2.1 Wind data

Wind data for this study have been available from Powergen's offshore mast located at Scroby Sands, near Great Yarmouth [6], the RES mast located off Skegness and the Powergen/Saorgus site at Kish Bank lighthouse, Dublin Bay, Figure 3. Anemometry is performed at various heights above mean sea level (AMSL): 33m/51m at Scroby Sands, 17m/29m/43m at Skegness and 31m at Kish Bank.

Figure 3 Location of offshore wind measurement sites used in this study



2.2 Tidal data

Measured sea-state data was not available at the offshore mast locations considered in this study. Shoreline tidal data are available at a series of ports and other coastal locations where measurements have historically been made. Measured tidal time series (at least ~3 months) are used to determine 'harmonic constants' which can be used to form a deterministic model of the tide at that location. These models are available in software packages, generally used for predicting the tide for navigational purposes. Historical time series of tide can be hindcasted using such packages, which have advantages over measured time series, including coverage of a greater number of ports and 100% availability. Errors are in the range of centimetres compared to measured data.

For this study, tidal time series have been taken from the nearest available port, see Table 1. At Lowestoft, measured tidal data have been obtained from the British Oceanographic Data Centre. At Skegness and Kish Bank, Proudman Oceanographic Laboratory's software 'POLTIPS' has been used to produce a tidal time history.

To transform the tide from the port to the site, Admiralty chart [7] was used. This indicates lines of co-tide (equal time) and co-range (equal range). Differences in range and tidal profile between the port and the site were assumed to be negligible while time differences were estimated to the nearest five minutes and applied to the time series.

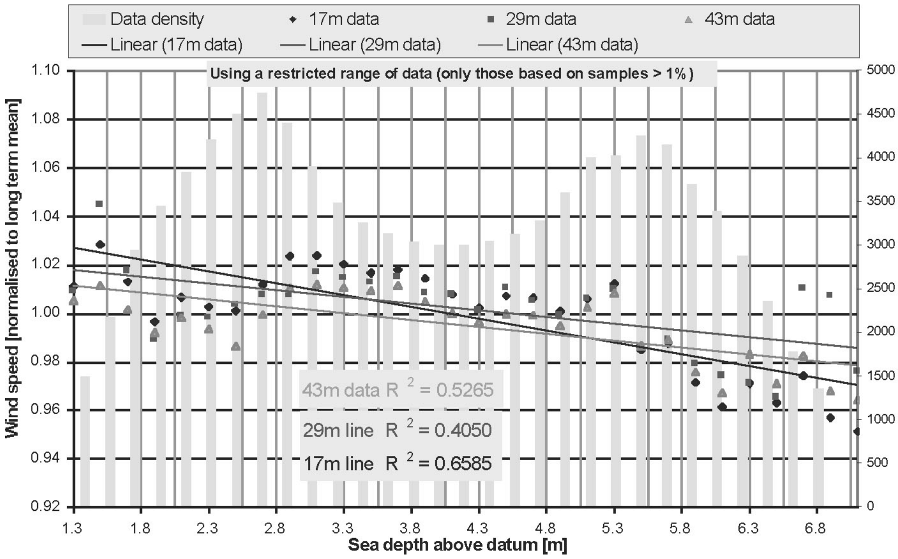
Table 1 Details of tide data sources for two offshore sites

Site Name	*Scroby Sands*	*Skegness*
Distance offshore	4.1km	5.3km
Height of wind measurements AMSL	33m, 51m	17m, 29m, 42m
Nearest Port with available tidal time series	Lowestoft	Skegness
Mean Spring Range at port	1.9m	6.0m
Mean Neap Range at port	1.1m	2.8m
Distance from port to site	21.3km	9km
Approx. tide time shift from port to site	90 mins earlier at site	5 mins earlier at site
Period of data used (complete years)	1996-1998	1999-2000

2.3 Wind speed vs. sea depth

Once concurrent time series of wind speed data and sea depth were obtained, the data were binned by sea depth. Figure 4 shows the result of two years of ten minute data at Skegness. A general trend of decreasing wind speed with increasing sea depth can be seen, which is most pronounced and consistent at the lowest elevation (17m). The wind speeds are normalised by their long-term mean to preserve confidentiality, hence the mean wind speed is unity.

Figure 4 Variation of wind speed with absolute sea depth at Skegness. Only bins containing at least 1% of data are shown



Note: R^2 is a measure of goodness of fit (1 = perfect, 0 = no fit)

At Scroby Sands and Kish Bank, the results do not demonstrate the same trend conclusively. Peaks of wind speed are noted at either end of the tidal spectrum, though the reasons for this are not yet clear.

2.4 *Systematic variation in wind speed in a tidal cycle*

The above analysis uses absolute sea depth values. The results show considerable scatter and variation in sample size, especially during extreme tides. The results from all three sites were not entirely coherent. To focus on the effect of the tide on the wind speed in each tidal cycle, a systematic analysis was performed as follows:

The time series was divided into N tidal cycles: 1942 cycles at Scroby, 1384 at Skegness, each of approx. 12 hours. The wind speed within each cycle, *U*, was scaled to the range of wind speeds in that cycle to produce a new measure of wind speed, *Ut*, which varies between 0 and 1:

$$Ut = \frac{U - U\min_n}{U\max_n - U\min_n} \quad \text{n = 1 to N} \tag{1}$$

where

U = 10 minute mean wind speed
Umin/Umax = minimum and maximum 10 min speeds within the n^th^ tidal cycle

The tidal depth *T*, was similarly scaled in each cycle:

$$Tt = \frac{T - T\min_n}{T\max_n - T\min_n} \quad \text{n = 1 to N} \tag{2}$$

where

T = sea depth above chart datum (10 min intervals)
Tmin/Tmax = minimum (low tide) and maximum (high tide) sea depths within the n^{th} tidal cycle

Thus the effect of variations in wind speed at non-tidal time scales was effectively removed and the effect of all tidal cycles averaged. New time series, *Ut* and *Tt* were produced, varying between 1 (max. in tidal cycle) and 0 (min. in tidal cycle). When the results from all tidal cycles were combined and binned by *Tt*, a clearer trend emerges: Figures 5-7. It can be seen that the effect of *Tt* on *Ut* is stronger at lower elevations, as expected from the shear profile (Figure 2).

Figure 5 Systematic variation of wind speed in tidal cycles at Scroby Sands

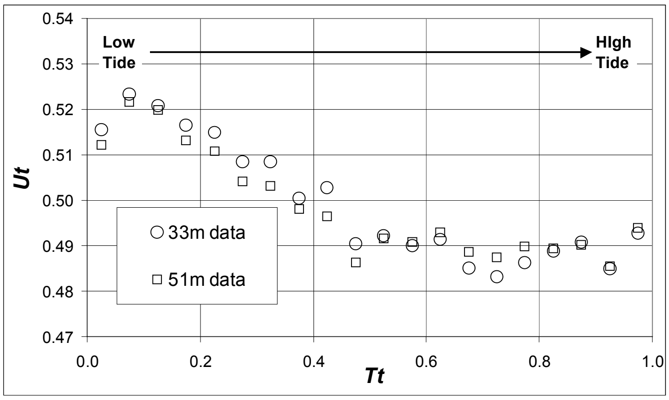


Figure 6 Systematic variation of wind speed in tidal cycles at Skegness

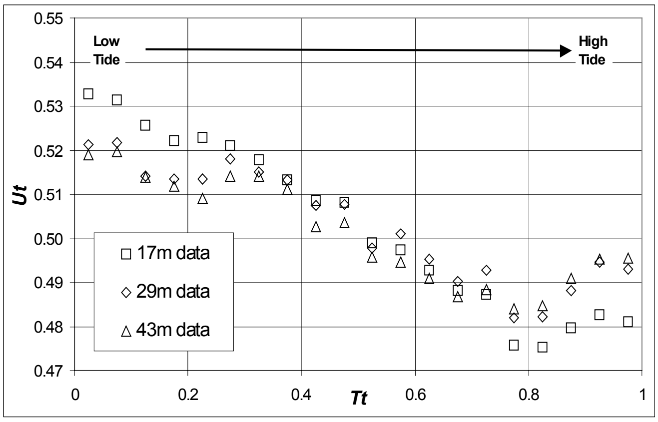


Figure 7 Systematic variation of wind speed in tidal cycles at Kish Bank, 31m height

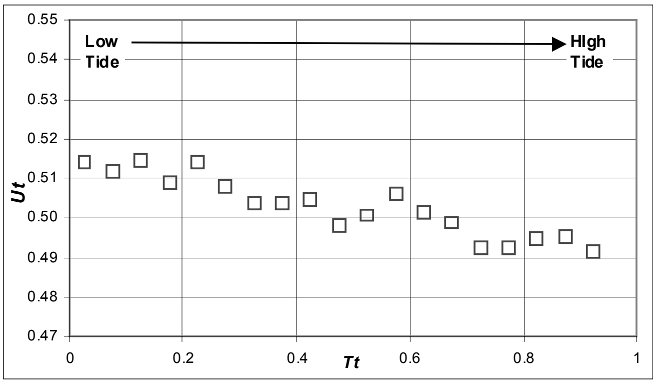
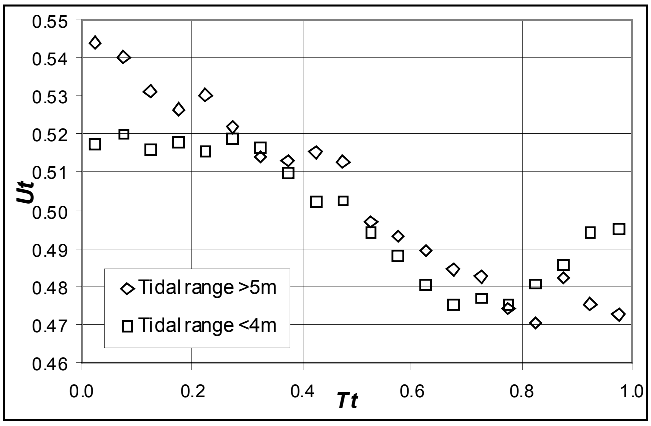


Figure 8 The effect of tidal range on systematic variation in wind speed during a tidal cycle at Skegness



Note: This example uses wind data measured at 17m elevation

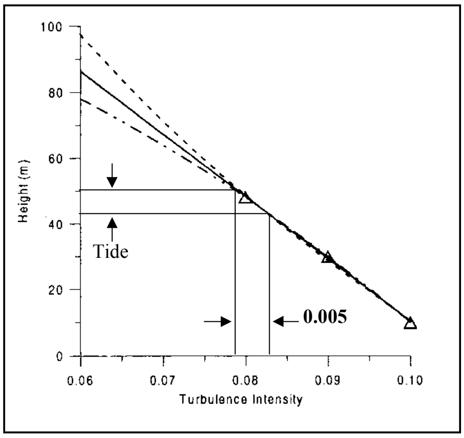
The effect is also greater during periods of larger tidal range, as shown in Figure 8. Here, the Skegness data were divided into large and small tidal cycles and the systematic analysis performed on each set. The impact on wind speed of larger tidal cycles can be clearly seen.

2.5 Systematic variation of turbulence in a tidal cycle

Turbulence levels are largest close to the sea surface, reducing with increasing height.

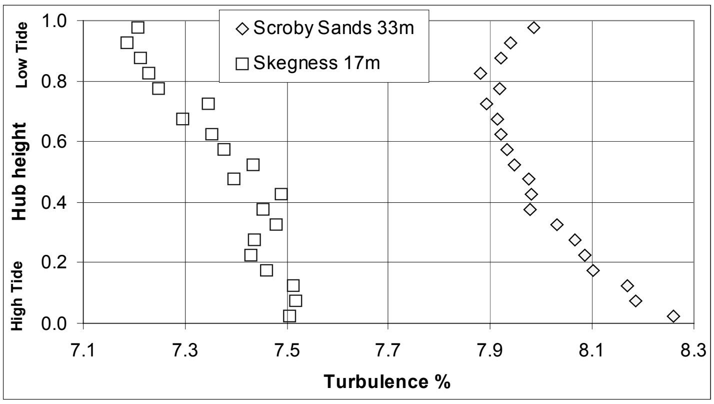
Thus turbulence levels are expected to show a similar tidal influence when analysed systematically, as described in Section 2.4. The results are shown in Figure 10.

Figure 9 Vertical turbulence profile measured at Vindeby offshore mast



Source: Barthelmie [5]

Figure 10 Results of systematic analysis of turbulence at Scroby Sands and Skegness



Note: The axes have been inverted to shown tide on the vertical and turbulence on the horizontal. Thus the shape of the results can be compared to that expected from Figure 9.

Since turbulence levels are not confidential, the mean absolute value, in percent, has been superimposed on the horizontal axis. The systematic variation has also been converted to an absolute value by a process of averaging. Thus the scales shown on Figure 10 give the reader a representative measure of how much the tidal cycle influences turbulence.

The result appears to be consistent with the scale of variation expected from Figure 9.

Since wake recovery is influenced by turbulence levels, the tidal influence may be relevant for current wake models, especially when applied to seas of large tidal ranges for the first time.

The lack of linearity seen in the above trends may be due in part to errors in the placement of the high/low tide times. The adjustment of tide times from the port to the sites used above is based on estimates from low resolution charts [2,7] rather than site measurements. Measured sea-state data from the sites is required for verification of these graphs.

2.6 Statistical evidence

An apparent effect of sea depth on wind speed has been identified above. Confirmation should be available from statistical calculations. Multi linear regression has been applied to identify a model of the form:

$$y = b_1X_1 + b_2X_2 + \dots\dots + b_nX_n \qquad (3)$$

This can be used to estimate the improvement in predicting offshore wind speeds, y, from onshore wind speeds, X_1, by including a tidal parameter, X_2.

The model was implemented by the Matlab function *stepwise.m* [8] which uses the regression technique by Draper and Smith [9], giving regression coefficients $b_1, b_2 \dots b_n$ with confidence intervals and the R^2 statistic of the multi-linear fit. Onshore wind data was available at Hemsby Met station [10] for Scroby Sands and an onshore mast at Skegness. The latter provided considerably more detailed measurement (ten min. average data, three heights, compared to hourly average at one height at Hemsby).

A factor was applied to the onshore wind speeds in order to avoid revealing the mean offshore wind speeds, which are commercially confidential. This did not affect the graphs and statistics relating to the tidal influence.

This analysis was not applied at Kish Bank, since the tidal effect identified there is smaller and a smaller quantity of reliable wind data is available than at the other two sites.

It can be seen from Table 2 that a negative coefficient is automatically assigned to the tidal data and the R^2 statistic is improved compared to using only onshore wind data. Where b_1 is 1, this is because the onshore data was factored to force the mean to be equal to the mean of the offshore 33m data. This did not affect the other parameters.

Table 2 Results of multi-linear regression at Scroby Sands

y	*X*		*B*				R^2
	X_1	X_2	b_1	std $error_1$	b_2	std $error_2$	
U33	Uhem	-	1.00	1.56%	-	-	0.848512
U33	Uhem	Tmes	1.00	1.56%	-0.02710	336%	0.848529
U33	Uhem	Tpol	1.00	1.56%	-0.03450	274%	0.848538
U33	Uhem	log(Tpol)	1.00	1.56%	-0.04778	270%	0.848541
U33	Uhem	$(Tpol)^2$	1.00	1.56%	-0.00961	326%	0.848532
U51	Uhem	-	1.02	1.61%	-	-	0.832867
U51	Uhem	Tmes	1.02	1.61%	-0.01190	829%	0.832870
U51	Uhem	Tpol	1.02	1.61%	-0.02640	389%	0.832881
U51	Uhem	log(Tpol)	1.02	1.70%	-0.03996	350%	0.832886
U51	Uhem	$(Tpol)^2$	1.02	1.70%	-0.00687	494%	0.832876

Note: Std $error_n$ = (95% confidence interval of b_n)/b_n

R^2 = The proportion of variation in observation explained by the model (1 is a perfect fit)

U33 = wind speed at Scroby Sands, 33m height AMSL

U51 = wind speed at Scroby Sands 51m height AMSL

Uhem = wind speed at Hemsby Met station (factored)

Tmes = measured tide at Lowestoft

Tpol = calculated tide at Lowestoft

Table 3 Results of multi-linear regression at Skegness

y	*X*		*B*				R^2
	X_1	X_2	b_1	*std error*$_1$	b_2	*std error*$_2$	
U17off	U10on	-	0.8690	1.2%	-	-	0.767304
U17off	U10on	Tpol	0.8689	1.2%	-0.02427	109%	0.767401
U17off	U10on	log(Tpol)	0.8689	1.2%	-0.06073	155%	0.767352
U17off	U10on	(Tpol)^2	0.8689	1.2%	-0.00311	100%	0.767417
U29off	U28on	-	0.9096	1.0%	-	-	0.822671
U29off	U28on	Tpol	0.9096	1.0%	-0.01159	200%	0.822691
U29off	U28on	log(Tpol)	0.9096	1.0%	-0.02268	378%	0.822677
U29off	U28on	(Tpol)^2	0.9096	1.0%	-0.00148	193%	0.822695
U43off	U46on	-	0.9199	0.9%	-	-	0.842268
U43off	U46on	Tpol	0.9200	0.9%	0.0152	146%	0.842302
U43off	U46on	log(Tpol)	0.9200	0.9%	0.06377	123%	0.842315
U43off	U46on	(Tpol)^2	0.9200	0.9%	0.001826	144%	0.842303

Note: *U[H]off* = offshore wind speed, [H]m height AMSL
U[H]on = onshore wind speed, [H]m height
Tpol = calculated tide at Skegness

At Skegness, the response of the regression to a tidal parameter is slightly better, Table 3 [11]. The improvement in R^2 is greater at lower elevations, where the wind shear has greatest effect. These encouraging results support both the presence of an appreciable tidal effect on wind speeds and the validity of including tidal data in an offshore/onshore wind correlation.

The form of the tidal parameter may need optimisation. At Scroby Sands, a log term appears to work best (lowest standard error, greatest improvement in R^2), whereas at Skegness, the square term fares better.

3 Use of tidal parameters in resource predictions

Two scenarios of data availability are considered. Firstly, where wind records are available from both the offshore development site and an onshore reference site and, secondly, where only wind records from an onshore reference site are available i.e. no offshore data. In both instances, knowledge of tidal behaviour may prove valuable and has hitherto generally been ignored by offshore wind resource analysts.

3.1 Offshore-onshore MCP

Most offshore wind developers will seek to correlate offshore wind speed measurements to onshore measurement to provide an estimate of the long-term mean. In this first scenario, the two data sets will be correlated in a Measure-Correlate-Predict (MCP) process. The presence of tidal fluctuations in the offshore wind records may degrade the correlation, as it is absent in the onshore wind. The scope for improving the correlation by removing the tidal fluctuations from offshore records is now considered.

3.1.1 Choice of tidal parameter

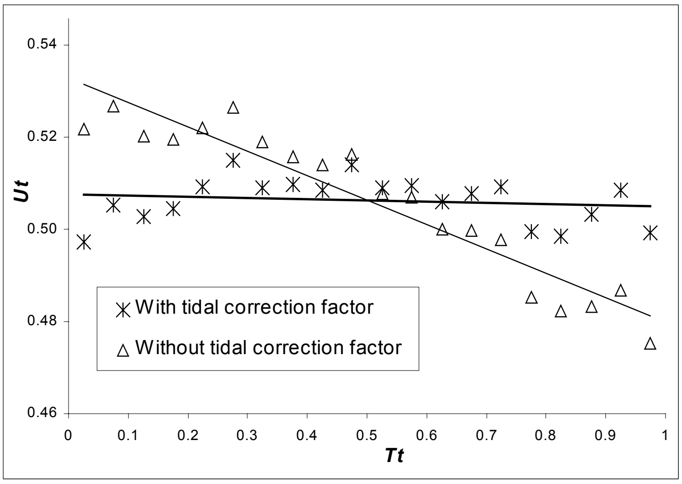
In order to improve the correlation between onshore and offshore data, the influence of tide has to be either added to the onshore data or removed from the offshore data. For this, a parameter proportional to the tide must be chosen. A possible test for a sensible tidal parameter is removal of the systematic trend discussed in Section 2.4. The result in Figure 10 shows the outcome using a linear parameter, optimised by trial and error. Here, the onshore wind speed was adjusted:

$$U' = U + b_2T \tag{4}$$

Then U' was input into equation (1) as before.

The coefficient b_2 used was 0.06, about twice the value suggested by multi-linear regression (Table 3). Note the tidal coefficient is positive here, as we need to remove the effect of the tide from the offshore wind speed, rather than add it to the onshore wind speed as in the regression analysis in the previous section. The results in Figure 11 show that the tidal trend was effectively removed by using this parameter.

Figure 11 Removal of systematic tidal variation in wind speed by use of a linear tidal parameter b_2



Note: Data used was the 17m elevation offshore wind speed at Skegness

3.1.2 Adjusted Measure-Correlate-Predict Process (MCP)

For MCP, in-house codes are commonly used. An example used here is WCORR, developed by wind engineers at PowerGen, (Power Technology Centre). This uses three straight line fits to each directional bin of data (below cut-in, up to rated and above rated) and calculates correlation coefficients for each directional bin.

To represent real conditions, the Scroby Sands site was chosen because the onshore data, from Hemsby Met. Station, was in the form of hourly means, rounded to the nearest knot. This is typical of what will be available for most offshore developers. The ten minute data available at the Skegness onshore mast may give a more accurate correlation, but is not a historical record.

For the current study, the onshore wind speed at Hemsby was adjusted (though the offshore wind could have been chosen), by a linear tidal parameter, b_2:

$$U_{hem}' = U_{hem} + b_2\, T_{pol} \tag{5}$$

The original and adjusted data were passed through the correlation routine and the correlation coefficients noted (closer to unity the better the correlation). As a further test, they were plotted in Excel and a least squares linear fit produced. The results are given in Table 4.

Table 4 Results of correlation with and without tidal parameter at Scroby Sands

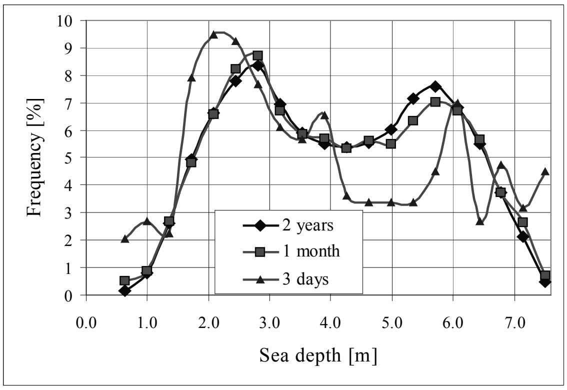
X	*Y*	*Correlation coefficient* [ii]	*Excel* R^2
Uhem	U33	0.9005	0.8109
Uhem’	U33	0.9006	0.8110

From Table 4, it appears that removal of the tide-induced scatter provides a slightly better correlation [12].

This could then be used to provide a prediction of mean offshore wind speed free of tide-bias. Finally, the long term tidal influence could be applied using the long-term tidal distribution, rather than the short-term measurements during the correlation period. In other words, the effect of the tide would be removed during the concurrent MCP period to reduce scatter, then put back to represent the long term mean.

The forgoing assumes that the frequency distribution of sea depths in a small sample (e.g. a correlation bin of wind speed and direction) is not representative of the long-term mean. Figure 12 shows an example based on two years of tidal data at Skegness, illustrating that the small amount of data included in each bin, or cell of a wind frequency distribution table, departs considerably from the long-term mean. If each of the distributions on the plot were more or less equal, we could say that indeed tide and any effect it produces, does average out over a short time. However, since the distributions are different, we cannot make this assumption.

Figure 12 Example of tidal depth frequency distributions: long term (all data two years), in 1 wind speed bin (one month of data), and in a wind speed/direction bin (three days of data)



If the technique were repeated for different periods of data, a clearer picture could be established of the benefits of a tidal-MCP. One might expect the improvement, *i*, in resource prediction accuracy to be a function of the following variables:

$$i = f\left\{ tidal\ \ range\ ,\ \frac{1}{data\ \ period}\ ,\ \frac{1}{hub\ \ height} \right\} \tag{6}$$

3.2 Offshore resource predictions using only onshore reference data

Some exceptions, such as the Blyth Offshore project in the UK are sites which are close to shore and have good coastal/harbour wind data available, hence no offshore wind data was used in resource predictions.

This second scenario, where no offshore wind data is available, is more common in the early stages of an offshore development. Generally, the reference wind speed will be derived from the nearest onshore measurement site. This, combined with terrain information will be input into a wind flow modelling package, such as WaSP, to produce the expected offshore wind regime. The hub height and shear profile will be assumed as if the sea level were static. But in the light of the present study, it may be questioned whether this is reasonable.

The tidal fluctuations in wind speed may not significantly affect the long-term average wind speed, as the fluctuations are symmetrical about the mean sea level. More significantly, the energy available in the wind may be affected, as the mean cube of the wind speed will be increased by such variations. The following equation quantifies how normal turbulence, *I* (a measure of variation about a mean) contributes to the mean cube and hence the energy available in the wind:

$$\overline{U^3} = \overline{U}^2 \left(\overline{U} + 3I^2 \right) \tag{7}$$

Where $I = \dfrac{\sigma}{\overline{U}}$

And $\overline{U}$ = mean wind speed in a sampling period
σ = standard deviation of wind speed
$\overline{U^3}$ = mean wind speed in a sampling period

We see that the 'extra energy' available from the turbulence is given by $3I^2$. This applies over a single sampling period, say one hour, but the same should apply to a longer time period such as is the case with tidal cycles. If we now define the tidal fluctuations as *Ti*, a proportion of the mean wind speed in a tidal cycle [13], we can say an increase in energy of $3Ti^2$ occurs. At a *Ti* fluctuation level of 4-5%, such as that found at Skegness, this would equate to an increase in power of 0.5-0.75%. This would not be identified by a WaSP and mean sea level approach.

An initial simulation was performed with and without the tidal influence, by using the correction factor identified in Section 3.1 and measured offshore data from Skegness. This found the increase in mean cube due to the tide was considerably smaller than suggested above. Further work is required, though empirical evidence of this 'extra energy' will be difficult to obtain, as any given site has fixed tidal characteristics.

The potential improvement in resource prediction accuracy suggested here, less than 1%, is small compared to known error levels due to wind speed records and wind flow models. However, in the process of making the best possible assessments, it may be prudent to include some representation of it.

4 Conclusions

The presence of a tidal influence on wind speeds at three offshore sites has been demonstrated. This effect varies with location and height above sea level. A tidal parameter can be chosen to remove the influence of tides and improve the correlation of offshore to onshore wind speeds. Furthermore, the tidal influence on hub height affects turbulence intensity. A thorough treatment of this effect within an offshore/onshore MCP may pay dividends of improved resource predictions, especially at high tidal range sites, or those where short periods of wind data are available.

The tidal-induced fluctuations in wind speed should produce slightly higher energy yields than are expected by assuming a static sea level.

5 Further work

CREST, Loughborough University, is engaging on a programme of research to investigate further the influence of tide on offshore wind fields, as well as surface roughness changes onshore to offshore and stability effects.

Acknowledgements

This research was performed as part of an MSc in Renewable Energy Systems Technology at CREST. It was supported by Powergen Renewables. In particular we would like to thank: Dr. Dave Pearce and Dr. Chris Ziesler of Power Technology Centre at Ratcliffe, for their valued assistance and support. Thanks are also due to Matt Rebbeck of Renewable Energy Systems Ltd. for providing the Skegness data and also to those at CREST who gave useful input.

Tidal range information was derived from Admiralty Charts 5058/9 by permission of the Controller of Her Majesty’s Stationery Office and the UK Hydrographic Office. Hemsby Meteorological data was supplied by British Atmospheric Data Centre, though their excellent academic web service www.badc.rl.ac.uk. Lowestoft tidal data was provided by the British Oceanographic Data Centre. Tidal hindcasting was performed using POLTIPS software (Leisure version) made available by the Proudman Oceanographic Laboratory.

References and Notes

1 (1997) ‘Threats and opportunities in the coastal areas of the European Union’, Ministry for Housing, Spatial Planning and Environment, the Netherlands, also reproduced at http://www.coastalguide.org/lands/landrcol.html

2 (1996) *Admiralty Chart 5058*, Fifth Edition, United Kingdom Hydrographic Office.

3 British Wind Energy Association website: www.offshorewindfarms.co.uk

4 (1998) ‘Offshore wind energy – building a new industry for Britain’, *Border Wind*, Greenpeace.

5 Barthelmie, R.J. (1999) ‘Monitoring offshore wind and turbulence characteristics in Denmark’, *Proc. BWEA21*, pp.311–316.

6 Pearce, D. and Ziesler, C. (1999) ‘The estimation of offshore wind resource’, *Proc. BWEA21*, pp.289–300.

7 (1996) *Admiralty Chart 5059*, Southern North Sea, United Kingdom Hydrographic Office.

8 (1998) *Stepwise Regression*, Matlab Statistics Toolbox Version 2.2 (R11), 24 July.

9 Draper, N. and Smith, H. (1981) *Applied Regression Analysis*, Second Edition, John Wiley & Sons, Inc., pp.307–312.

10 British Atmospheric Data Centre website, with kind permission.

11 The positive coefficient of b_2 at Skegness 43m data – an exception – is not fully understood.

12 This improvement may be more evident at sites with a larger tidal range, or with ten minute, unrounded onshore data, or where shorter periods of concurrent data are available.

13 The systematic analysis was done using wind speeds averaged over ½ a tidal cycle which is around six hours