

Lidar Turbulence Measurements for Wind Farm Energy Yield Analysis

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Abstract

A significant body of work has been produced in support of the ability of lidar systems to accurately measure wind speed for wind resource assessment. Lidar measurements at heights significantly greater than those achievable with industry-standard mast anemometry enable reduction of project uncertainties through direct measurement of resource at hub height and reduction of uncertainty in measured shear profiles. Measurement of turbulence intensity (TI) at hub height plays a role in wind resource assessment through the estimation of energy losses due to turbine wakes and is also a key component of site classification and turbine selection studies. In the work presented here deviation in TI measurements observed at the ZephIR Ltd. IEC compliant tall mast test facility are considered in the context of a typical wind farm Energy Yield Analysis (EYA) methodology to determine the associated deviation in net Annual Energy Production (AEP) for calculations based on data from ZephIR 300 and the mast. For a typical turbine separation, wind speed distribution and direction distribution the deviation in net AEP with observed deviation in measured TI is small compared to that associated with the uncertainty attributed to other inputs to the EYA methodology. Analysis of the wake model implemented suggests that the results obtained should hold for general turbine layouts within the scope of the model. This result is considered as evidence of the ability of ZephIR 300 to measure TI values in non-complex terrain to an accuracy suitable for use in a typical wind farm energy yield analysis.

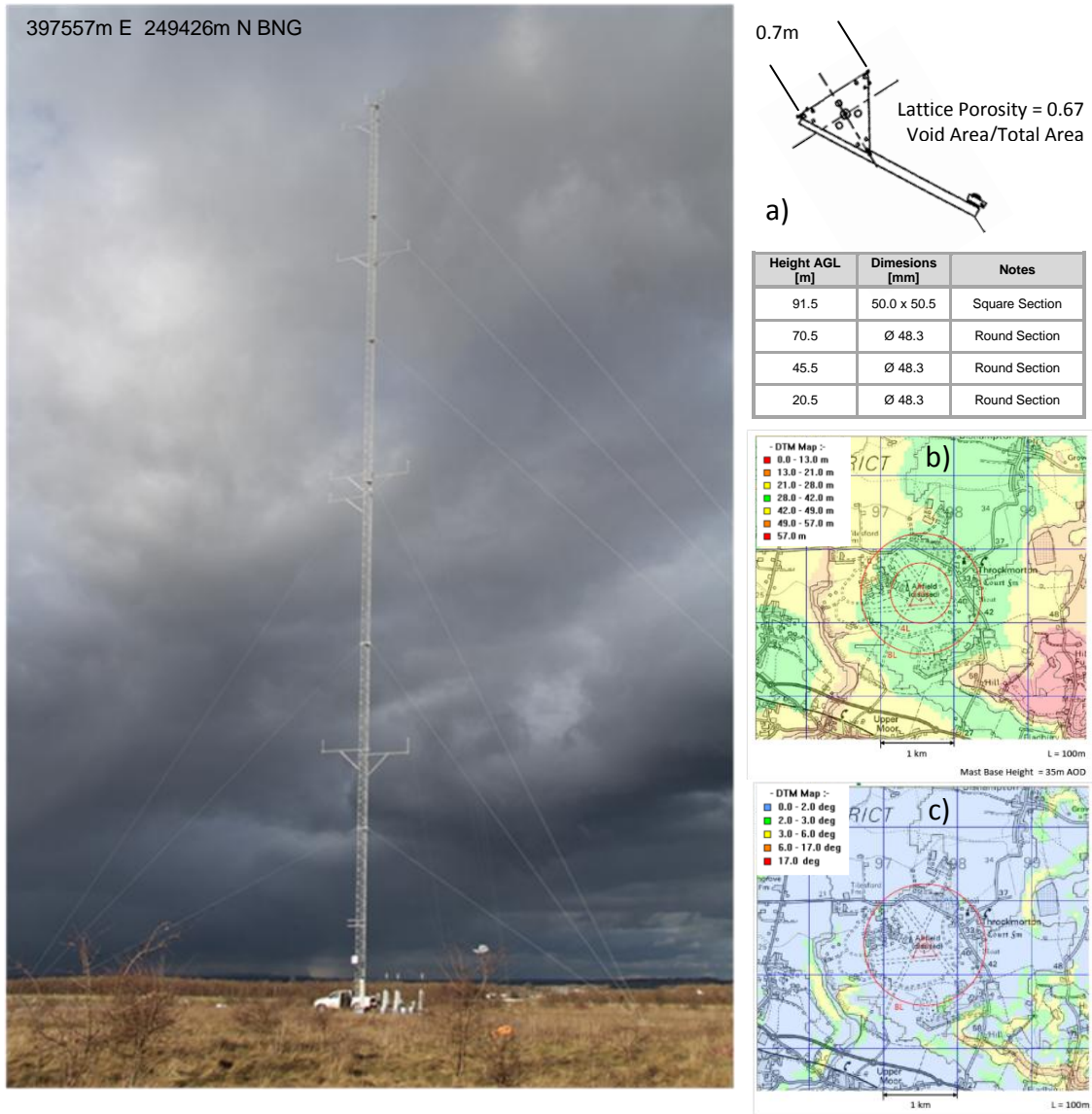
1 Introduction

A significant body of work has been produced in support of the ability of lidar systems to accurately measure wind speed for wind resource assessment [1],[2]. Lidar measurements at heights significantly greater than those achievable with industry-standard mast anemometry enable reduction of project uncertainties through direct measurement of resource at hub height and reduction of uncertainty in measured shear profiles [3]. Measurement of turbulence intensity (TI) at hub height also plays a role in wind resource assessment through the estimation of energy losses due to turbine wake effects and variation in turbine performance [4],[5]. As well as having a role in energy yield studies, TI information is also a key component of site classification and turbine selection studies [6],[7],[8]. Where lidar data is to be used as an input to established methodologies for wind resource assessment in place of mast data, consideration of the performance of lidar systems in measuring turbulence intensity with respect to industry-standard mast anemometry is of relevance. The analysis of TI data recorded during 34 ZephIR 300 deployments at the ZephIR Ltd. IEC compliant tall mast test facility in Pershore, Worcestershire, UK is presented in [9]. TI measured by ZephIR 300 up to a typical turbine hub height is shown to be in good agreement with that measured by the mast. This is maintained across the wind speed and turbulence intensity ranges and atmospheric stability conditions encountered over a calendar year within a tolerance of $\pm 10\%$ (91.5m). The effect of the deviation observed in [9] has been analysed in terms of its effect on AEP for a standard EYA methodology that employs the Eddy Viscosity wake model to quantify the significance of the observed deviation and establish the suitability of ZephIR 300 TI measurements for use in wind farm energy yield analysis.

2 Description of the Measurements

2.1 Test Mast

Natural Power Ltd. operate the U.K.'s only dedicated lidar and sodar test site at Pershore in Worcestershire, England. The test mast at Pershore has been constructed to be compliant with the current edition of IEC 61400-12-1 [10] and the terrain complexity of the site falls within requirements for power curve testing without a site calibration. All cup anemometers installed on the mast are class 1A instruments as defined by [10] and have undergone individual rotor specific MEASNET calibration [11]. Boom and upright dimensions have been determined using the lattice porosity and mast dimensions in compliance with [10] to operate within a maximum flow distortion of 0.5%, Figure 1. Three different instrument types for the measurement of wind flow are installed on the mast. On the North-Western side of the mast Risø P2546A cup anemometers are installed at 20.5m, 45.5m, 70.5m and 91.5m above ground level (AGL). These instruments are used for comparison of ten-minute average and mean wind speed measurements. On the South-Eastern side of the mast Vector A100LM cup anemometers are installed at 20.5m, 45.5m and 70.5m AGL. These instruments are classified as fast-response cup anemometers and are used for comparison of measurements of standard deviation and turbulence intensity. A METEK USA1 3D ultrasonic anemometer is installed at 91.5m on the South-East side of the mast. This instrument is used for fine-grained investigation of standard deviation and turbulence measurements, atmospheric stability and vertical wind flow. The specification and installation of the instrumentation at Pershore is such that all instruments are suitable for use in wind speed verification in unshadowed sectors. Standard deviation and turbulence intensity measurements are restricted to the Vector A100LM and METEK USA1 anemometers due to the poorer dynamic response and sampling performance of the Risø P2546A anemometers. The analysis of turbulence intensity presented in this paper has therefore been carried out against the instruments on the South-East side of the mast only, in unshadowed sectors. The wind climate at Pershore as measured by the South-Eastern instruments on the mast over the period covered by this analysis is shown in Figure 2.



Lab el	Height (m)	Orientation (°) Mast to Instrument	Type	Manufacturer/Model	Calibration*	Calibration Date	Cup to boom centre height (mm)	Instrument to mast centre length (mm)
A	91.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	07/2011	1500	1025
B	91.5	120	3D Sonic Anemometer	Metek USA1	-	-	1500	1025
C	88.0	300	Direction Vane	Vector W200P	-	-	920	3700
D	88.0	120	Temperature/Humidity	Campbell Scientific CS215	-	-	-	-
E	70.5	300	Cup Anemometer	Risø P2546A	SOH MEASNET	06/2010	960	3700
F	70.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	07/2011	1160	3700
G	45.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	07/2011	960	3700
H	45.5	120	Cup Anemometer	Vector A100LM	SOH MEASNET	06/2010	1160	3700
I	43.5	300	Direction Vane	Vector W200P	-	-	920	3700
J	43.5	120	Temperature/Humidity	Campbell Scientific CS215	-	-	-	-
K	20.5	300	Cup Anemometer	Risø P2546A	SOH MEASNET	06/2010	960	3700
L	20.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	07/2011	1160	3700
M	6.0	-	Pressure	Campbell Scientific CS1000	-	-	-	-
N	6.0	-	Data Logger	Campbell Scientific CR1000	-	-	-	-

Figure 1 : Pershore 91.5m IEC Compliant Anemometer mast Specifications and Environment
a) Mast Lattice and Boom Specifications , b) Local Deviation from Plane*, c) Local Slope*.

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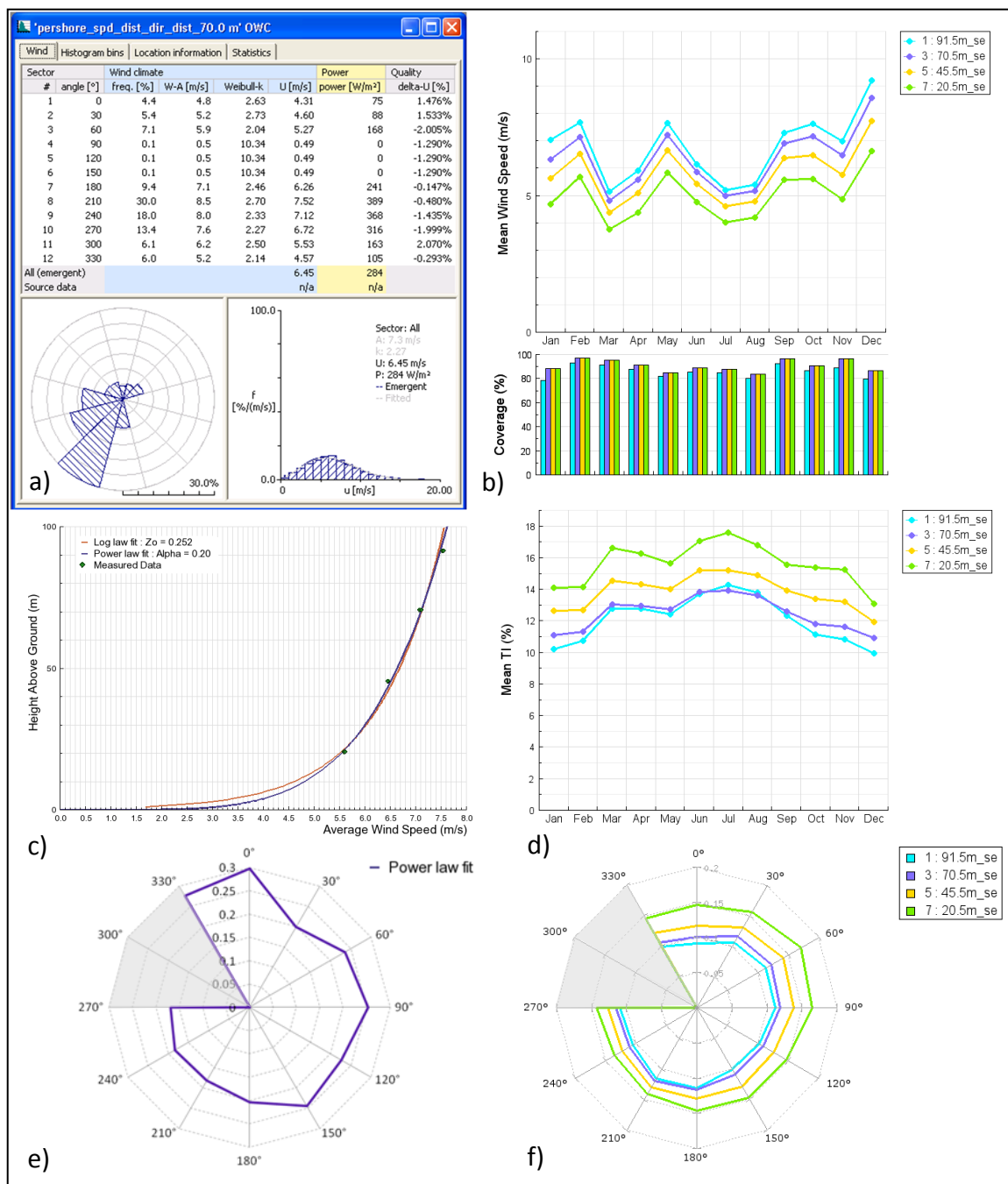


Figure 2 : 2011 Wind Climate at Pershore Measured by South-Eastern Mast Instruments.

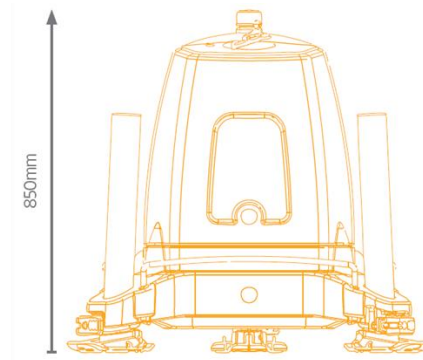
a) 70m TAB File, b) Seasonal Wind Speed Profile and Coverage, c) All sector shear, d) Seasonal TI Profile, e) Shear rose, f) TI Rose. Grey sectors shaded.

2.2 ZephIR 300

ZephIR 300 is the next generation of all-fibre continuous wave laser remote sensing wind profilers (lidar) produced by ZephIR Ltd. [12]. Banks' Engineers recommend ZephIR onshore and offshore to both complement and replace traditional masts. ZephIR has proven performance across 450 lidar deployments globally including extreme conditions from -40 Celsius to +50 Celsius. System features include remote profiling of horizontal and vertical wind speed, turbulence intensity and wind direction across 10 user defined heights from 10 metres (33 ft) to 200 metres (656 ft), Figure 3.



SAFETY	ZephIR
Laser classification	Class 1
Eye safety standard	IEC 60825-1
IP Rating	IP67 (excl. external fans)
EMC compliance	EN55022 Class A, EN61326 Industrial, FCC Radiated & Conducted Emissions



PERFORMANCE	ZephIR
Range (min.)	10 metres
Range (max.)	200 metres
Extended range	300 metres
Probe length @ 10 m	0.07 metres
Probe length @ 100 m	7.70 metres
Heights measured	10 (user configurable)
Sampling rate	50Hz
Averaging period	1 second upwards (user configurable)
Scanning cone angle	30° (other angles available)
Speed accuracy™	< 0.5%
Speed range	< 1 m/s to 70 m/s
Direction accuracy	< 0.5°

OPERATIONS	ZephIR
Temp range (min.)	-40° C
Temp range (max.)	+50° C
Power consumption	69 Watts
Power input DC	12 V
Weight	55 kg

Figure 3 : ZephIR 300 Specifications.

Since the introduction of the original ZephIR 150 model in 2004 independent verification studies have demonstrated the capability of ZephIR to produce accurate and reliable measurement of wind resource at hub height and beyond. [13],[14],[15]. As part of the commissioning process for ZephIR 300 the performance of each system is verified at the Pershore test facility.

3 Methodology

In the typical EYA methodology used in this analysis, sector-wise measurements of mean TI at hub height are applied as ambient TI inputs to the Eddy Viscosity wake model [4] in *WindFarmer* [5]. Although ambient TI will in general vary with wind speed this is not accounted for in most standard EYA methodologies. Net AEP is the energy output of a wind farm in gigawatt hours per year after topographic and wake losses. The ambient TI values affect AEP in the model by determining the rate of wake decay downwind of a turbine. To isolate the behaviour of the wake model no surface roughness or orography has been used in the analysis, i.e. the site is modelled as being completely flat with no vegetation or obstacles, so no topographic losses are incurred. As part of the analysis the Eddy Viscosity model has been re-implemented in software and validated against the output of *WindFarmer* to allow detailed investigation of its behaviour with respect to variation in the input parameters including ambient TI. The wind speed calculated by the Eddy Viscosity model is symmetrical about the wake centreline with the maximum deficit in a plane parallel with the rotor occurring on the centreline. The maximum turbulence deviation induced power deviation is shown to occur along the wake centreline at a distance from the rotor determined by the wind speed and turbulence intensity. The effect of TI deviation on AEP is firstly determined for a turbine continuously located on the centreline of the wake of an upwind turbine at different turbine spacings (D) for values of

deviation in ambient TI encompassing the maximum observed deviation of $\pm 10\%$ at constant wind speed. In practice variations in wind speed and direction modulate deviation in AEP by shifting the maximum power deviation along the wake centreline and shifting the wake centreline away from the downwind turbine. The analysis is therefore repeated adding in the wind speed and direction distributions measured at the Pershore test site across 2011 to produce more representative results. Finally deviations in AEP established are compared with values attributed to other sources in the assessment of uncertainty in a typical wind farm EYA .

4 Results

The deviation in TI measured by ZephIR 300 and the test mast determined in [9] at a typical turbine hub height is presented in Table 1 and Figure 4. The larger deviation extremes at 91.5m in [9] have been selected for conservatism.

	Mean of Deviation [%]	Extremes of Deviation [%]	
Height	-	Upper	Lower
91.5m	-0.5	10.2	-6.4

Table 1 : Mean and Extremes Monthly Moving Average Mean TI Deviation Across 2011.

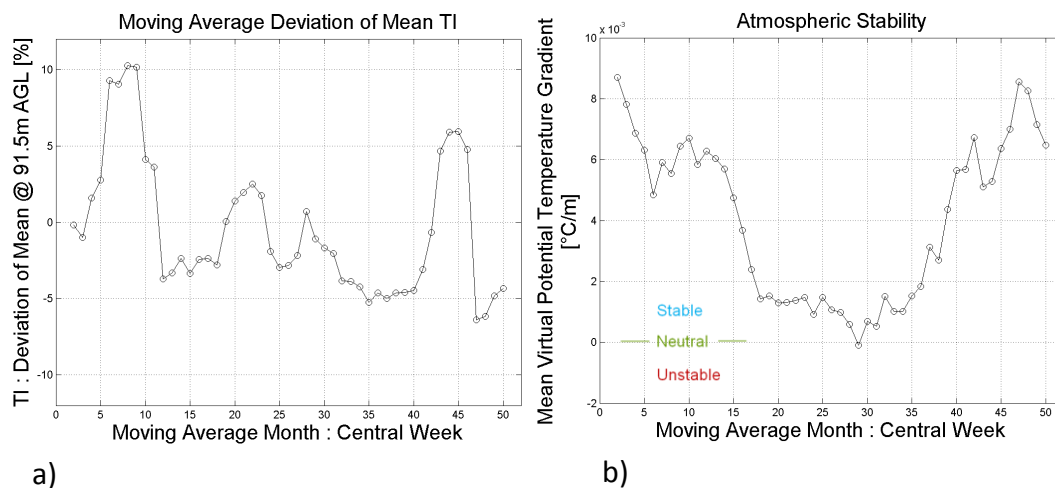


Figure 4 : Monthly Moving Average TI Deviation Across 2011.

a) Deviation in Mean TI vs Central Week, b) Atmospheric Stability vs Central Week.

Figure 5a shows the difference in turbine power output calculated in a wake at 6.5 m/s for a base TI of 15% and deviation in ambient TI of +18%. The 6.5m/s wind speed value has been used as it is the mean of the wind speed distribution measured at the test site applied later in the analysis. 15% is a typical mid-range value for the mean TI at a wind farm site and is the value recorded by the mast at Pershore at 70.5m over the period of the ZephIR deployments. The figure shows that the maximum deviation occurs along the centreline of the wake. This is consistent with that predicted by the formulation of the Eddy Viscosity model and is constrained to always be the case. Figure 5b shows how the maximum positive power output deviation varies with wind speed and turbulence intensity for a deviation in ambient TI of +18%. The point along the wake centreline at which the maximum positive power output deviation occurs shifts with wind speed and turbulence intensity. Figure 5c plots variation in this point along the wake centreline with wind speed and turbulence intensity for a positive TI deviation of 18%. Similar results are obtained for negative deviation in measured TI but with power deviation of the opposite sign. Figure 5d shows variation in turbine power output deviation with wind speed and deviation in ambient TI for a base ambient TI value of 15%.

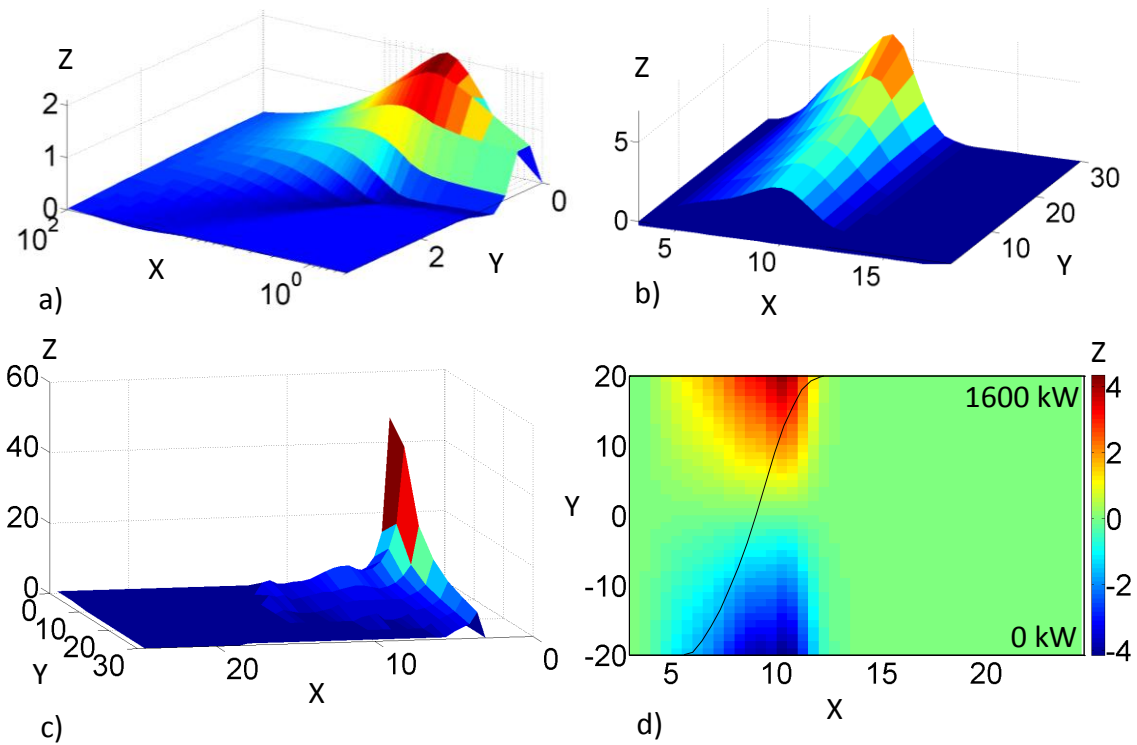


Figure 5

- a) Turbine Power Output Deviation by Position in Wake. Wind Speed = 6.5 m/s, TI = 15%, TI Deviation = +18%, Turbine = GE 1.6 100.
- b) Maximum Positive Turbine Power Output Deviation vs Wind Speed and Turbulence Intensity for TI Deviation = +18%. Turbine : GE 1.6 100
- c) Distance along Wake Centreline of Maximum Positive Power Deviation vs Wind Speed and Turbulence Intensity for TI Deviation = +18%. Turbine : GE 1.6 100
- d) Turbine Power Output Deficit vs Wind Speed and Deviation in Turbulence Intensity for TI = 15%. Top View. Turbine : GE 1.6 100. Turbine Power Curve Overlaid.

5a(X) : Distance Downwind Along Wake Centreline (WCL) [Rotor Diameters]

5a(Y) : Radial Distance from WCL [Rotor Diameters]

5a(Z), 5b(Z), 5d(Z) : Turbine Power Output Deviation [% Rated Power]

5b(X), 5c(X), 5d(X) : Wind Speed [m/s]

5b(Y), 5c(Y) : Turbulence Intensity [%] :

5c(Z) : Distance along WCL of Maximum Positive Power Deviation [Rotor Diameters]

5d(Y) : Turbulence Intensity Deviation [%]

In the first AEP scenario constant wind speed and direction is applied in calculating the net AEP. This calculation is carried out outside WindFarmer as WindFarmer requires a wind speed distribution that can be satisfactorily characterised by a Weibull distribution. A mean wind speed of 6.5 m/s and mean TI of 15% is used. In this scenario the downwind turbine is placed such that it is always exactly on the centreline of the wake of the upwind turbine. As such this represents a worst case scenario for deviation in AEP for a given wind speed. The layout and results for this scenario are shown in Figures 6a and 6b respectively. For deviation in TI of $\pm 10\%$ the deviation in AEP for typical turbine spacings between 4D and 6D is approximately 2%.

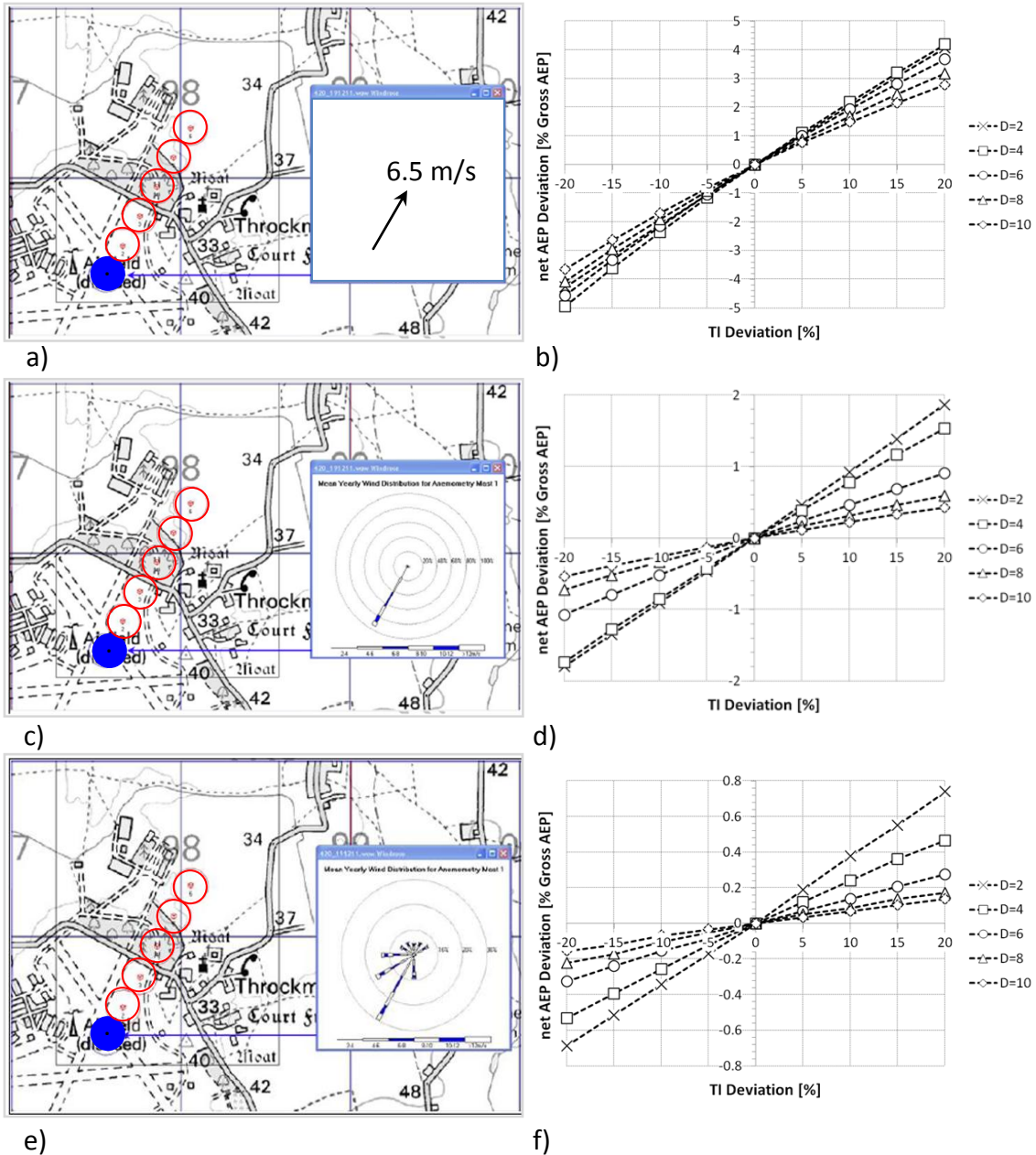


Figure 6 : GE 1.6 100 at blue Location. GE 1.6 100 at one of locations nx2D downwind in the predominant wind direction where $n = 1:5$ and D is the turbine rotor diameter.

- a) Turbine Layout and Wind Climate : Constant Speed and Direction.
- b) AEP Deviation for Downwind Turbine vs Deviation in TI and Turbine Separation (Diameters D). No Wind Speed or Direction Distribution Applied. Wind Speed = 6.5 m/s, TI = 15%.
- c) Turbine Layout and Wind Climate : Wind Speed Distribution Only.
- d) AEP Deviation for Downwind Turbine vs Deviation in TI and Turbine Separation (Diameters D). Pershore Wind Speed Distribution Applied. TI = 15%.
- e) Turbine Layout and Wind Climate : Wind Speed and Direction Distribution
- f) AEP Deviation for Downwind Turbine vs Deviation in TI and Turbine Separation (Diameters D). Pershore Wind Speed and Direction Distribution Applied. TI = 15%.

In the second scenario the wind speed distribution recorded at the Pershore test site over the duration of the ZephIR trial is applied in calculating the net AEP but no wind direction distribution is applied. This calculation is carried out in WindFarmer. A mean TI of 15% is used. The wind direction in this scenario is set at a constant value of 210° which is the predominant wind direction in the mast data set from Pershore. The turbines locations are sited away from the upwind turbine along a line with a bearing of 30°. The downwind turbine is therefore constantly on the centreline of the wake of the upwind turbine. The wind speed distribution observed at the Pershore test site across 2011 and the effect of introducing this into the analysis are shown in figures 6c and 6d respectively. The deviation in AEP between 4D and 6D is reduced to between 0.8% and 0.5% by application of the wind speed distribution.

In the third scenario both the wind speed and direction distributions recorded at Pershore are applied in calculating the net AEP. The turbines locations are sited away from the upwind turbine along a line with a bearing of 30°. As the predominant wind direction in the mast data set from Pershore is 210° this maximizes the amount of exposure of the downwind turbine to wake effects. This scenario is intended to suggest realistic bounds for the effect of deviation in TI measurements produced by ZephIR 300 on the output of a typical wind farm energy yield assessment. The wind speed and direction distribution observed at the Pershore test site across 2011 and the effect of introducing this into the analysis are shown in figures 6e and 6f respectively. The deviation in AEP between 4D and 6D is reduced to between 0.24% and 0.14% by application of the wind speed and direction distributions.

The results in figures 6b, 6d and 6f show that the when wind speed and direction distributions are taken into account the deviation in net AEP with deviation in ambient TI of the magnitude observed in the ZephIR 300 data in [9] becomes small. In the context of other uncertainties associated with the prediction of AEP, Table 2, the deviations in AEP at typical turbine spacing of 4D in figure 6f are negligible.

Source	Uncertainty [%]	Associated AEP Deviation (Typical) [%]
Anemometry	2 - 4	3 - 10
Long Term Reference	2	3
Correlation to Long Term	1 - 2	1 - 3
Wind Shear	0 - 3	0 - 7
Flow Modelling	0 - 4	0 - 10
Power Curve	1 - 4	0.2 - 0.5

Table 2 : Typical Wind Farm Energy Prediction Uncertainties and AEP Deviation by Source

The application of the direction distribution has the greatest impact on deviation in AEP. A small shift in wind direction such that the downwind turbine no longer lies exactly on the centreline of the wake of the upwind turbine results in a significant reduction in the effect of deviation in ambient TI on the power output of the downwind turbine.

5 Conclusions

For a typical turbine separation, wind speed distribution and direction distribution the deviation in net AEP with deviation in ambient TI of the magnitude observed in [9] is small compared to that associated with the uncertainty attributed to other inputs to a typical EYA methodology. Power deviation induced by TI deviation drops off rapidly as the position of the downwind turbine moves away from the wake centreline suggesting that for the wake model implemented the results obtained should hold for general turbine layouts within the scope of the model. This

result is considered as evidence of the ability of ZephIR 300 to measure TI values in non-complex terrain to an accuracy suitable for use in a typical wind farm energy yield analysis.

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