



**Title** **PROJECT CYCLOPS:  
THE WAY FORWARD IN POWER CURVE MEASUREMENTS?**

**Authors:** Simon Feeney(1), Alan Derrick(1), Alastair Oram(1), Iain Campbell(1), Gail Hutton(1), Greg Powles(1), Chris Slinger(2), Michael Harris(2), John Medley(2), Edward Burin Des Roziers(2)

**Organisation** (1) Renewable Energy Systems Limited  
(2) ZephIR LiDAR

**Address:** Renewable Energy Systems Ltd, Beaufort Court, Egg Farm Lane, Kings Langley, Hertfordshire, WD4 8LR, United Kingdom

**Telephone:** +44 (0)1923 608 294

**Email:** [simon.feeney@res-ltd.com](mailto:simon.feeney@res-ltd.com)

**Summary:** A new wind turbine power curve measurement technique is investigated on a wind farm in Southern England. The technique combines Rotor Equivalent Wind Speed (REWS) power curves and measurements close in to the rotor. This technique captures the varying energy available in the wind due to the vertical wind shear and is anticipated to reduce the wind flow propagation uncertainty due to terrain effects.

A ZephIR DM LiDAR was mounted on the nacelle of a wind turbine adjacent to a fixed mast and a ground based vertically profiling ZephIR DM. The wind speed measurements from the nacelle LiDAR were in very close agreement with these references showing very little bias or scatter.

Reducing the measurement distance had very little effect on the category A uncertainty of the power curve, which is most likely due to the relative simplicity of the site considered here. A discussion of the category B uncertainties suggests that there will be appreciable reductions in measurement uncertainty for this technique, although the real benefit will only be appreciable in complex terrain.

## Introduction

The power output of a wind turbine is a function of a wide range of inflow conditions, including wind speed, air density, vertical wind shear, vertical wind veer, turbulence intensity, directional variation and inflow angle [1]. Turbine performance assessments which use the hub height (HH) wind speed alone, such as those described in the IEC standard 61400-12-1 [2], don't capture all of these dependencies.

In addition it is becoming increasingly expensive to erect meteorological masts to measure the wind speed as turbine hub heights increase. In the offshore environment this expense is now prohibitive for most developers.

An alternative would be to use a LiDAR mounted on the nacelle of a wind turbine to measure the wind speed directly as it approaches the rotor. Previous studies have shown good potential for turbine performance assessments using HH measurements at distances of circa 2.5 rotor diameters (2.5D) [3,4] . However, for complex sites, the flow can evolve significantly between 2.5D and the turbine, resulting in a reduction of correlation with the measured power. Additionally, HH measurements take no account of varying wind shear or veer over the rotor disc.

A new nacelle LiDAR measurement technique is proposed here and the results of the first trial are presented. The technique combines using Rotor Equivalent Wind Speed (REWS) power curves [5] and measurements close to the rotor, where the effects of complex terrain will be reduced.

## Method

A ZephIR DM LiDAR [6] was deployed on the nacelle of a wind turbine in Southern England (figure 1), located 2.62 D from an IEC compliant met mast, and a second ZephIR DM adjacent to the met mast operating in ground-based mode (figure 2).

This type of scanning LiDAR can measure wind speeds across the full rotor disk, allowing rotor-equivalent power curves to be determined. Wind speeds were measured at 6 distances in front of the rotor, 2.62D, 2D, 1.5D, 1D, 0.5D and 0.11D, where D signifies the turbine rotor diameter.

*Figures 1 & 2 – Installation of the ZephIR DMs on the nacelle and adjacent to the met mast*



The REWS calculations were performed using a ZephIR post-processing tool at 5 slices over the rotor area using the formula:

$$v_{REWS} = \left( \sum_{i=1}^n (v_i \cos(\varphi_i))^3 \frac{A_i}{A} \right)^{1/3}$$

where

$n$  is the number of available measurement heights ( $\geq 3$ ) across the rotor disk

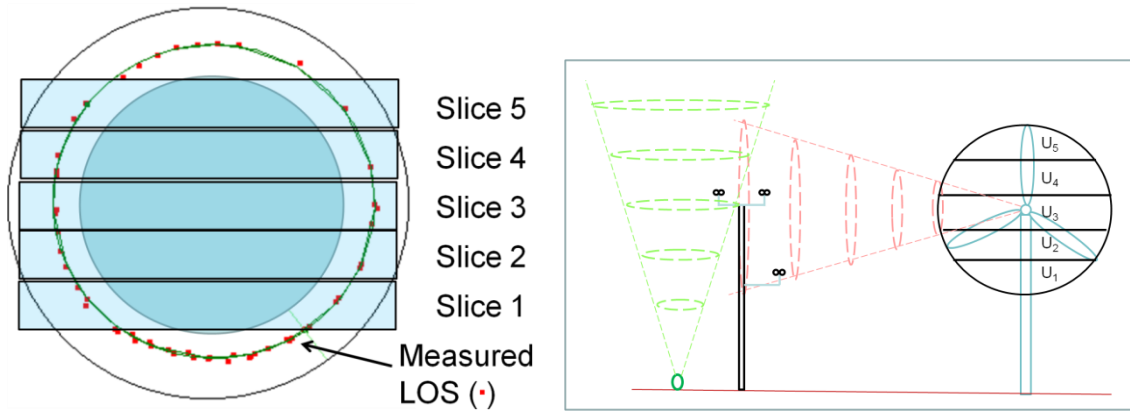
$v_i$  is the wind speed measured at height  $i$

$\varphi_i$  is the angle difference between the wind direction at hub height and at segment  $i$

$A$  is the total rotor swept area

$A_i$  is the area of the  $i$ th segment

The ZephIR DM uses inclination and roll sensors along with the known polar beam scan angles to determine the line of sight wind speeds (LOS) at a 3 Dimensional point in space. LOS pairs on opposite sides of the scan circle are selected at the desired height. Separate means for the left and right hand side LOS are calculated over 10 minutes, which are then translated into the horizontal REWS and wind direction relative to the ZephIR.



*Figure3 – TREWSpeed REWS calculation for 5 uniformly distributed slices over the rotor area with measurement set up schematic*

One of the inputs of the ZephIR DM firmware when initially setting up the measurement campaign is the desired measurement height above ground level. This feature allows sloping terrain to be accounted for by re-running using the post-processing tool multiple times, on each occasion optimising the measurement height for the terrain approaching the turbine from a particular measurement sector and measurement distance.

In order to test whether the measurement technique was relatively insensitive to complex inflow conditions, three sectors were selected with varying complexity as shown in figure 4. One of the sectors is adjacent to rather than coincident with the met mast and ground based LiDAR (M1 and L1 respectively) direction sector. The sector coincident with the turbine to mast direction could not be used as the LiDAR measurement cone was found to be waked by a neighbouring turbine.

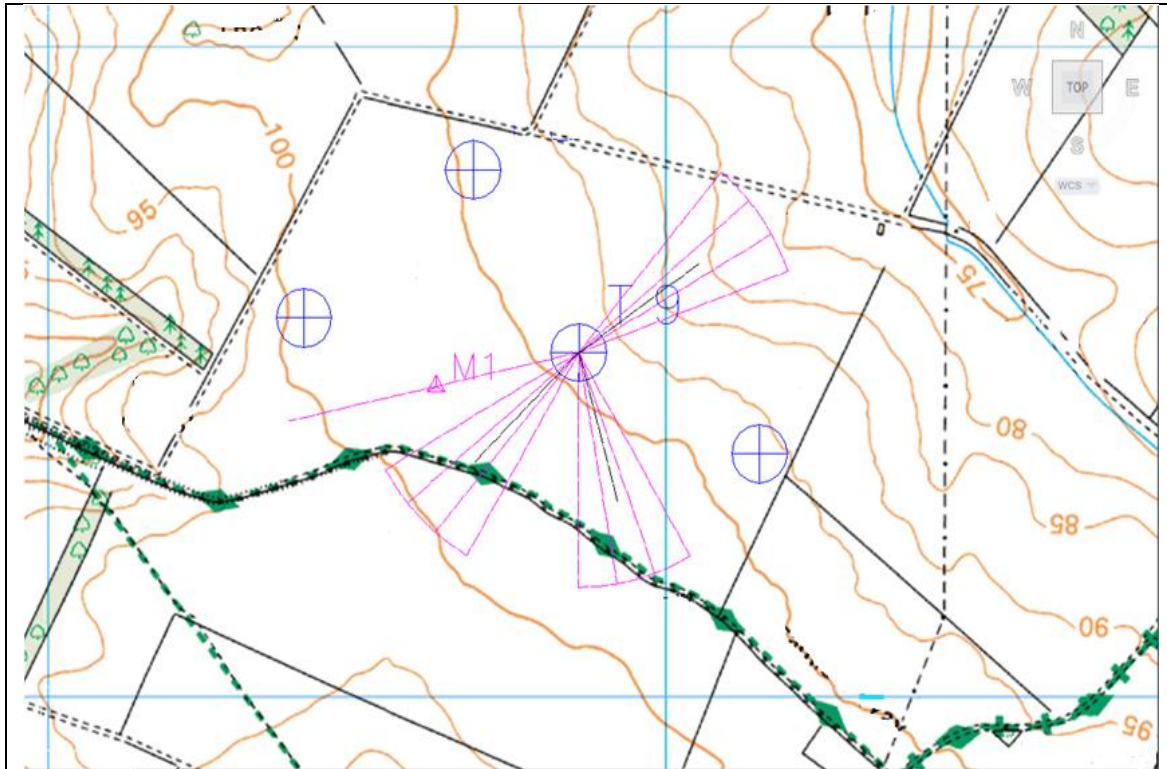


Figure4 – Wake free sectors selected with varying complexity, 40-70°, 150-180° & 210-240°

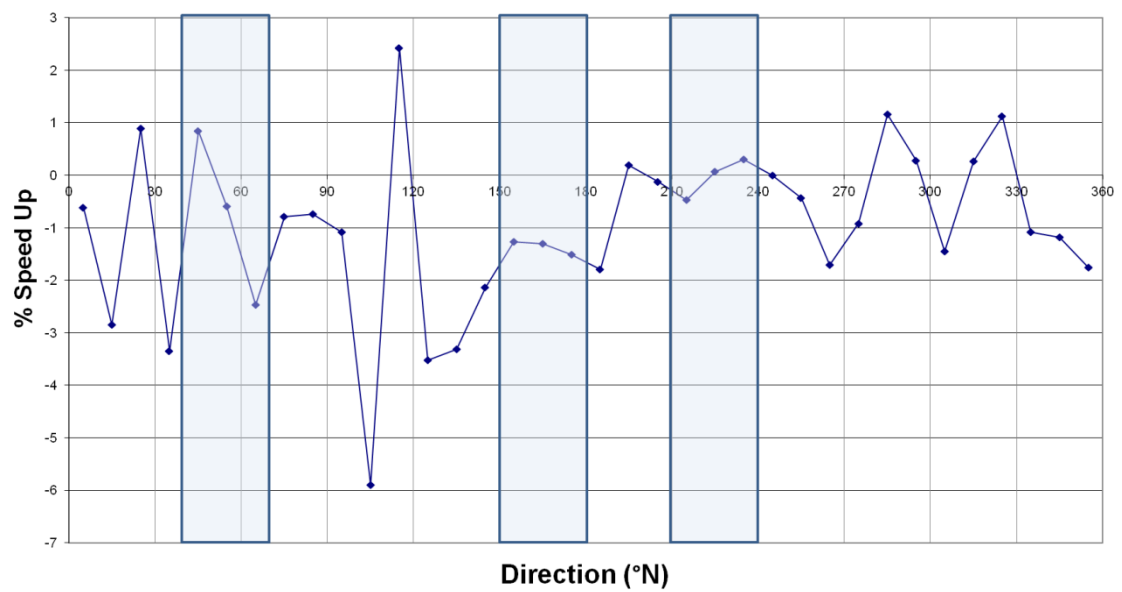


Figure 5 – Speed up percentages from original site calibration with the sectors in figure 4 highlighted. The direction sectors 150-250° were used in the original turbine performance assessment.

## Results

In order to gain confidence in the ability of the LiDAR to measure the wind accurately, the wind speed measurements were first compared to the anemometers mounted at hub height on the meteorological mast for the direction sector adjacent to the mast (210-240°). The slope and correlation achieved for both the binned and scatter comparisons is close to unity.

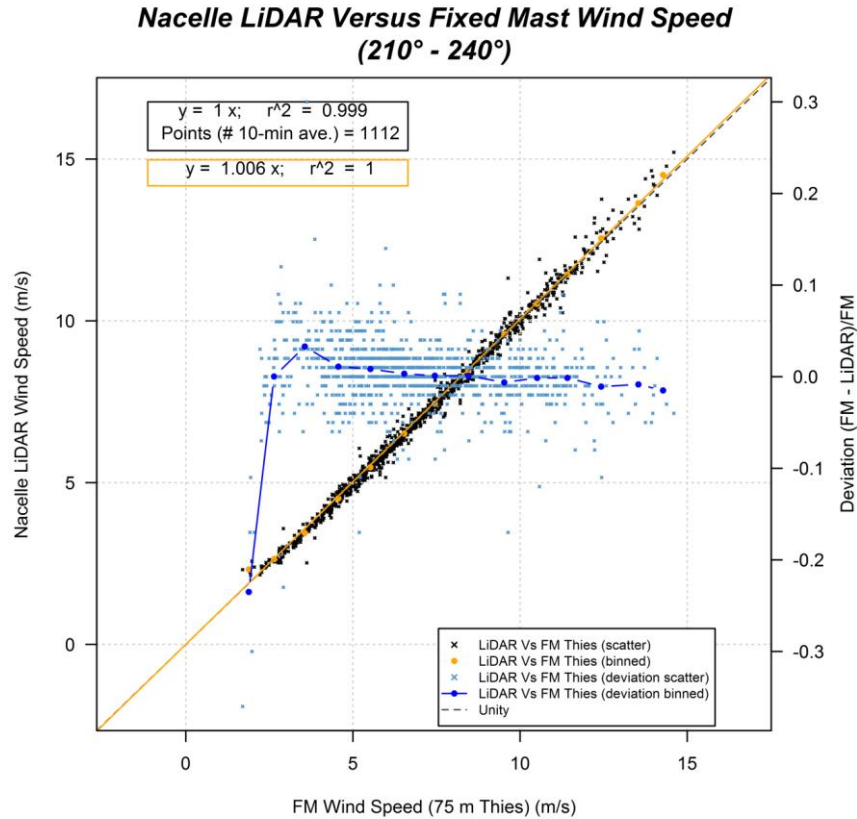


Figure 6 – Binned and scatter comparison plot for the HH nacelle LiDAR and fixed mast cup anemometer wind speeds.

It is noted that there is a large apparent deviation in the binned comparison residuals at the lowest wind speed bin, indicating some deviation in the agreement at lower wind speeds. It is also evident that there is an increase in scatter above 11-12 m/s. At these wind speeds the onset of power regulation occurs as the test turbine is operating at rated power, and the nacelle experiences increased vibrations which is a possible cause of the increased scatter.

The REWS was then compared to that derived using the ground based ZephIR DM and again the slope for the binned and scatter comparison is close to unity. The analysis was run with and without the veer correction term for the REWS ( $\cos \phi_i$ ) and this was found to have a very small effect on the calculated values.

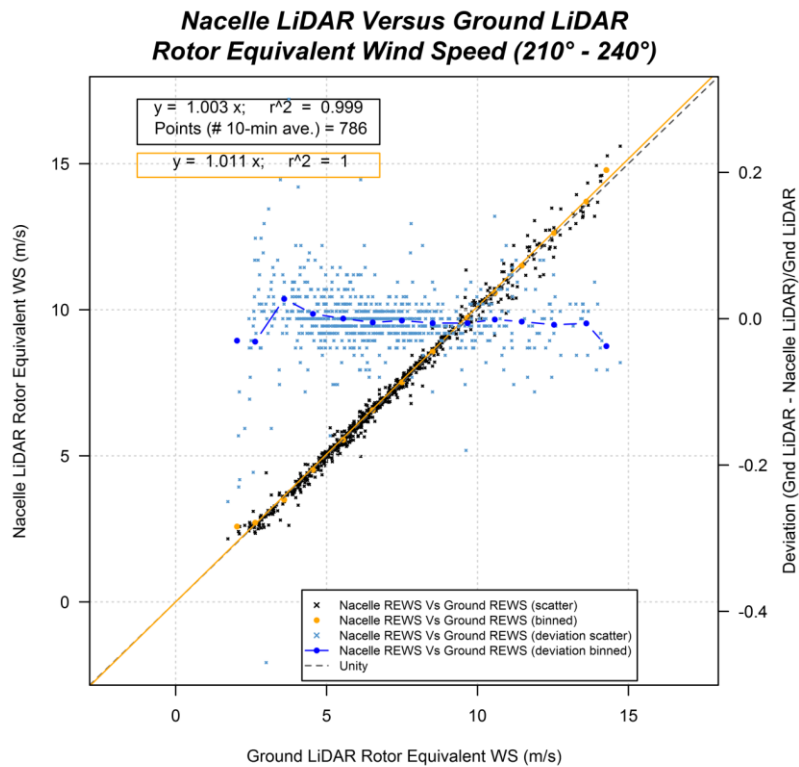


Figure 7– Binned and scatter comparison plot for the nacelle LiDAR REWS and that measured using the ground based LiDAR

The effect of reducing the measurement distance on the power curve is shown in figures 8 & 9 for the direction sector 210-240°. The curves for measurement distances greater than 1D are very similar and are difficult to distinguish from each other. This was found for all sectors that were not affected by the wake of neighbouring turbines

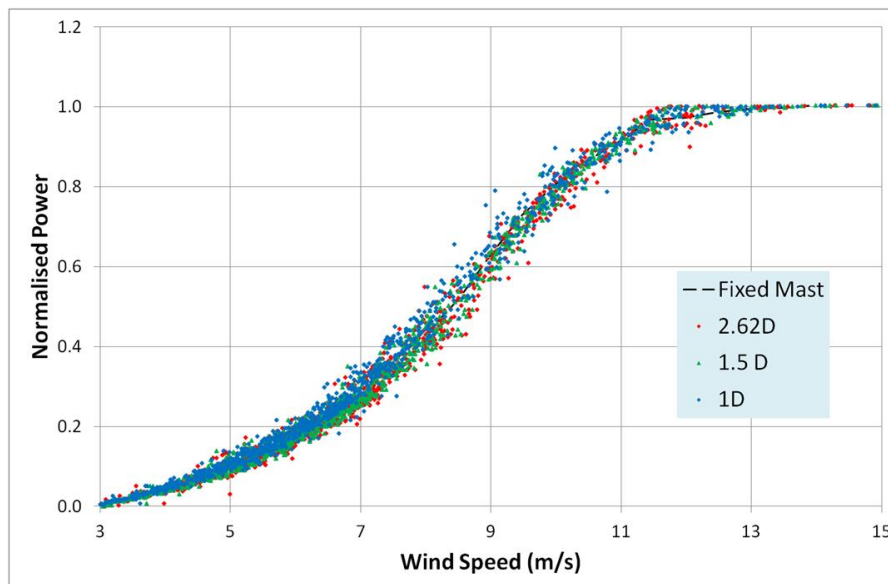


Figure 8– Normalised power curve scatter plot comparison for different measurement distance in front of the turbine rotor using the nacelle LiDAR. The direction sector used is 210 – 240 and the manufacturer turbine availability filters are applied



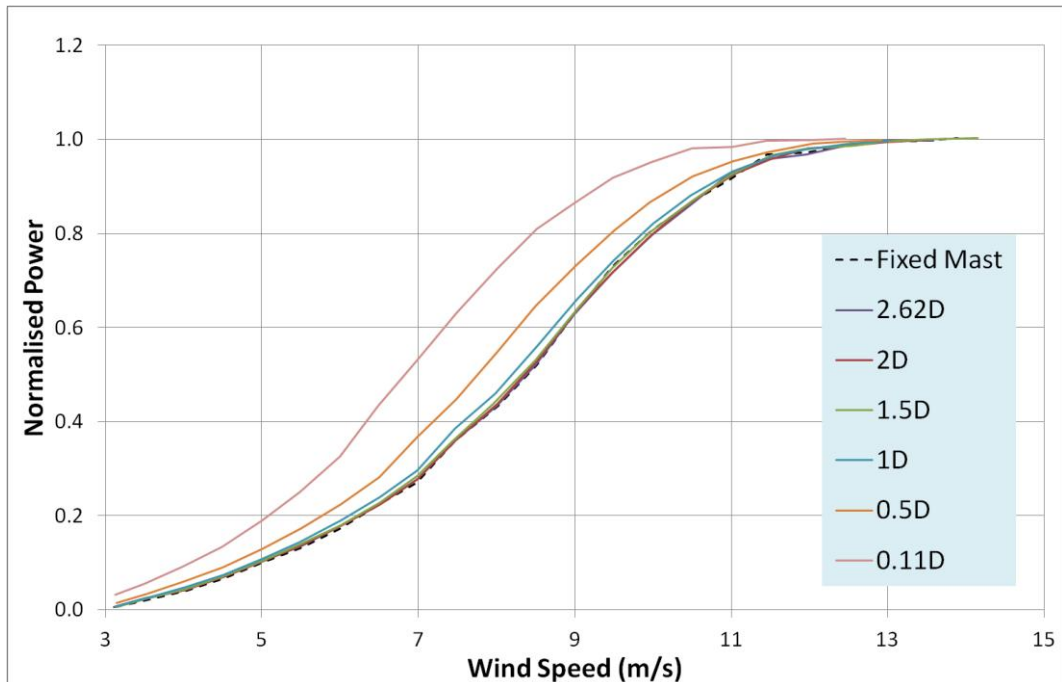


Figure 9– Normalised binned power curve comparison for different measurement distance in front of the turbine rotor. The direction sector used is 210 – 240 and the manufacturer turbine availability filters are applied

The effect of varying the measurement distance for the 3 measurement sectors is shown in figure 10. The REWS is used to take account of varying wind shear profiles, although it should be noted that shear extrapolation is required at the 1D measurement range as the LiDAR beam spread can't reach the required measurement point in the upper and lower slices.

The curves are very similar (without site calibration), showing the relative simplicity of this site.

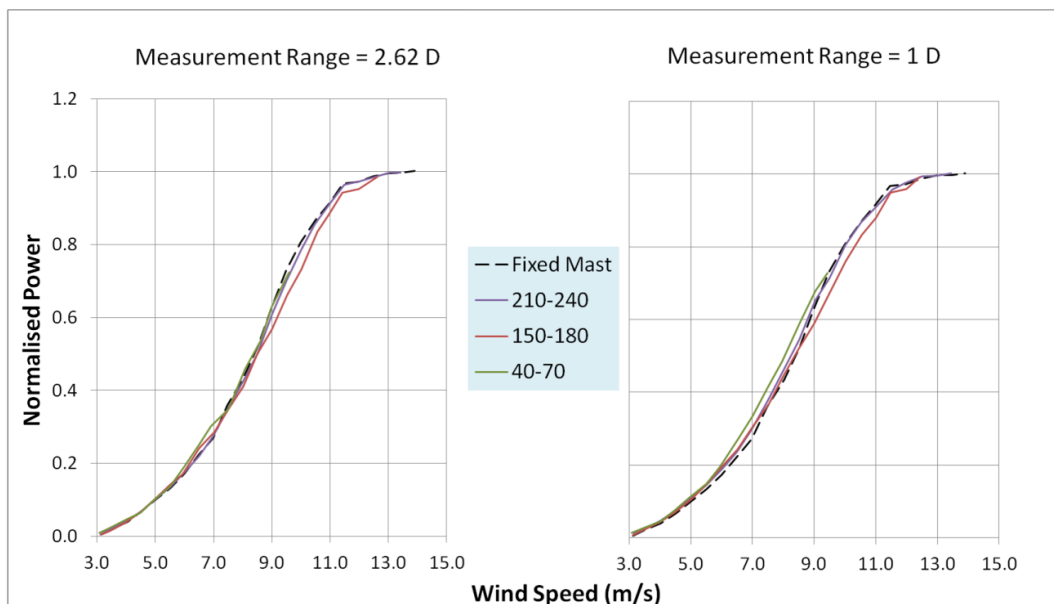


Figure10 - Binned power curves at 2 ranges for the direction sectors 40-70°, 150-180° & 210-240°. The wind speed axis is the REWS measured using the nacelle LiDAR

## Uncertainty

An uncertainty analysis has been completed on the nacelle LiDAR power curves. Encouragingly it was found that there were no statistically significant differences between the power curve measured by the fixed mast and the power curve measured by the nacelle LiDAR at the mast distance.

The category A uncertainty has been calculated (Table 1) for all power curves in order to assess whether reducing the measurement distance in front of the turbine has a beneficial effect on the power curve for increasing terrain complexity (i.e. reduced scatter at distances closer to the turbine). Reducing the measurement distance has had a negligible effect.

Direction Sector	LiDAR Measurement Distance		Comparison with Fixed Mast
	2.62D	1D	
40°-70°	0.75 %	0.96 %	N/A (waked)
150°-180°	0.47 %	0.46 %	0.48%
210°-240°	0.23 %	0.25 %	0.27%

*Table 1 – Category A uncertainty for the power curves at 2 ranges for the direction sectors 40-70°, 150-180° & 210-240°. The uncertainties for each direction sector are expressed as a percentage of the 2.62D LiDAR power curve for that sector*

Calculating the Category B uncertainties for nacelle LiDAR power curves is beyond the scope of this study. Instead a qualitative approach has been adopted where the factors which will affect the nacelle LiDAR power curve uncertainty relative to an IEC power curve measured with a fixed mast are discussed (Table 2), as well as the relative effects of reducing the measurement distance of the nacelle LiDAR wind speed.

The HH power curve should become significantly more uncertain with increasing terrain complexity and rotor diameter, as it becomes less likely that a single point measurement is describing the true average wind speed incident on the rotor disc. This is ignored in the existing standard [2], as the site calibration doesn't account for this potential discrepancy between the HH and rotor average wind speed. The proposed revision of [2] will however address this failing through the use of a ground mounted, vertical profiling remote sensing device (e.g. a LiDAR) located near the met mast to derive a REWS power curve with the intention of reducing the uncertainty in the power curve measurement. We have here further extended this principle to the case of a nacelle mounted forward facing lidar.

Component	Discussion	Relative Uncertainty Impact
Wind speed measurement	The wind speed uncertainty of the nacelle LiDAR measurements can only be assessed relative to a reference instrument – a cup anemometer – so it must be greater	The correlations shown in this trial suggest that the added uncertainty component would be a small increase for the direction sector 210-240° for this site. However, this uncertainty may be dependent on the wind turbine structural dynamics and hence turbine type dependent. The measurements have shown an increase in wind speed correlation scatter associated with higher



		wind speeds when this particular turbine's tower top vibrations increase.
Site calibration	Carrying out a site calibration using fixed masts would defeat the purpose of the nacelle LiDAR. A short in-situ calibration with the turbine powered down could be carried out	Having prior knowledge of the site calibration at this site has allowed a sector with almost no site calibration effect to be selected. It is not clear whether this could be established with the nacelle LiDAR alone. This is a potential increase in uncertainty for this technique
Wind speed variability with height across rotor disc	The uncertainty at each nacelle LiDAR measurement height will vary as the wind speed and turbulence intensity do not change linearly with height. This results in more complex flow in the lower measurement slices regardless of terrain complexity. The installation of the LiDAR on the nacelle (in this case tilted upwards to avoid nose cone strike) can also mean that the width of the measurement circle is less at lower measurement heights, meaning successful measurements are less likely	There will be a relative decrease in power curve uncertainty as more information is known about the flow over the entire rotor disc. There will be some small reduction in the uncertainty on the REWS wind speed by increasing the number of measurement slices, but this is assumed to be very low for shear profiles approaching the power law.
Wind veer variability with height across rotor disc	The uncertainty associated with each wind veer measurement will also change with measurement height for the reasons outlined above	There is no provision for wind veer in the current standard, so including a correction for this must decrease the uncertainty. For this site including the veer correction changed the wind speed by only 0.2% but this effect could be larger for other sites
Horizontal wind shear across the rotor disc	In complex terrain there is a potential for large differences in the measured radial wind speeds from one side of the measurement circle to the other. The nacelle LiDAR calculations in this paper assume homogeneous flow when resolving the wind speed for a particular slice which should be accounted for when considering complex terrain.	Horizontal veer can be captured by the ZephIR DM and accounted for in the subsequent analysis, although it has not been undertaken in this case as the simplicity of this site would mean that any horizontal shear impact is likely to be minimal. There is no account for horizontal shear in the standard so measuring and accounting for this must decrease the uncertainty relative to HH measurements
Terrain effects	The fundamental idea behind this measurement approach is that there are significant uncertainties on all power curves in complex terrain as the wind flow changes in unseen ways as the wind travels from the reference position to the turbine. Although some of this is accounted for in the site calibration, large uncertainties remain.	Measuring wind speeds with a nacelle LiDAR at distances of 2.5D will incur the same terrain induced uncertainties as fixed masts. By reducing the spatial separation between the measurement point and the power take off point a new type of power curve is being defined, which has the potential to be more repeatable from site to site. It is not clear at this point whether an uncertainty comparison with the 2.5D curve is valid however.

Table 2– Category B uncertainty discussion for the Cyclops technique

## **Optimum Measurement Distance**

In order to minimise the sources of category B uncertainty the optimum measurement distance should be far enough in front of the rotor to successfully measure 5 rotor slices, but no further to minimise terrain effects. For the ZephIR DM used in this study, the optics half cone opening angle was 15°, and the optimum range calculated to be 1.5D.

The optimum distance is very dependent on the installation setup of the nacelle LiDAR, and will increase with height above the nacelle and any initial tilt on setup.

## **Conclusions**

The campaign has given high confidence in the ability of the ZephIR DM to measure both HH and REWS power curves in excellent agreement with the fixed mast and ground based LiDAR respectively.

At any specific measurement distance the terrain impact on the LiDAR derived power curve and category A uncertainty is near constant. This is likely to be due to the relative simplicity of this test site. The method described still shows merit for simple sites, as we believe there will be a reduction in category B uncertainty compared to nacelle LiDAR measurements at 2.5 D due to the increased knowledge recorded on flow through the rotor disc. The real benefit of the Cyclops technique will only be evident in complex terrain, where further tests are planned.

The ultimate goal of this research is encourage the manufacturers of wind turbines to offer two power curves to potential customers. The first power curve would be based on conventional HH measurements for energy yield assessments, and the second would be measured using a nacelle LiDAR and would form the basis of a warranty test. For turbines which are to be sited in complex terrain, manufacturers could consider the possibility of offering the second curve which has been measured at a closer distance to the rotor, which we believe will allow for a more reproducible and consistent test.

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