Finance Grade Wind Measurements with lidar

Will Barker(1), Michael Harris(2), John Medley(3),
Edward Burin des Roziers(4), Chris Slinger(5), Mark Pitter(6)
(1) – (6) ZephIR lidar

(1) : Will Barker : ZephIR, The Old Barns, Fairoaks Farm, Hollybush, Ledbury, England, HR8 1EU.
willb@zephirlidar.com, Phone : +44 (0) 1531 650 757, Fax : +44 (0) 1644 430009.
(2) : Mike Harris : ZephIR Ltd., The Old Barns, Fairoaks Farm, Hollybush, Ledbury, England, HR8 1EU.
michaelh@zephirlidar.com, Phone : +44 (0) 1531 650 757, Fax : +44 (0) 1644 430009

Abstract

Site wind speed measurements form a major potential source of uncertainty in wind farm energy yield assessments (EYAs). In particular, significant uncertainty may exist in the vertical extrapolation of measured wind data. Lidar measurements enable reduction of uncertainties through measurement of resource at hub height and reduction of uncertainty in fitted shear models. In this paper the implications of the use of hub height lidar data as the primary data source in wind energy projects is quantified in financial terms in the context of a typical onshore EYA in non-complex terrain. A finance grade EYA methodology is applied using data from an IEC compliant 91m anemometer mast and co-located ZephIR 300 lidar spanning a full year. Data from the mast and lidar at 91m above ground level (AGL) are applied as hub-height inputs in separate EYAs. Mast data at 70m AGL and below is applied with a standard shear extrapolation methodology to calculate AEP from a sub-hub height measurement. A bank's financing model is applied to the results. The long term wind climates derived from the mast and lidar data at 91m AGL are shown to be equivalent. Deviation between the hub height mast and ZephIR derived long-term P90 energy yield predictions is found to be 0.2%. For the shear extrapolated mast data deviation is significantly larger. Financing terms obtained for the hub height mast and lidar measurement scenarios are shown to be equivalent. Significant savings on equity investment and increase in P90 revenue are demonstrated using hub height data.

1 Introduction

The financing terms agreed between lending institutions and Wind Farm developers are a critical element in determining the financial success of an operational Wind Farm. These terms are negotiated with the lending institution based upon a number of project specific details that the lender uses to model the financial viability of the project. Of these details one of the most important is the projected annual revenue. This is based on engineering modeling that integrates wind data measured on the site, long term wind trends, site topography, site orography, turbine type and layout to produce a prediction of the annual energy production (AEP) of the wind farm. The AEP is stated in relation to a probability of exceedance which is calculated based on uncertainties associated with the inputs and methods applied in the AEP calculation. This is generally the 90% probability of exceedance (P90) and 99% probability of exceedance (P99) in Europe and the USA respectively. Uncertainty and accuracy in the predicted annual revenue derived from the AEP has a significant impact on project viability both in terms of the financial terms offered by lenders and the ability of the wind farm to meet its financial obligations once operational.

Site wind speed measurements form a major potential source of bias and uncertainty in the predicted AEP. Traditionally measurements have been made using anemometer masts at a small number of locations on the prospective wind farm site. Due to technical and financial limitations in reaching the hub height of modern turbines with anemometer masts, these measurements have often been made at elevations as much as 1/3 of the hub height below the prospective hub height. The measured data is then extrapolated to hub height using a shear profile fitted to data collected at multiple heights on the anemometer mast or using a model based on the estimated roughness lengths of the orography on the site. Significant uncertainty may exist in the spatial extrapolation of measured wind data vertically to account for wind shear and horizontally to determine wind flow at required points on the site using shear and flow models. Additional uncertainty in wind measurements made by anemometer masts are incurred through the distortion imposed on the flow regime around the anemometer by the infrastructure required to support the instrument at the measurement height.

A significant body of work has been amassed 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. Alternative measurement strategies for wind farm projects including multiple spatially separated measurement points and measurements at individual turbine locations are enabled by lidar systems due to their portability, re-usability and the lack of a requirement for planning permission. Such strategies can significantly reduce uncertainty in predicted annual revenue derived from shear extrapolation and spatial extrapolation of the measured resource using wind flow models while also reducing the cost of measurement campaigns and reducing measurement timescales [3][4].

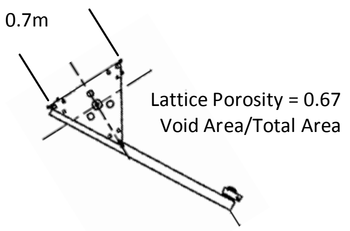
In this paper the implications of the use of lidar in wind energy projects is quantified in financial terms based on measured data for a typical onshore wind energy project.

2 Onshore Wind Energy Project

ZephIR lidar have carried out a banks level wind farm energy yield analysis using mast and lidar data from the ZephIR lidar tall mast test site located at Pershore, Worcestershire, UK. The analysis is based upon data collected from an IEC compliant 91m anemometer mast and co-located ZephIR 300 lidar spanning a full calendar year.

2.1 Test Mast

ZephIR lidar operate the U.K.'s first dedicated lidar and sodar test site at Pershore in Worcestershire, England.



Height AGL [m]	Dimesions [mm]	Notes
91.5	50.0 x 50.5	Square Section
70.5	Ø 48.3	Round Section
45.5	Ø 48.3	Round Section
20.5	Ø 48.3	Round Section

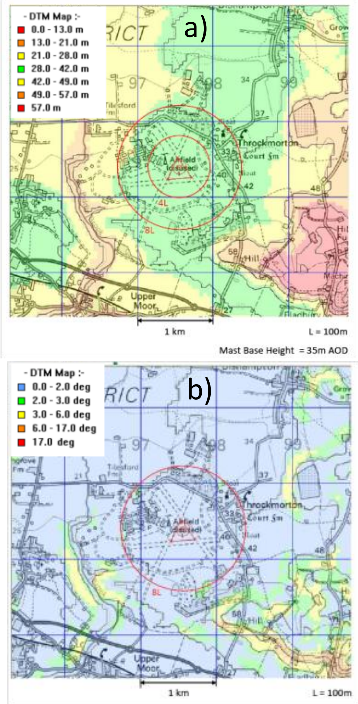


Figure 1 : Pershore 91.5m IEC Compliant Anemometer Mast and Environment
a) Local Deviation from Plane*, b) Local Slope*.

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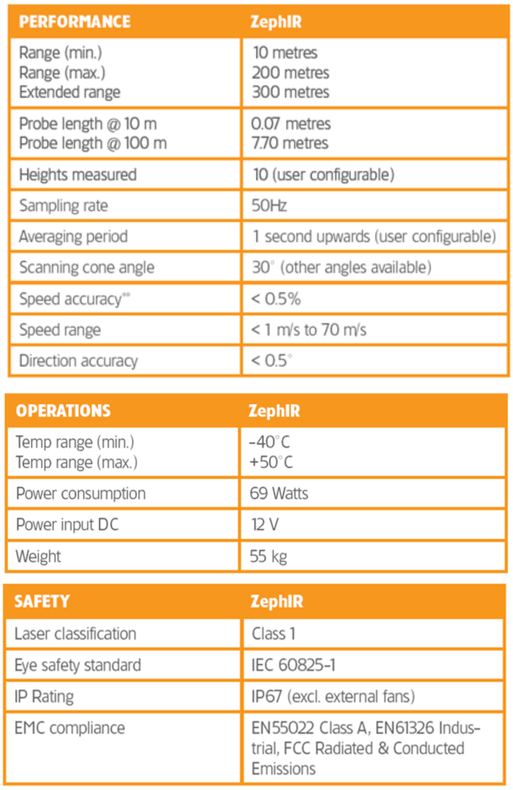
The test mast at Pershore has been constructed to be compliant with the current edition of IEC 61400-12-1 [5] and the terrain of the site falls within the definition of non-complex terrain as defined in [5]. All cup anemometers installed on the mast are class 1A instruments as defined by [5] and have undergone individual rotor specific MEASNET calibration [6]. Boom and upright dimensions have been determined using the lattice porosity and mast dimensions in compliance with [5] to operate within a maximum flow distortion of 0.5%, Figure 1, Table 1.

Label	Height (m)	Orientation (°) Mast to Instrument	Type	Manufacturer/Model	Calibration*	Cup to boom centre height (mm)	Instrument to mast centre length (mm)
A	91.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	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/DWG MEASNET	960	3700
F	70.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	1160	3700
G	45.5	300	Cup Anemometer	Risø P2546A	SOH/DWG MEASNET	960	3700
H	45.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	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/DWG MEASNET	960	3700
L	20.5	120	Cup Anemometer	Vector A100LM	SOH/DWG MEASNET	1160	3700
M	6.0	-	Pressure	Campbell Scientific CS1000	-	-	-
N	6.0	-	Data Logger	Campbell Scientific CR1000	-	-	-

Table 1 : Pershore 91.5m IEC Compliant Anemometer mast Instrumentation

2.2 ZephIR 300

ZephIR 300 is the next generation of all-fibre continuous wave laser remote sensing wind profilers (lidar) produced by ZephIR lidar, [7].



PERFORMANCE	ZephIR
Range (min.) Range (max.) Extended range	10 metres 200 metres 300 metres
Probe length @ 10 m Probe length @ 100 m	0.07 metres 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.) Temp range (max.)	-40°C +50°C
Power consumption	69 Watts
Power input DC	12 V
Weight	55 kg

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

Figure 2 : ZephIR 300 Specifications

Banks' Engineers recommend ZephIR onshore and offshore to both complement and replace traditional masts. ZephIR has proven performance across 650+ 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 2.

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. [8],[9],[10]. As part of the commissioning process for ZephIR 300 the performance of each system is verified at the Pershore test facility.

2.3 Methodology

The data set used in the energy yield analysis consists of co-located mast and ZephIR 300 data spanning a full calendar year. Following best practice siting recommendations for mast comparisons [11] the ZephIR deployment was located within 10m of the mast base, Figure 3.

Figure 3 : ZephIR Siting at Mast Base. ZephIR 150 (left) and ZephIR 300 (right).

Data from the mast and ZephIR at 91m above ground level (AGL) were applied as hub-height wind speed measurement inputs in separate energy yield analyses that calculate the AEP for an eight turbine layout on the test site, Figure 4. A standard finance grade energy yield analysis methodology was applied in calculating the AEP values. Data from the mast and ZephIR were correlated against industry standard down-scaled mesoscale data to generate a long term predicted wind climate for the site. WAsP [11] and WindFarmer [13] were then used to extrapolate the wind resource from the measurement location to the turbine locations and calculate the AEP. Additionally wind data measured at 70m AGL from the test mast was applied with a standard finance grade shear extrapolation methodology to calculate AEP for the layout from a sub-hub height wind measurement. A bank's financing model was then applied to the AEP results from these analyses with suitable uncertainty, cost, project and market details to determine the financial terms of an investment based upon the data.

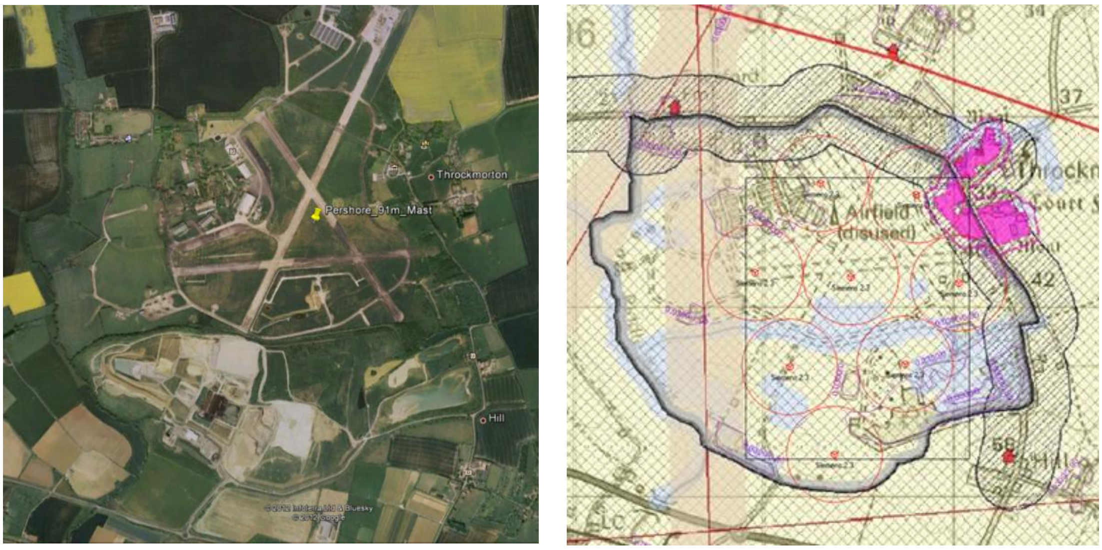
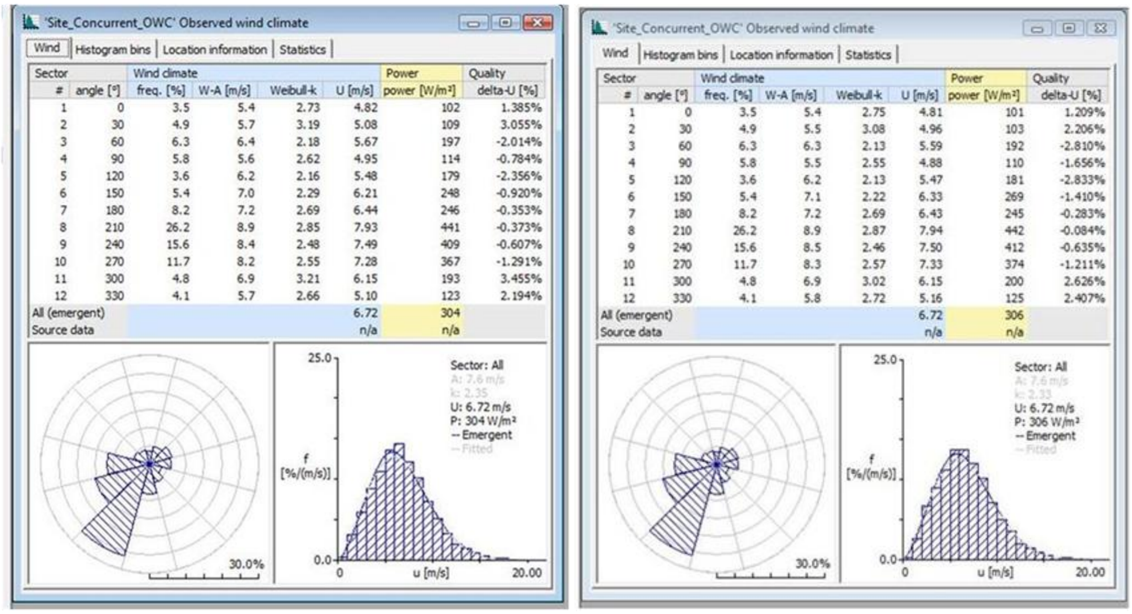


Figure 4 : Layout : 8 x Siemens 2.3 MW, 101m diameter 91m Hub Height.

2.4 Results

Figure 5 shows the long-term predicted wind climate at the test site at 91m AGL derived from concurrent measurements from the Mast and ZephIR at 91m AGL.



'Site_Concurrent_OWC' Observed wind climate

Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	3.5	5.4	2.73	4.82	102	1.385%
2	30	4.9	5.7	3.19	5.08	109	3.055%
3	60	6.3	6.4	2.18	5.67	197	-2.014%
4	90	5.8	5.6	2.62	4.95	114	-0.784%
5	120	3.6	6.2	2.16	5.48	179	-2.356%
6	150	5.4	7.0	2.29	6.21	248	-0.920%
7	180	8.2	7.2	2.69	6.44	246	-0.353%
8	210	26.2	8.9	2.85	7.93	441	-0.373%
9	240	15.6	8.4	2.48	7.49	409	-0.607%
10	270	11.7	8.2	2.55	7.28	367	-1.291%
11	300	4.8	6.9	3.21	6.15	193	3.455%
12	330	4.1	5.7	2.66	5.10	123	2.194%
All (emergent)					6.72	304	
Source data					n/a	n/a	

a) Mast

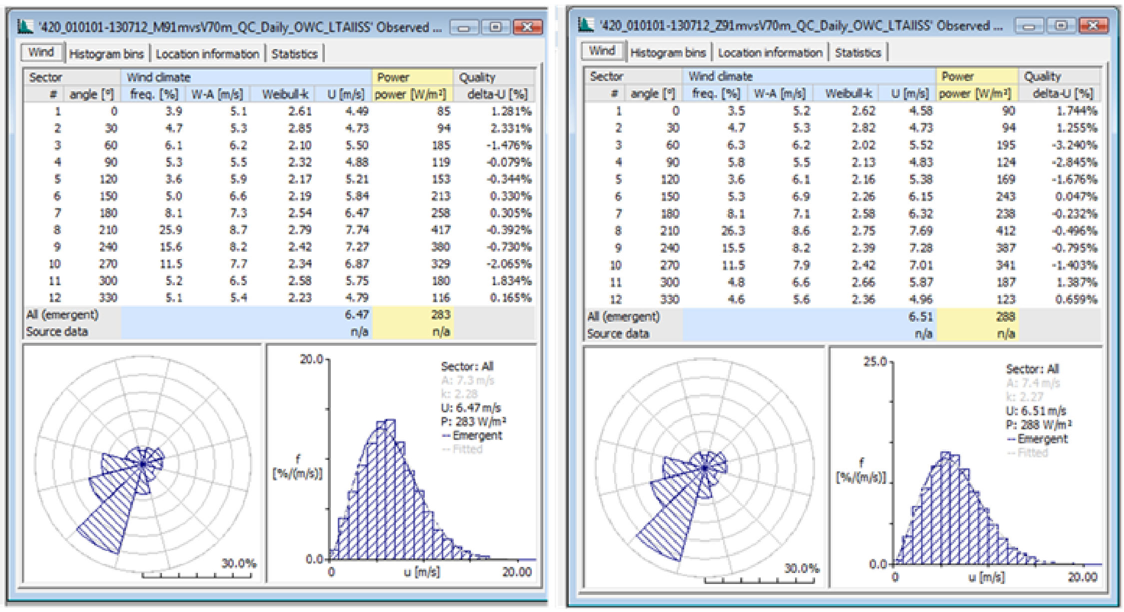
'Site_Concurrent_OWC' Observed wind climate

Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	3.5	5.4	2.75	4.81	101	1.209%
2	30	4.9	5.5	3.08	4.96	103	2.206%
3	60	6.3	6.3	2.13	5.59	192	-2.810%
4	90	5.8	5.5	2.55	4.88	110	-1.656%
5	120	3.6	6.2	2.13	5.47	181	-2.833%
6	150	5.4	7.1	2.22	6.33	269	-1.410%
7	180	8.2	7.2	2.69	6.43	245	-0.283%
8	210	26.2	8.9	2.87	7.94	442	-0.084%
9	240	15.6	8.5	2.46	7.50	412	-0.635%
10	270	11.7	8.3	2.57	7.33	374	-1.211%
11	300	4.8	6.9	3.02	6.15	200	2.626%
12	330	4.1	5.8	2.72	5.16	125	2.407%
All (emergent)					6.72	306	
Source data					n/a	n/a	

b) ZephIR

Figure 5 : Long-Term Predicted Wind Climate at 91m AGL : Concurrent Data.

Figure 6 shows the long-term predicted wind climate at 91m AGL derived from measurements at the test site from the Mast and ZephIR at 91m AGL for all of the recovered data.



'420_010101-130712_M91mvsV70m_QC_Daily_OWC_LTAIISS' Observed ...

Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	3.9	5.1	2.61	4.49	85	1.281%
2	30	4.7	5.3	2.85	4.73	94	2.331%
3	60	6.1	6.2	2.10	5.50	185	-1.476%
4	90	5.3	5.5	2.32	4.88	119	-0.079%
5	120	3.6	5.9	2.17	5.21	153	-0.344%
6	150	5.0	6.6	2.19	5.84	213	0.330%
7	180	8.1	7.3	2.54	6.47	258	0.305%
8	210	25.9	8.7	2.79	7.74	417	-0.392%
9	240	15.6	8.2	2.42	7.27	380	-0.730%
10	270	11.5	7.7	2.34	6.87	329	-2.065%
11	300	5.2	6.5	2.58	5.75	180	1.834%
12	330	5.1	5.4	2.23	4.79	116	0.165%
All (emergent)					6.47	283	
Source data					n/a	n/a	

'420_010101-130712_Z91mvsV70m_QC_Daily_OWC_LTAIISS' Observed ...

Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	3.5	5.2	2.62	4.58	90	1.744%
2	30	4.7	5.3	2.82	4.73	94	1.255%
3	60	6.3	6.2	2.02	5.52	195	-3.240%
4	90	5.8	5.5	2.13	4.83	124	-2.845%
5	120	3.6	6.1	2.16	5.38	169	-1.676%
6	150	5.3	6.9	2.26	6.15	243	0.047%
7	180	8.1	7.1	2.58	6.32	238	-0.232%
8	210	26.3	8.6	2.75	7.69	412	-0.496%
9	240	15.5	8.2	2.39	7.28	387	-0.795%
10	270	11.5	7.9	2.42	7.01	341	-1.403%
11	300	4.8	6.6	2.66	5.87	187	1.387%
12	330	4.6	5.6	2.36	4.96	123	0.659%
All (emergent)					6.51	288	
Source data					n/a	n/a	

a) Mast

b) ZephIR 300

Figure 6 : Long-Term Predicted Wind Climate at 91m AGL : All Data.

Figures 5 and 6 demonstrate the equivalence of the long term wind climates derived from site measurements collected by the mast and ZephIR at 91m AGL. The 0.6% deviation in the mean wind speed (U) in figure 6 is attributable to a difference in data coverage for the mast and ZephIR. Data coverage from the ZephIR was above the 80% minimum requirement generally used for wind farm energy yield analysis. Missing lidar data in the period covered by the analysis was mainly attributable to removal of the lidar from the test site as part of the ZephIR 300 development programme. Table 2 compares the central estimate (P50) and 90% probablility of exceedance (P90) values derived from the mast and ZephIR data.

	Mast 91m			ZephIR 91m			Mast 70m		
P50 [GWh]	47.12			47.25			46.47		
Deviation [%]	-			0.28			-1.38		
	1 Year Average			**10 Year Average**			**Long-term**		
	Mast 91m	**ZephIR 91m**	**Mast 70m**	**Mast 91m**	**ZephIR 91m**	**Mast 70m**	**Mast 91m**	**ZephIR 91m**	**Mast 70m**
P90 [GWh]	35.20	35.27	33.51	39.06	39.14	36.76	39.61	39.69	37.19
Deviation [%]	-	0.20	-4.80	-	0.20	-5.89	-	0.20	-6.11

Deviation = [Scenario – Mast 91m]/Mast 91m [%]

Table 2 : Predicted Central Estimate (P50) and P90 AEP Comparison

Standard uncertainties have been applied in combination with statistics from the long term wind climate prediction and energy yield calculations to determine the P90 estimate from the P50 estimate in Table 2. Following current industry consensus on the performance of cup anemometry and ZephIR 300 in the conditions apparent at the test site the wind speed uncertainty has been set at 2% for both the ZephIR 300 and mast measurements at 91m AGL. Following standard uncertainties for wind shear extrapolation an additional 1% uncertainty per 10m of extrapolation has been applied for the 70m shear extrapolated scenario. Uncertainty exists in the shear extrapolation due to lack of information about wind flow above the top measurement level of a sub hub-height anemometer mast. Assumptions regarding the form of the mean wind shear above this height based on measurements at and below it may not be entirely valid. Degrees of freedom also exist in the fit of an assumed profile to the measured data as the data points will not all lie directly upon it. The effect of this freedom on the magnitude of the extrapolated resource increases with increasing extrapolation height.

The deviation between the mast and ZephIR derived long-term P90 energy yield predictions can be seen in Table 2 to be 0.2% for the hub height measured data. For the shear extrapolated mast data deviation in the long-term P90 energy yield prediction is significantly larger representing a 6% under-estimation of resource. These figures are presented in terms of their effect on project finance in Table 3.

Scenario	IRR [%]	NPV [K£]	Equity Investment [K£]	Debt Size [%]	P90 Revenue [£]
Mast 91m	9.54	6271.2	11,150	71.1	3,762,950
ZephIR 91m	9.60	6366.0	11,094	71.2	3,770,730
Mast 70m	7.80	3412.7	12,832	66.6	3,533,071

Table 3 : Financial Measures Based on Predicted P90 Annual Energy Production

The figures in Tables 2 and 3 show financing terms obtained for the hub height mast and ZephIR measurement scenarios to be equivalent. A £1.7 million saving on equity investment is demonstrated with an increased projected annual P90 revenue of approximately £238,000 for the prediction derived from the hub height measured data in comparison to that derived from the mast data extrapolated from 70m AGL. Details of the inputs to the financial model used to generate the results in Table 3 are included in Table 4.

Project Life [Years]	20
Debt Term [Years]	17
Number of Turbines [#]	8
Total Capacity [MW]	18.4
CAPEX [M£/MW]	1.15
Hub Height [m]	91.5
Inflation [%]	2.5
Annual O&M [£/Turbine]	35,300
Discount Rate [%]	6.0
Revenue [£/MWh]	95
DSCR	1.2

Table 4 : Financial Model Inputs

3 Conclusion

The results presented demonstrate the ability of ZephIR 300 to measure finance grade wind data. Results from the analysis of wind resource based on data measured by ZephIR 300 and an IEC compliant hub-height anemometer mast are shown to be equivalent for an onshore assessment in terms of the predicted annual revenue drived from the measured wind data and the key terms of investment determined from bank's financial modelling. The banks level resource assessment methodology applied is accepted by financial institutions as the basis for lending in situations where anemometer mast data of lower quality than that used in the analysis is available. This includes projects where only sub hub height data is available. Results obtained show significant improvement in predicted P90 revenue and terms of investment for a hub height lidar measurement in comparison to a sub hub height anemometer mast measurement.

For a project with a rate of return (IRR) in excess of the cost of capital, maximizing the debt to equity ratio maximizes the profitability of the investment. The lower the amount of equity required to be invested by the developer, and therefore the higher the debt size, the greater the return on investment accrued by the developer over the lifetime of the project. A saving of £1.7 million on equity investment and an increase of £238,000 in predicted P90 revenue is obtained from analysis of an 8 turbine, 91m hub height, 18.4 MW onshore project using hub height lidar data in comparison to that derived from a 70m mast measurement.

Current trends are for onshore turbines with hub heights in excess of 80m. The installation of an anemometer mast that provides measurements at such heights represents a significant one-off investment in a static resource that cannot be effectively re-used. The portability, re-useability and lack of planning requirements associated with lidar systems make their use in place of hub height mast anemometry an attractive option for wind resource assessment in the context of proven equivalence in the quality and bankability of the data obtained.

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