Relative Power Curve Measurements Using Turbine Mounted, Continuous-Wave Lidar

Chris Slinger, Matthew Leak, Mark Pitter, Michael Harris

ZephIR Ltd., The Old Barns, Fairoaks Farm, Hollybush, Ledbury, Herefordshire, HR8 1EU, UK.
chris.slinger@zephirlidar.com, +44 1531 650 757

Summary

Power curves are an important way of measuring turbine performance. IEC standard 61400-12-1 describes procedures to measure absolute power curves using ground-based metmasts. However, in many situations, it is more convenient and efficient to use turbine-mounted lidars to measure power curves. This arrangement ensures measurement of wind incident on the rotor irrespective of the wind direction, avoids the considerable difficulties associated with offshore metmast deployment, allows rapid measurement at multiple upwind ranges from the turbine and permits straightforward measurement of both hub height and rotor equivalent wind speeds. A circular scan lidar also permits a sampling of the wind field around the full rotor disk, and wake visualisation is also possible. Power curves derived from these measurements can allow turbine performance to be measured and compared pre- and post- intervention / adjustment / maintenance. The lidar measurements also allow calibration of other turbine instrumentation and permitting accurate measurement of yaw alignment and the investigation of the impact of atmospheric effects such as vertical wind shear and turbulence.

This paper presents the results of measurements from a nacelle-mounted, circular scanning continuous-wave ZephIR lidar, operating on a 2 MW onshore, horizontal axis turbine in Jutland, from January to April 2012. Lidar measurements at ranges from 10 m, 30 m, 50 m, 100 m and 180 m were taken (corresponding to ranges from 0.14 D to 2.5 D). Hub height wind speeds, wind yaw direction and vertical wind shear time series were obtained from these measurements. The measurements helped identify a consistent 14 to 16 degree yaw misalignment of the turbine. The pre and post yaw wind vane sensor calibration power curves are compared in the paper. The influence on power curves of lidar-measured high and low vertical wind shear, high and low atmospheric turbulence are also shown. By examining the wind speed at various ranges upwind of the turbine, the effects of turbine blade induction were also observed and measured. Turbulence and wind shear are found to have significant effects on the power curves.

The measurements confirm that turbine-mounted, circular scan, continuous wave lidar can be a useful tool for turbine characterisation and instrumentation calibration. Measurement of turbine power curves, particularly offshore, is an important application area for turbine-mounted lidars.

1 Introduction

Power curves are an important and succinct way of characterising turbine performance. They aid the development of new turbines, allow manufacturers to warrant their products, assist operators in choosing an appropriate turbine model for a particular site and allow them to benchmark and track performance of a turbine when in use.

IEC Standard 61400-12-1 [1] describes measurement procedures for power curves. To determine a power curve, hub-height (HH) measurement of the free wind speed is required between 2 and 4 turbine diameters upwind of the turbine. The current version of the standard requires the use of a hub-height metmast. A new version of the standard is in preparation (IEC Standard 61400-12-1 CD). In addition to permitting the use of a ground-based lidar (light detection and ranging) when supplemented by a short metmast, the new standard will also introduce the concept of rotor equivalent (RE) wind speeds. RE wind speeds allow incorporation of vertically varying wind speeds over the height of the rotor disc, and evidence suggests [e.g. 2] that they are indeed a more reliable way of measuring large turbine performance, especially where wind conditions occur with significant vertical shear or veer. Because the free stream wind velocity is measured and air density corrections performed, this type of standards-driven measurement procedure can be termed an “absolute power curve”.

In contradistinction, relative power curves can use a broader range of measurement techniques and are useful for quantifying relative performance changes in a turbine’s performance. For example, they allow comparison of performance pre- and post- turbine maintenance or adjustment. In addition to nacelle-based instruments to be used, measurements can also be made inside the blade induction zone (< 2 rotor diameters). This can be advantageous in complex terrain, where wind flow evolution can mean that a more accurate measurement of the wind incident on the turbine can be measured at the shorter ranges.

2 Turbine-mounted lidars for power curve measurements

One way of measuring power curves is to use a turbine-mounted lidar. Over recent years, lidars have become increasingly accepted as an alternative to metmasts. If mounted on the nacelle of a turbine, they have the advantage of being able to measure and characterise the wind flow incident on the turbine, irrespective of the wind direction. Their costs are comparative or lower than hub-height metmasts, they require lower maintenance (typically every 2 years), can be deployed in under half a day and can be used both on- and off-shore with equal ease.

Depending on the type and model of the lidar used, a nacelle roof mounted lidar can measure a variety of wind field quantities around the rotor disk. These include hub height and rotor-averaged horizontal wind speeds, vertical shear exponents, wind yaw alignment relative to the turbine axis, wind veer (variation of wind direction with height), turbulent intensity (TI) and other turbulence measures, windfield complexity (its deviation from uniform flow) and, potentially, horizontal shear and inflow angle. Turbine wakes and the effects of complex terrain can also be visualised and measured.

3 Continuous wave (CW) lidars

CW lidars use a focussed beam of continuously emitted, invisible, near-infrared laser light. This light is backscattered off aerosols naturally present in the wind. The class of lidars described and used in this paper are the ZephIR models, designed and manufactured by Zephir Ltd. [3]. ZephIRs were the first lidars to be operated on wind turbines. In addition to nacelle mounting, these CW lidars can be deployed in the turbine's spinner [4] and experiments are underway using them as blade mounted lidars, for angle of attack optimisation [5].

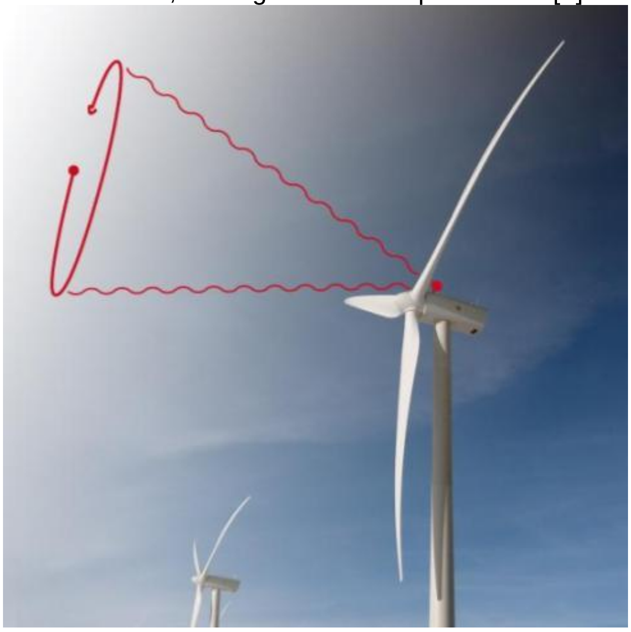

Figure 1 A circular scan lidar will always measure the wind flow incident on the rotor disk, irrespective of the wind direction.

As the wind (and the aerosols within it) are moving relative to the lidar, the backscattered light will be Doppler shifted. The extent of this Doppler frequency shift is directly proportional to the line-of-sight (LOS) wind speed, so by measuring the Doppler shift around the scan at any particular range, the LOS wind speeds at 50 points around the scan are known and can be used to determine wind information.

The operating range of these CW lidars is from 10 m to 300 m in front of the turbine. A circular scan is used to interrogate and measure wind speeds at 50 points around the circular scan at a specific range. At a scan rate of 1s per full scan, each LOS reading is measured in 20 milliseconds. Rapid refocusing of the laser allows LOS measurement at up to 10 ranges.

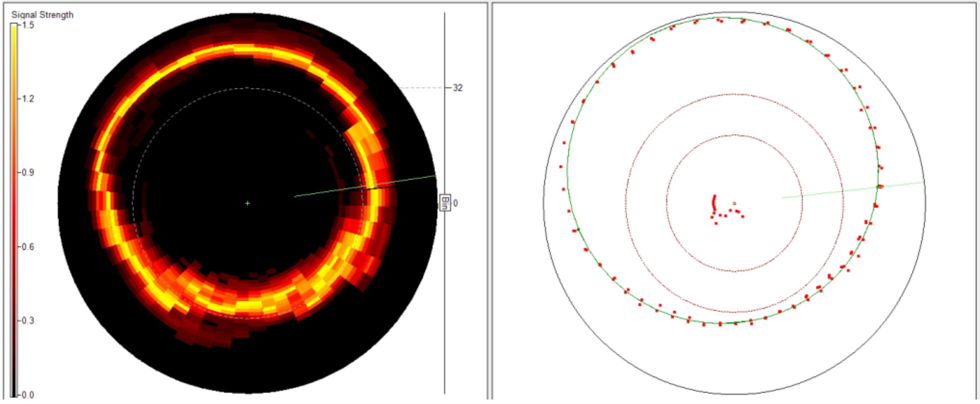

Figure 2. An example of real-time visualisation of data from a turbine-mounted ZephIR. Left: polar plot of raw data, showing line of sight Doppler shifts with scan angle. Radial axis is the LOS speed. The breadth and structure of plotted distribution gives an indication of the spatial turbulence within the scan volume e.g. ground induced turbulence can be seen in the lower range of angles. Low level wind jets and wakes from other turbines can also be detected in this manner. Right: centroids of the received line-of-sight Doppler shifts (red dots) and fitted wind parameters (indicated by the green closed curve). The central red dots are turbine blade returns and are filtered out automatically prior to fitting.

The advantages of CW lidar include high sensitivity (due to their high photon flux and coherency), and therefore the possibility of wind measurements in even very clear atmospheres. The 20 ms fast sample and integration time allows "snapshot" measurements, avoiding any adverse effects due to nacelle motion. Sensitivity is independent of the measurement range. Short ranges down to 10 m or below are possible, and these can be useful for exploring blade induction effects. Importantly, this type of scanning, CW lidaris Class 1 eye safe, so requires no special handling or safety procedures.

Pulsed lidars are an alternative type of system operating on different principles, and have their own merits, especially if ranges longer than 300 m are required.

Different algorithms can be used to extract various wind metrics from the time series of LOS measurements. The first one used in this paper uses a least squares fit (LSF) of the LOS measurements around the scan to determine the parameters of a wind model. Directly derived quantities include horizontal wind speed u, and the yaw alignment (or crosswind) relative to the lidar scan axis θ_w. Because LOS data is gathered around a near-vertical plane on the circular scan, it is also possible to measure the wind shear exponent α. Secondary outputs include TI and a quantification of the measured wind flow's complexity (i.e. its deviation from the wind model used in the LSF). By combining measurement from more than one range Kapp [6] has described a technique of extracting wind flow and disambiguating horizontal shear from wind yaw, although this remains a research topic at the moment. An additional benefit of the LSF approach is the high measurement quality that results from combining many data points around the scan and the data redundancy this allows. High data availability, irrespective of turbine blade obscuration of the beam, is also achieved. Various data filters are implemented to detect blade blockages and returns, and the LOS signals due to them and other non-wind objects are easy to detect and remove, prior to the LOS fitting process.

The second algorithm uses pairs of measurements from opposite sides of the scan. This pairwise algorithm does not directly extract vertical shear information, but by performing pairwise calculations at different heights across the disk, both wind shear exponent and wind veer can be measured.

Both algorithms allow calculation of hub height or rotor equivalent wind quantities.

4 The measurement campaign

The data presented in this paper is predominantly from a turbine-mounted lidar trial. The main aim of the trial was to demonstrate and quantify turbine performance improvements after turbine tuning, explore the benefits of using turbine-mounted lidar for this, and refine practical aspects of the lidar design.

Lidar data was gathered on a 2 MW, 72 m rotor diameter NEG-Micon turbine. The turbine contained 2 electrical generators: a low speed (2.5 to 5 ms^{-1} wind speed) 500 kW generator and the main 2 MW generator (~ 5 ms^{-1} to 25 ms^{-1}). The turbine was part of an on-shore wind farm in flat terrain in Eastern Jutland. A ZephIR 300 lidar was positioned on the nacelle roof of the turbine. The ZephIR was mounted in a frame such that its scan axis was horizontal and parallel to the main turbine axis. The cone half angle of the circular scan of the ZephIR was 30º. Scan ranges (measured along the scan axis) were set to be 180 m (corresponding to 2.5 rotor diameters), 100 m, 50 m, 30 m and 10 m. The ZephIR recorded raw spectral data (i.e. the Doppler spectrum of each LOS reading around the scan), unaveraged wind data and 10 minute averaged wind data internally, and was also networked. In addition to turbine SCADA data being logged during the trial, a pulsed laser system and a hub-mounted sonic anemometer were also used for comparative purposes. Atmospheric data (temperatures, pressures, humidity) was recorded from the ZephIR's metstation and other sources.

The trial was organised and run by ROMO Wind [7]. The trial was split into two parts: the first part ran from 03 January 2012 to 15 March. During this part of the trial, the performance of the turbine was measured prior to any performance adjustment. The second part of the trial, post turbine optimisation, ran from 15th March to 5th April 2012. Lidar and turbine data were recorded throughout the trial.

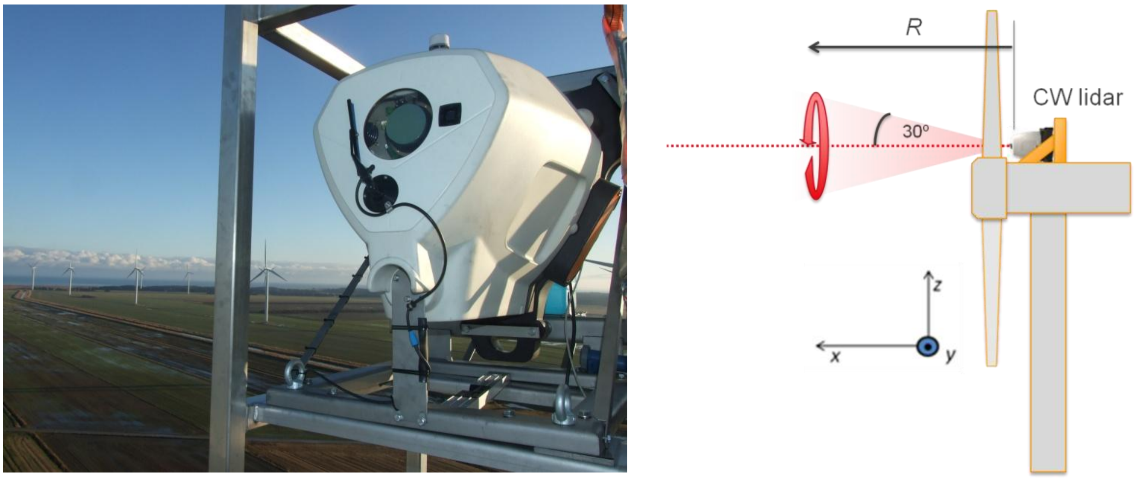

Figure 3. Left: ZephIR 300 mounted on the nacelle roof of the 2 MW turbine. Right: scan geometry chosen

5 Some results from the campaign

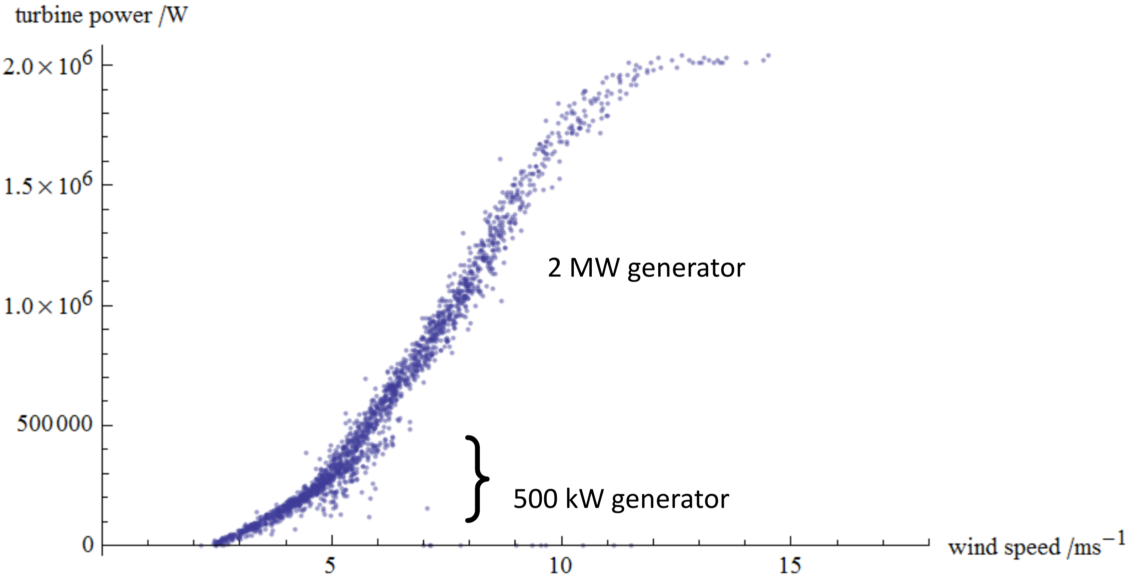

Figure 4. Scatter plot of unfiltered data. Lidar operating range R of 10 m. The influence of the two generators within the turbine can be clearly seen.

5.1 Yaw alignment

During the first part of the trial, the ZephIR's wind yaw measurements immediately indicated a consistent 14° to 16° yaw misalignment between the rotor axis and the incoming wind direction. On the 15th March, the turbine was shut down and the turbine wind vane realigned, based on the data gathered by the ZephIR and other instruments. On restarting the turbine, an immediate improvement in the turbine's yaw alignment was measured. Figure 5 shows the yaw misalignment throughout the trial, as measured by the ZephIR. The same figure also shows the hub height power curves measured using the ZephIR for the first and second parts of the trial. A significant improvement in the turbine power curve is evident. ROMO Wind estimated that the yaw correction resulted in an estimated AEP (annual energy production) increase of 5%. These power curves, and all the power curves subsequently shown in this paper, were for hub height wind speed, and calculated using the procedures described in IEC 61400-12-1, including correction for air density effects.

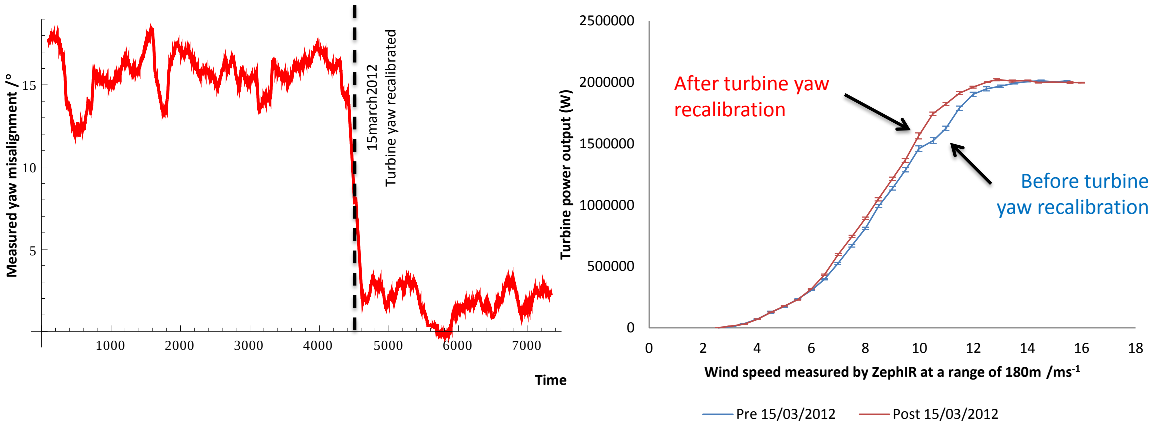

Figure 5. Left: turbine yaw misalignment measured by the ZephIR during the trial. Right: power curves pre and post yaw recalibration. The error bars are standard uncertainty. All power curves in this paper are hub height (HH), and corrected for air density, as specified in IEC 61400-12-1

5.2 Atmospheric stability

It is well documented [e.g. 7] that atmospheric stability can have an important influence on measured hub height power curves. Although there are some conflicting measurements in the literature, stable atmospheres, corresponding to high vertical wind shear and low TI, produce generally lower performance power curves than unstable atmosphere, characterised by low vertical wind shear and high TI. For a given average wind speed, there is more energy available in a wind with high TI. The measurements taken from the ZephIR also indicate this. Figure 6 shows power curves calculated from recorded turbine power outputs and ZephIR measured wind quantities for low and high wind shear, and low and high TI. The mean of the shear exponent and TI measurements were used to filter for low and high shear and TI.

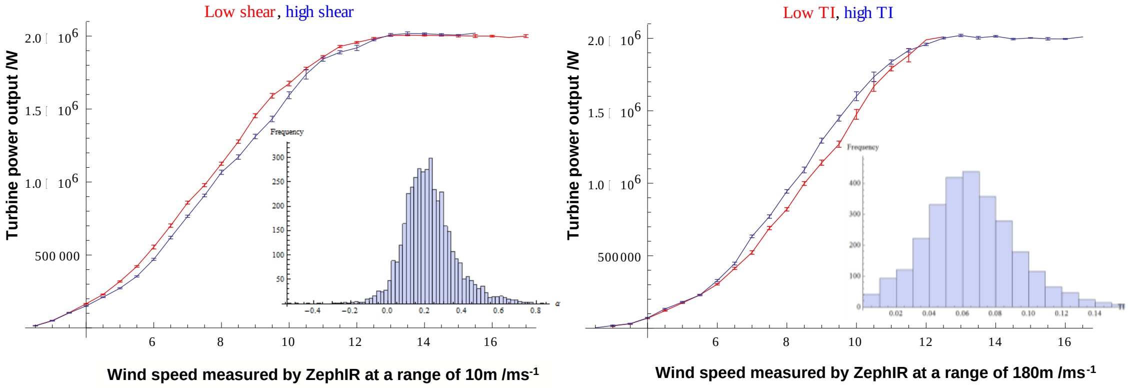

Figure 6. Atmospheric stability effects on measured hub height power curves. Left: influence of vertical shear. Right: influence of TI. Data from the post-turbine wind vane recalibration part of the trial.

More sophisticated power curve calculation techniques, using rotor-equivalent wind speeds, taking into account the variation of wind speed and direction across the rotor disk, can be expected to be less strongly affected by atmospheric conditions [2]. The ZephIR lidar's wind measurement methodology, being based on a full circular scan around the rotor disk, is capable of supplying data for calculation of rotor equivalent windspeeds. Data from the ROMO Wind trial is currently being reanalysed to allow rotor-equivalent-based power curves to be calculated, including the effects of veer.

5.3 Investigation of blade induction effects.

Blade induction effects manifest themselves as a slowing of the wind as it approaches the turbine [9]. The ZephIR lidar was used to investigate these effects during the trial. The wind speeds from the second part of the trial, at the various scan ranges used, are shown in figure 7

As expected, the results confirm that the wind slows significantly as it approaches the turbine, in a monotonic fashion. Comparatively little slowing of the wind is observed at > 100 m (~1.5 D).

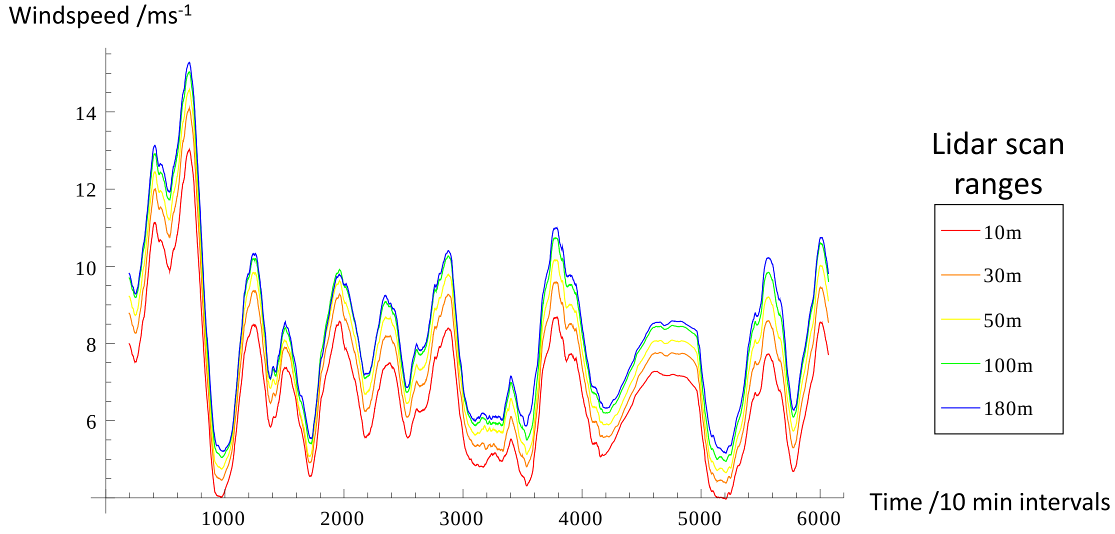

Figure 7. Lidar measured wind speeds, showing monotonic decrease of the windspeed as it approaches the turbine.

Power curve scatter plots are shown in subsequent figures and show the influence of blade induction. There is scope for further scientific analysis of these effects from the data measured by the ZephIR. These measurements are believed to be the first of their kind reported in the open literature, and would be difficult to perform by methods other than the one employed here.

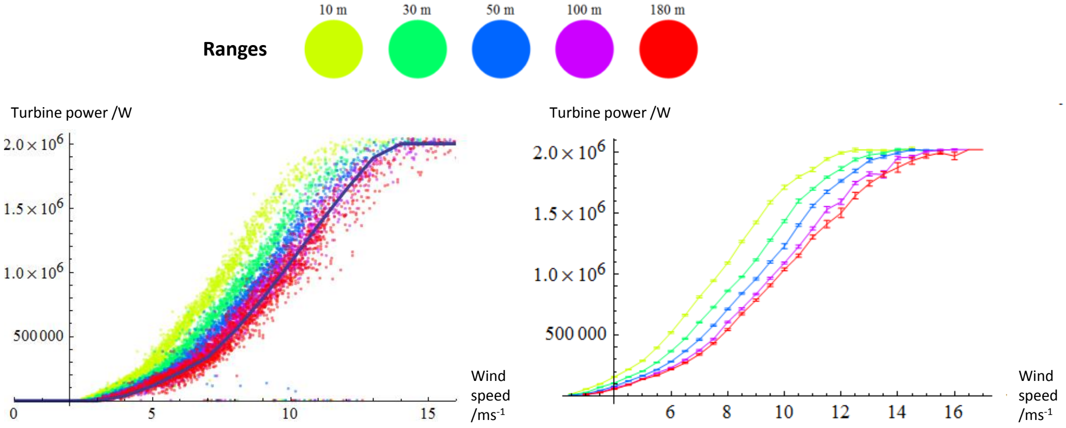

Figure 8. Left: unfiltered multi-range scatter plots, with turbine manufacturer's power curve. Right: binned power curves from a nacelle-mounted ZephIR. 25 days data, post turbine wind vane recalibration. Note the monotonic trends with upwind range.

6 Practical considerations for turbine-mounted lidars

In addition to data gathering, the measurement campaign served to highlight practical aspects of turbine-mounted lidar deployment. Important considerations include minimising mass and size of the lidar and its frame to allow 2 man deployment, permit the use of the turbine's internal crane for hoisting and facilitate easy passage through internal turbine spaces and hatches.

Safety is paramount in nacelle roof deployments of equipment. So another important consideration is the installation procedure, in particular, careful tethering of all loose parts as they are assembled on the roof. An adaptable mounting frame, capable of correctly levelling the lidar on a variety of flat, sloping and curved nacelle roofs, is also a requirement.

Correct alignment of the lidar during installation, in pitch and roll, but also in scan axis direction, is vital. The former can be facilitated by both mechanical reference surfaces on the lidar and calibrated, real time electronic levels within the unit itself, as well as a visible laser projection system to align the scan axis with that of the turbine axis. The latter is important if accurate turbine yaw measurements are required. The real time electronic levels can be used to log inclination and roll during data gathering. Incorporated properly into the lidar's algorithms, they ensure that hub height and rotor-equivalent wind speed measurements are correctly calculated, irrespective of turbine roll and pitch. For example, the current IEC standard specifies measured hub height wind speed must be ±2.5 % of hub height. The new draft standard requires measurements at ±1 % of hub height. At 300 m range, a change in the nacelle inclination of just 0.1° corresponds to a height change of 0.5 m. A new, turbine optimised, ZephIR DM (dual mode) has been produced, designed as a result of these requirements (figure 9).

Figure 9. Left: new dual mode ZephIR lidar. Right: undergoing final trials in Denmark.

7 Conclusions

Some of the benefits of nacelle-mounted lidar for power curve measurement have been discussed. A ZephIR CW, scanning lidar was used to help identify performance deficits in a 2 MW turbine, specifically identifying a persistent wind yaw misalignment of 14° to 16° due to incorrect calibration of the turbine's wind vane. Hub height power curves were generated from data before and after the wind vane recalibration and used to help estimate an AEP improvement of 5%. Wind shear and TI were also measured by the lidar and shown to have a significant effect on hub height power curves. The capabilities of this type of lidar to measure rotor equivalent wind speeds will become increasingly important with increasing rotor diameter, as the effects of TI, shear and veer can be incorporated in the energy flux measurement. Blade induction was also quantified, at ranges from 2.5 to 0.14 rotor diameters. These are believed to be the first lidar measurements of close-in blade induction effects.

Power curve measurements are an application that is addressable by lidar technology now. However, longer term developments of lidar technology will address the use of lidars integrated into the turbine control loop. Several studies have identified the benefits of this. A recent one [10] quantifies some of the turbine load reductions, especially fatigue load reductions, that can be accrued by a circular scanned lidar giving a few seconds of lookahead time. Experimental verification of the design configurations and benefits of lidar controlled turbines is underway.

Acknowledgements

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