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Title **Evaluation of wind flow with a nacelle-mounted, continuous wave wind lidar**

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Summary: Nacelle-mounted lidar is becoming widely recognized as a tool with potential for assessing power curves, understanding wind flow characteristics, and controlling turbines. As rotor diameters continue to increase, and the deployment of turbines in complex terrain becomes more widespread, knowledge of the characteristics of the incident wind field beyond the mean speed and direction at hub height become essential, for example, in the calculation of rotor-equivalent power curves. A scanned, continuous wave lidar can provide a wealth of such information.

This paper evaluates data collected from a ZephIR DM lidar mounted on the nacelle of a 550 kW turbine at the Risø campus of the Technical University of Denmark (DTU). Lidar measurements of wind speed and turbulence were compared against those made by anemometers on a high-quality traditional mast. Analysis showed excellent correlation between mast and ZephIR, increasing the confidence in the ZephIR for measuring wind parameters in this configuration.

SCADA data from the turbine was combined with measured wind speeds and directions to derive power curves from the mast data (hub-height) and from ZephIR data (hub-height and rotor-equivalent). The rotor-equivalent power curves were derived in accordance with the procedure detailed in the February 2013 draft of the IEC Guidelines and accounted for the effects of varying air density, shear, veer and turbulence. Once again, the ZephIR and the mast were shown to give very similar results.

It is believed that this is the first time that a commercially available nacelle-mounted lidar has been used to evaluate such rotor-equivalent power curves.

Introduction

Nacelle-mounted lidar is becoming widely recognized as a tool with potential for assessing power curves, understanding wind flow characteristics, and controlling turbines. As rotor diameters continue to increase, and the deployment of turbines in complex terrain becomes more widespread, knowledge of the incident wind field beyond the mean speed and direction at hub height become essential, for example, in the calculation of rotor-equivalent power curves. The use of a scanned, continuous wave lidar can provide a wealth of such information.

In this paper, an experiment is described in which a ZephIR DM lidar was mounted on the nacelle of a turbine. Measurement data was collected from the lidar and its performance verified by comparison with measurements from anemometers on an adjacent met mast.

ZephIR DM

The ZephIR DM (Dual-Mode) lidar is capable of both vertical ground-based and horizontal turbine-mounted operation. It is a monostatic, 1 Watt, 1560 nm continuous wave (CW) lidar, and measures 50 line-of-sight (LOS) speeds around each 1-second circular scan, at up to 10 user-selected measurement heights (ground-based) or ranges (turbine-mounted). The 20 ms fast sample and integration time allows “snapshot” measurements, avoiding any adverse effects due to nacelle motion, and permits simple rejection of turbine blade reflections. Due to the CW configuration, sensitivity is almost independent of the measurement range. Short measurement ranges, as close as 10 m, are possible, and these can be useful for exploring blade induction effects. Importantly, with this type of continuous scanning, the ZephIR DM lidar qualifies as laser safety class 1 according to the international standard IEC 60825-1 and therefore no special handling or safety procedures are required.

Other important features include low system mass and size to permit rapid installation by a 2-man team, a highly adaptable carbon fibre leg tripod to allow standard installation on a variety of nacelle roof types, and a laser alignment system to ensure accurate ($< 1^\circ$ uncertainty) yaw misalignment measurements to be taken.

In turbine-mounted mode, the ZephIR DM uses inclination and roll sensors along with the known polar beam scan angles to determine the LOS wind speeds at fixed measurement points in space, irrespective of nacelle motion and attitude changes. LOS pairs on opposite sides of the scan circle are selected at the desired heights. These are then averaged over typically a 10 minute averaging period and translated into horizontal wind speeds and yaw misalignment angles.

This approach allows hub-height (HH) and rotor-equivalent (RE) wind speeds to be measured, as well as complex vertical shear profiles, wind veer and yaw misalignment as a function of height across the rotor disk. Various turbulence intensity measures can also be obtained.

Experiment description

A ZephIR DM lidar was installed on the nacelle of a NEG Micon Nordtank 550 kW test turbine with a rotor diameter (D) of 41 m on the Risø campus of the Technical University of Denmark (DTU) (see Figure 1) for approximately 5 months, starting in December 2012.

A high-quality meteorological (met) mast was situated approximately 90 m (2.2 D) to the west of the turbine (see Figure 2). The ZephIR was set to measure at a range of 90 m to optimize the comparison of lidar and mast measurements. This distance is within the 2-4 D limits recommended by the IEC for turbine power curve assessment with a met mast. A second measurement range of 50 m (1.2 D) was also set to illustrate the effects of measuring within the induction zone of the rotor. The ZephIR was configured with a 30° scan angle, so its scan at a range of 50 m still covered the full extent of heights in the sweep of the rotor and allowed rotor-equivalent wind speeds to be derived.

Measurement data was collected from the ZephIR and the cup anemometers and wind vanes on the met mast. SCADA data, including turbine yaw, rotor rotation rates and generated power, was collected from the turbine to enable power curves to be generated.

Wind vane and turbine yaw data were used to filter results to only include winds from the western sector, when the turbine was facing within $\pm 45^\circ$ of the direction to the mast.



Figure 1: ZephIR DM installed on nacelle of turbine at DTU Risø Campus

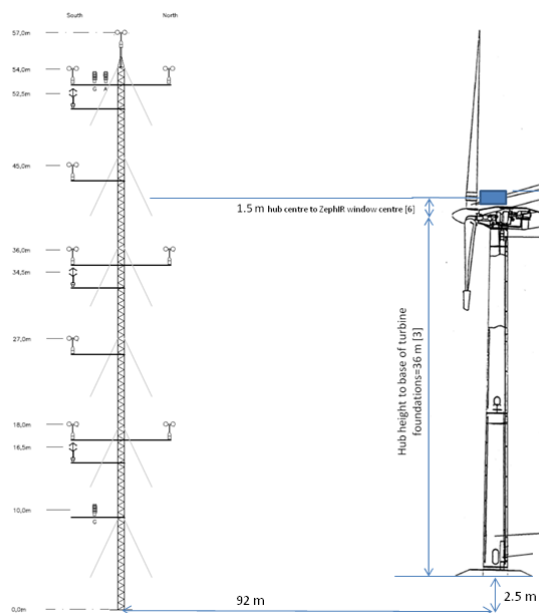


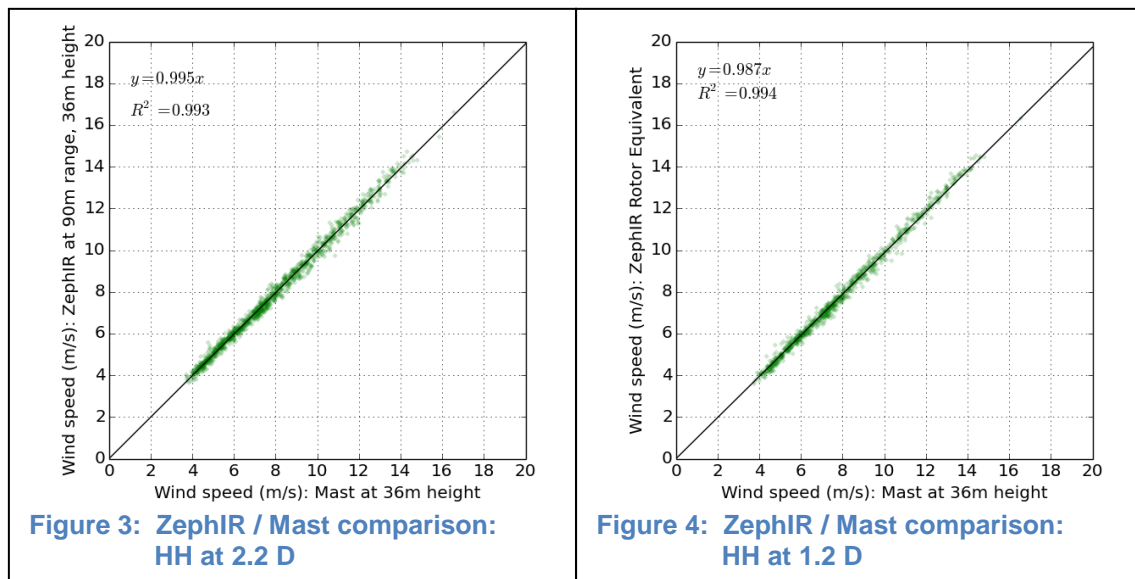
Figure 2: Turbine and mast layout

Hub-height wind speed measurement

The turbine hub is 36 m above its base. Cup anemometers were mounted on the mast at 36 m above its base to measure wind speed at hub height. A sonic anemometer at 34.5 m allowed the direction of the wind near hub height to be measured.

The lidar was mounted on the turbine nacelle approximately 1.5 m above the hub centre. The ground sloped down from the turbine towards the mast, meaning that the base of the mast was 2.5 m below the base of the turbine. The centre of the scan of the horizontally-pointing lidar was therefore approximately 40 m above the ground when the turbine was facing the mast. As the lidar has a scan angle of 30° , at a focus range of 90 m its scan encompasses heights from ground level to just over 90 m. The HH wind speed was assessed by analysing the part of the lidar scan at that height.

A plot showing the correlation between 10-minute averaged HH wind speeds measured by the lidar and the mast anemometers is shown in Figure 3. Only 10-minute periods for which the mast instruments indicated the wind direction as within $\pm 45^\circ$ of the turbine-to-mast bearing are plotted. A least-squares analysis was performed to find the best fit regression line forced through the origin. The agreement is excellent, with a regression slope of 0.995, and very little scatter considering the fact that, depending on wind direction, the lidar is sometimes measuring at points over 100 m away from the mast.



For about half of the trial, a second, closer focusing range of 50 m (1.2 D) was also set on the ZephIR. The associated correlation plot, Figure 4, shows that, as expected, the wind is slowed by the blockage effect of the turbine rotor. By comparing the slopes of the two correlations against the mast it is seen that the speed measured by the ZephIR is reduced by about 0.8%.

Despite measuring in the turbine induction zone, the correlation is still very tight, with a scatter comparable to the measurement at 2.2 D.

Wind shear and veer

The lidar scans its beam in a circular path, the diameter of which is determined by the scan cone angle and the measurement range. If that range is far enough from the turbine, measurements will be made across the full span of heights within the sweep of the turbine's rotor. The vertical wind shear and veer across the full rotor swept area can therefore be assessed for each 1-second scan of the lidar.

Figure 5 shows 10-minute averaged ZephIR-measured wind profiles across the rotor from a typical day in the deployment. Five measurement heights were considered: 19.6 m, 27.8 m, 36 m, 44.2 m and 52.4 m, although the ZephIR data can be processed to give results at any number of heights within its circular scanning range.

The profiles show that there was a relatively low level of (vertical) wind shear and (vertical) wind veer across the rotor during the trial, which is to be expected with such a small rotor.

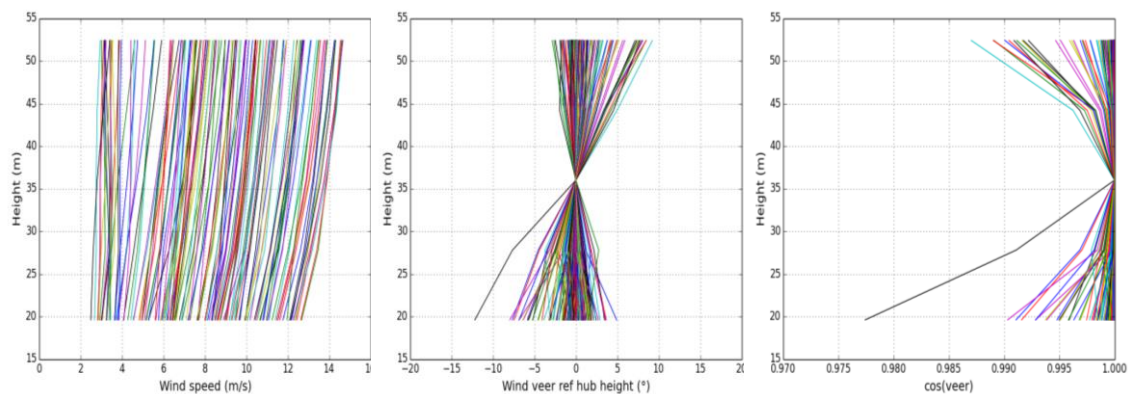


Figure 5: 10-minute averaged wind profiles from 4th January 2013.
Left to right: shear, veer and cosine of veer.

Turbulence intensity

A lidar measures turbulence intensity (TI) with mixed wind components on a different scale to a cup anemometer, primarily due to volume averaging effects. This difference can be quantified by comparing the TIs derived from HH ZephIR and mast measurements, as in Figure 6.

The level of correlation is quite high, with an R^2 of 0.78, while the slope of 0.917 shows that the TI measured by the ZephIR does tend to be lower than that measured by the mast. This difference should be taken into account in any comparison of measurements.

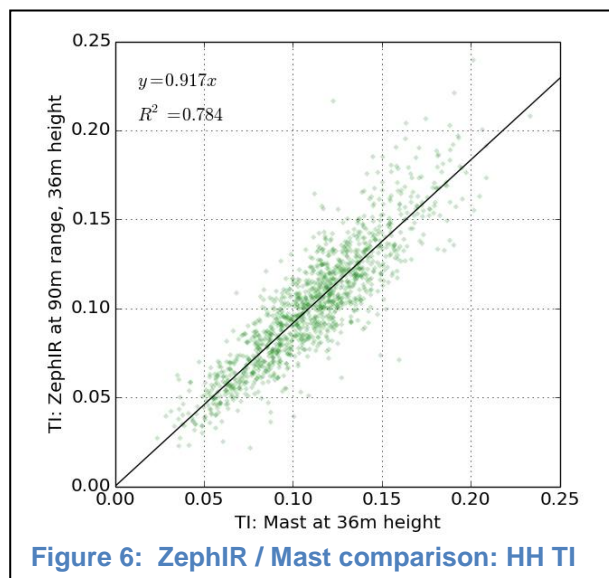


Figure 6: ZephIR / Mast comparison: HH TI

Power curves: Hub-height

The SCADA data collected from the turbine was used to generate power curves. The 10-minute power readings were normalised to the mean air density during the trial (1.27 kg/m^3) following the procedure for stall-regulated turbines described in section 8.1.1 of [1].

The bin-averaged power curve derived from 10-minute averaged HH wind speeds measured by the ZephIR is plotted as a red line with bin markers in Figure 7. The width of the wind speed bins is 0.5 m/s. The 10-minute averaged values are plotted in green and show a low level of scatter about the bin-averaged curve.

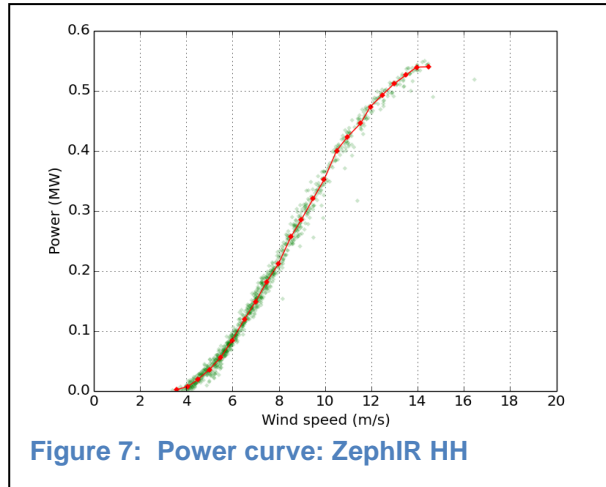


Figure 7: Power curve: ZephIR HH

Power curves: Rotor-equivalent

In the presence of wind shear and veer, it is not sufficient to rely on the HH wind speed alone to get an accurate assessment of the power available in the wind, and hence the turbine's efficiency. The concept of a rotor-equivalent wind speed has been proposed [2] as a method for generating more representative power curves. The RE wind speed is found by combining the measured wind speeds at a number of different measurement heights equally spaced across the swept area of the rotor (see Figure 8).

As the power available in the wind is proportional to the third power of the wind speed, the RE speed is defined as the cube root of the mean of the cubed wind speeds, weighted by the proportion of the rotor swept area that wind speed represents.

To account for veer, the wind speeds are weighted by the cosine of the difference in wind bearing from hub height before being combined by the RE formula. This leads to the following equation, (Q.1) of [1], for the RE wind speed (U_{RE}):

$$U_{RE} = \left(\sum_{i=1}^N (U_i)^3 \cos \varphi_i \frac{A_i}{A} \right)^{\frac{1}{3}},$$

in which U_i , φ_i and A_i are the wind speed, wind veer (difference in wind direction from that at hub height) and area, respectively, representative of slice i of the rotor swept area.

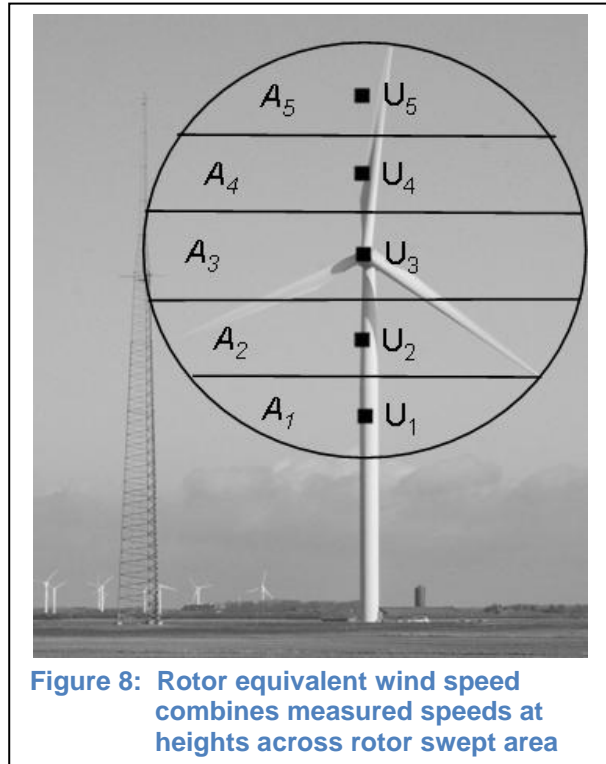
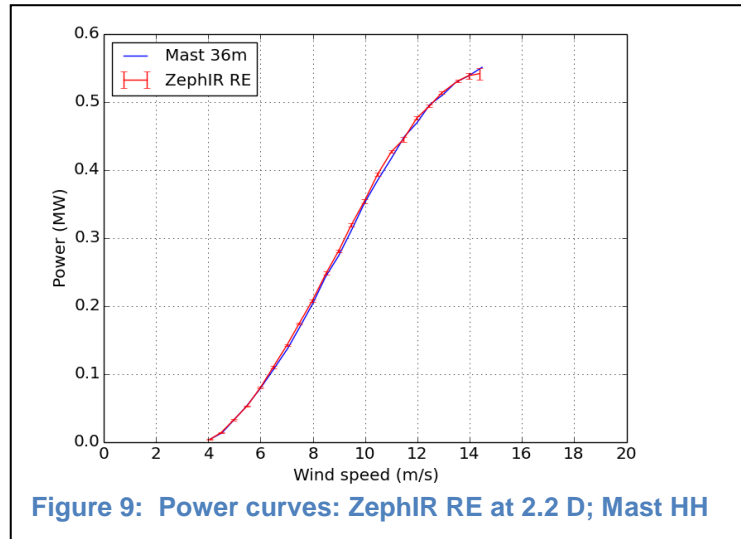


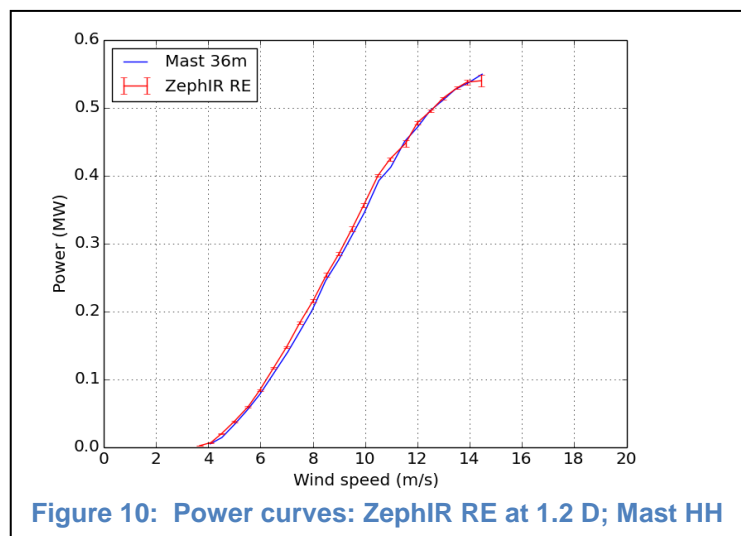
Figure 8: Rotor equivalent wind speed combines measured speeds at heights across rotor swept area

The bin-averaged power curve plotted in red in Figure 9 was generated from RE wind speeds derived from ZephIR measurements at 5 heights across the rotor. The red vertical bars show the standard uncertainty of the values in each bin, that is the standard deviation of the observed powers in that speed bin divided by the square root of the number of observations.



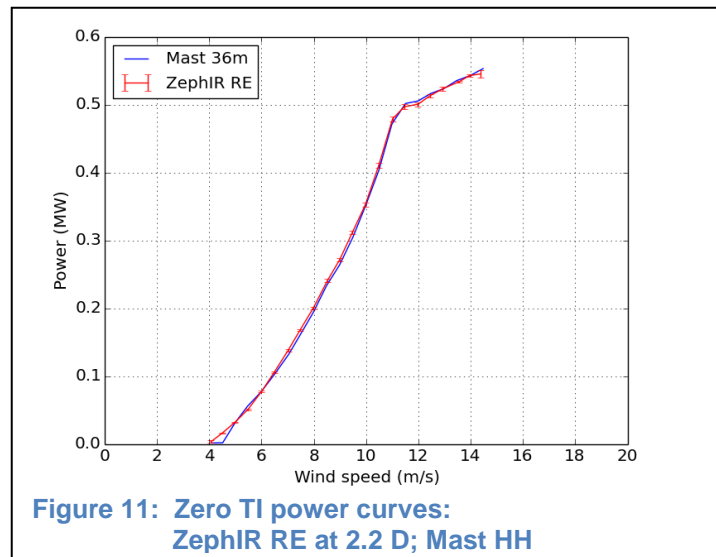
The blue power curve shown in the same figure was calculated purely from the wind speed measured by the HH anemometers on the mast. It is very close to the curve generated from the RE wind speeds derived from the ZephIR measurements, which is consistent with the good correlation between the ZephIR HH measurements and the mast data (Figure 3) and also the low levels of shear and veer (Figure 5).

An RE power curve generated from the ZephIR measurements at 1.2 D is shown in Figure 10. Note that the measurement period was not as extensive as for the previous power curves, leading to slightly larger uncertainties in the bin-averaged powers. The mast data for this same reduced period is also shown for reference. By comparison with the mast hub-height power curve, the RE curve has shifted to the left slightly. This is consistent with the slow-down in wind speed due to turbine blockage effects, as has been observed in previous trials with a nacelle-mounted ZephIR [3, 4].



Power curves: Normalized to zero TI

One further characteristic of the wind that can affect the power available to the turbine is the TI. Annex M of the draft IEC guidelines for assessing turbine performance [1] describes a method proposed for removing the effects of turbulence from the measured power curve and subsequently normalizing the power curve to any reference TI. This procedure has been implemented using the programming language Python and was used to produce the ZephIR RE (2.2 D) and mast hub-height power curves, normalized to zero TI, that are plotted in Figure 11.



**Figure 11: Zero TI power curves:
ZephIR RE at 2.2 D; Mast HH**

Note that the TI measured by the ZephIR was used to normalize the power curve derived from the ZephIR wind speed measurements to zero TI whereas the TI measured by the cup anemometers was used to normalize the cup wind speed measurements. Comparing the “zero TI” power curves of Figure 11 to the uncorrected power curves in Figure 9, the main effect of turbulence is seen in the area of the “knee” of the power curve, around rated speed. In this region, the faster wind speeds that contribute to each 10 minute average are approaching, or within, the (stall-) regulated operating range and hence no longer deliver the expected cubic relationship between speed and generated power.

The two “zero TI” power curves in Figure 11 are very close. This gives support to the process of normalizing ZephIR measurements to zero TI using the ZephIR-measured TI. The zero TI power curve can subsequently be corrected to any reference TI as described in Annex M of [1].

Conclusion

This investigation provides experimental evidence that a nacelle-mounted CW lidar installed on a full-scale instrumented test turbine can perform high quality measurements of several characteristics of the wind flow around the full rotor disc. These measurements have been used to assess turbine performance by deriving power curves that account for wind shear, veer and turbulence. It is believed that this is the first time that a commercially available, turbine-mounted lidar has been used to derive rotor-equivalent power curves.

As the nacelle-mounted lidar yaws with the turbine, and is therefore always measuring the wind about to strike the turbine’s rotor, there is potentially less restriction on wind direction when assessing turbine performance, which in turn can lead to shorter measurement campaigns.

The reliability of the measurement data, and the full coverage of the wind turbine rotor area, improve confidence in the application of this technique for other critical tasks, such as turbine control for fatigue load reduction and power output optimisation [5, 6].

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