Measuring wind farm 'fuel' efficiency

Can you name any other energy plant that you build, operate and try to understand if it's performing efficiently, without actually measuring the fuel that you're supplying? A wind farm is often exactly that.

According to a recent 'A Word About Wind' study, almost 50% of those surveyed placed the validation of their production plant as the Number One priority for them – and currently almost half the interviewed were not confident in what's actually happening with their asset at any given time.

Until recent years the cost and complexity of measuring with met masts across a wind farm has made this measure of wind farm 'fuel', i.e. the wind, impractical. Nacelle or spinner anemometry is given the challenging job of trying to do its best whilst measuring wind behind, or close the rotor and the disturbed air flow. Add to that site complexity, wakes and turbine array effects… it has meant that estimations of wind speed based on rotor speed, power generation or forecasting are often the only choice.

In contrast, Nacelle Based Lidars remotely and precisely measure the wind ahead of a turbine and provide meaningful validations of how wind turbines and wind farms are performing providing information for asset optimisation. In wind farm development Ground Based Lidars have replaced the need for met masts as, according to a recent study by renewable energy company RES, they are 'safer, cheaper, faster and better'.

However, with respect to on-turbine measurements the more advanced Nacelle Based Lidars do something that has never realistically been achievable before: assess the entire wind field approaching the turbine, across the whole rotor from bottom tip, through hub height and to top tip. This wealth of data is enabling the industry to go beyond existing practice, and indeed IEC standards, creating new wind measurement baselines and allowing innovative operational strategies. And also, for wind turbine OEMs to broaden further their own understanding of new turbine design performance.

What is a wind Lidar?

The principles of Ground Based Lidars are well known and widely published and are summarised in Figure 1.

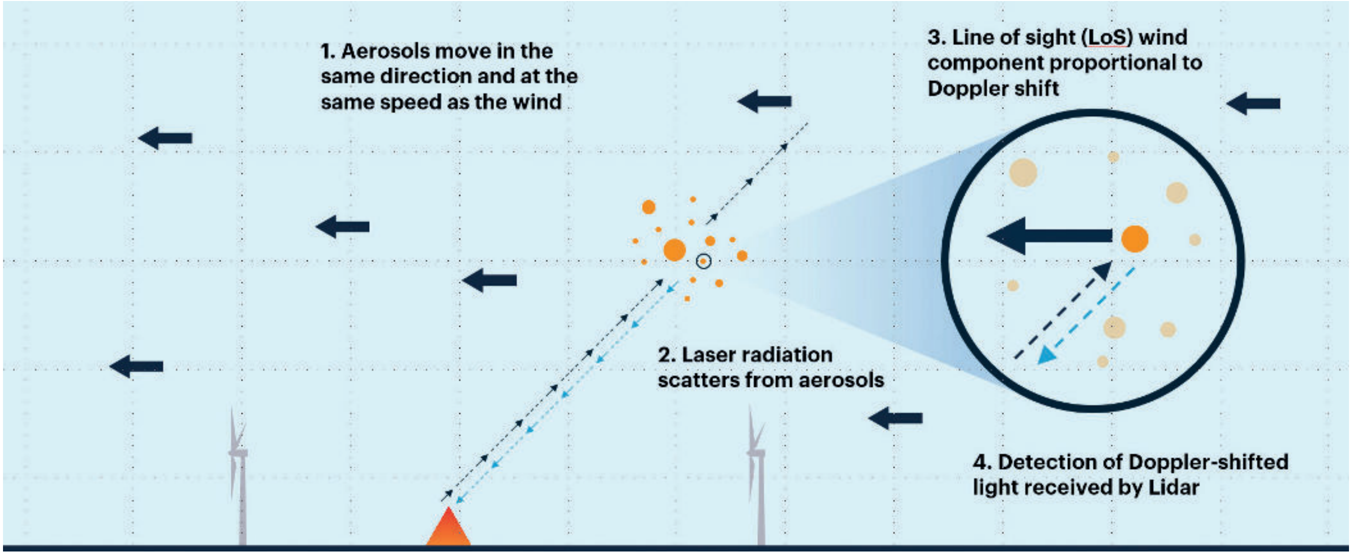

Figure 1: Ground Based Lidar principles of measurement

A Nacelle Based Lidar is the same, but measures horizontally from its installed location on the nacelle roof (or alterative mounting location) of a wind turbine as shown in Figure 2.

Wind is measured remotely from close ranges at just 10 metres out to ranges beyond 550m. This ensures the nominal 2.5 Rotor Diameter measurement can be achieved in accordance with IEC 61400-12 Ed. 2 for Power Performance Tests on the most recently launched and largest turbines offshore including the GE Haliade-X 12 MW, the MVOW V174-9.5 MW and the SGRE 14-222 DD.

Wind can and should be characterised according to:

- Wind speed - Hub height and rotor equivalent (REWS), and at multiple heights over the rotor disk
- Vertical shear - Power law shear exponent, as well as determining arbitrary shear profiles (anomalous shears, low level jets etc)
- Wind yaw misalignment and veer profiles (change in wind direction with height) at multiple heights over the rotor disk
- Various turbulence measures, including TI
- Flow complexity measures

In addition, a locally-mounted Lidar met station provides pressure, temperature, humidity, GPS location, direction while raining frequency and rotor axis alignment to within 0.2 degree accuracy is also determined by on-board Lidar processing.

More advanced, modern Nacelle Based Lidars use a circular scan to deliver up to 50 data points at each measurement range of interest – a wind measurement every 20 ms. This high definition view of the upwind conditions allows several use cases to be realised from a single Lidar system including:

- a '2 beam' mode, used in some legacy Power Performance Test procedures to measure hub height wind speed and direction. Because the density of measurement points is so high, there are always direct readings at hub height, as required by IEC 61400-12 Ed. 2
- a '4 beam' mode, which emulates the measurements taken by some wind Lidars that only provide a pillar-box view of the wind ahead. Unfortunately, a fixed and narrow pillar-box size becomes increasingly restrictive as rotors increase in diameter – a progressively large blind spot is developed
- a 'full rotor' mode, which allows up to 13 slices or 26 'beams' to quantify the wind field more fully and is often deployed to overcome the blind spots of a 4-beam mode of operation. Vertical sheer and veer over the full rotor disk are determined and allow super-accurate determination of rotor equivalent wind speed (REWS) as described in IEC 61400-12 Ed. 2 and 50-3. Rotor equivalent wind speed becomes particularly significant as rotor sizes on modern turbines gain in size. With such large rotors, veer and shear profiles can have a significant impact on accurate turbine performance determination

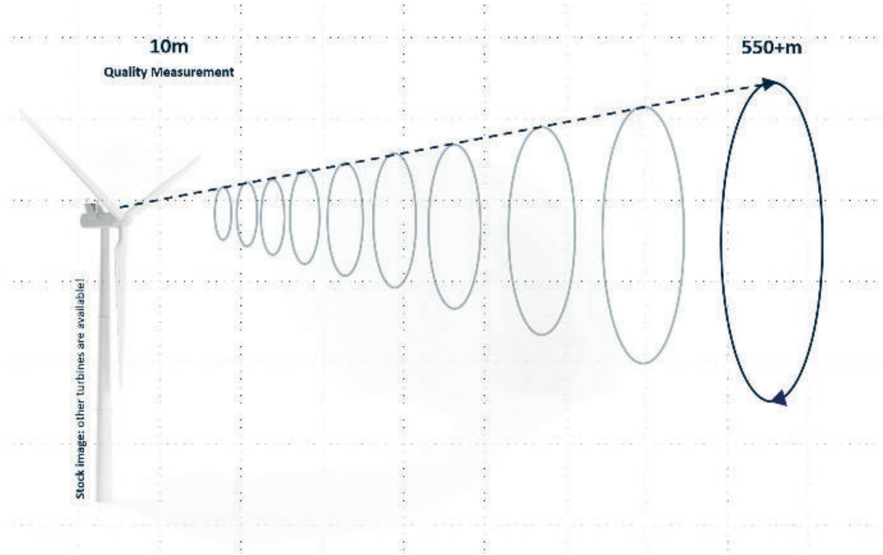

Figure 2: Nacelle Based Lidar scan pattern

In addition to these useful measurement parameters, a further advantage unique to the circular scan is the ability to detect complex flow caused by wakes and terrain. Each mode of operation is illustrated in Figure 3.

The ability to measure complex flow allows for circular scanning Nacelle Based Lidars to be used in complex terrain onshore where power performance measurements can be undertaken accurately and more rapidly as the Lidar intrinsically recognises clean sectors for inclusion within the turbine test. Category A uncertainties are significantly reduced using this approach. Similarly, any turbine experiencing waked conditions will be identified by the Lidar allowing Annual Energy Production losses to be quantified and curtailment strategies to be implemented.

Use cases

With the ability of Nacelle Based Lidars explained above and useful features identified when considering what type of

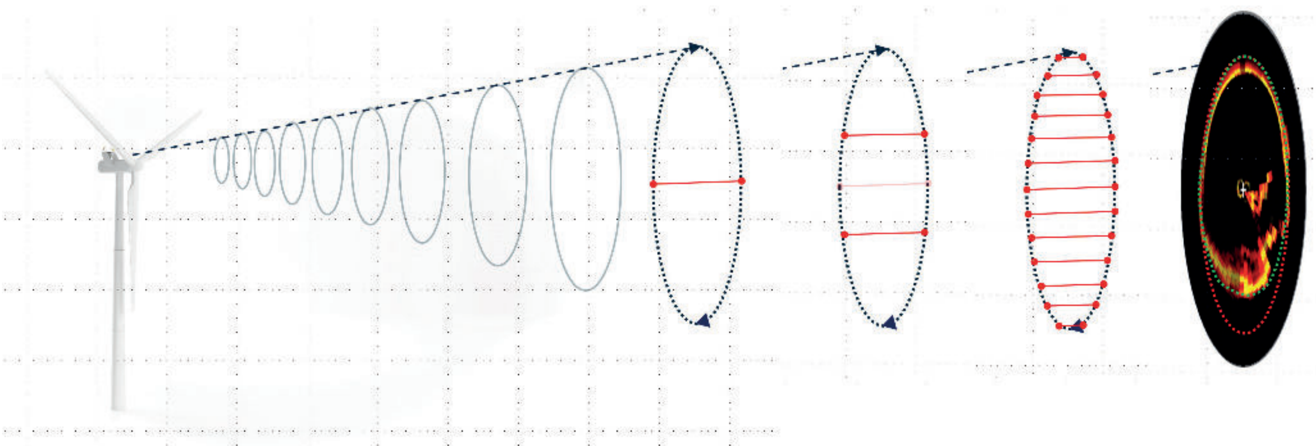

Figure 3: Nacelle Based Lidar modes of operation: 2-beam, 4-beam, 13-slice and full rotor scan (Left to Right)

Lidar to use, the context of validating turbine performance and optimising either wind turbine or wind farm configurations can be explored. These Use Cases are defined as simple click-to-select Applications in some Lidar systems.

Operational power curve measurements & power performance testing

The Nacelle Based Lidar should be configured to measure ~2.5D ahead of the turbine, or the Absolute Power Curve or Relative Power Curve Application should be selected and an ability to use both Hub Height and REWS is useful in the case of suspected performance deviations in a turbine. Often changes in wind conditions above and below Hub Height may be the root cause of any positive or negative impact on turbine production and would be otherwise overlooked when considering only a Hub Height or narrow pillar-box view of the upwind conditions.

Clean sectors are identified using the complex flow parameter removing any impact of terrain or wakes.

Warranted power curves are then compared to the Lidar wind measurement generated power curves and any deviations noted for further investigation as shown in Figure 4.

There are examples of over and under performance in turbines, but generally nacelle anemometry may be inaccurate due to its mounting, which is close to the disturbed flow from the rotor, or due to calibration of the Nacelle Transfer Function that can be non-optimal for the actual site conditions experienced. The more accurate Lidar generated power curve allows for more targeted analysis.

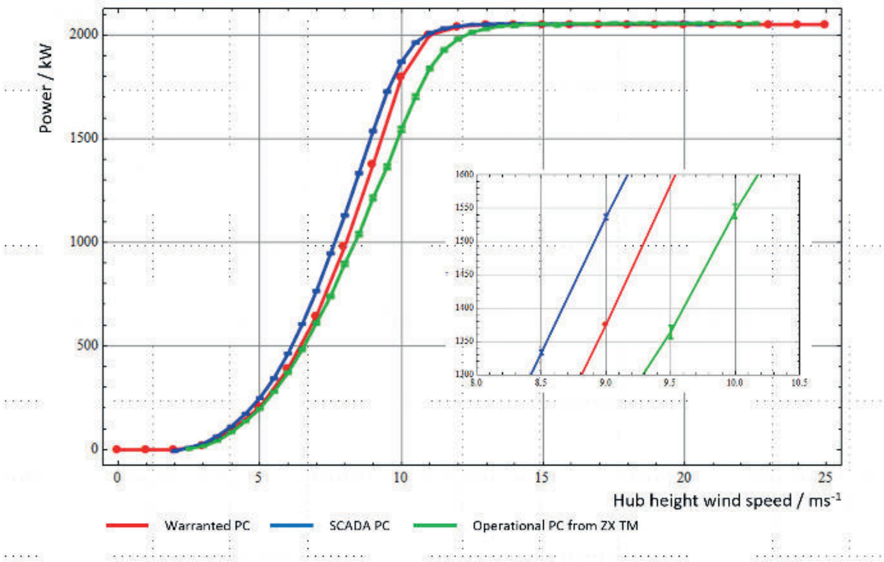

Figure 4: Comparison of warranted, operational and SCADA-based power curves identifying SCADA over estimation and turbine underperformance. Error bars show the Category A standard uncertainties. ZX TM is an advanced Nacelle Based Lidar.

Measurement of the power curve ahead of a project sale can also support recalculation of the Post Construction Yield Analysis and add value to the Net Present Value of the wind farm at the point of any project transaction.

In time, IEC 61400-50-3 will recognise the use of Nacelle Based Lidar for wind measurements and will be supported by the already significant evidence from enforced Turbine Supply Agreements that have utilised Nacelle Based Lidars for the contractual power performance measurements.

Once a baseline of actual turbine performance has been undertaken and areas of over or under performance vs. real world wind conditions identified, a series of Application Modes, accessed on the Lidar, assist users in optimising turbine or even wind farm operation.

Turbine yaw misalignment

A turbine yaw misalignment to the oncoming wind can lead to sub-optimal performance and increased loads. Nacelle Based Lidars are used to measure this misalignment so it can be corrected, allowing the turbine to convert all available energy from the wind and limit the loads experienced during energy to power conversion. Using 50 measurements around the Lidar scan derives the most robust yaw misalignment measurement, a standard output from circular scanning Lidars.

A 95% confidence interval delivering < 0.4 degree of any yaw misalignment can be achieved typically within 15-20 days of operation. Alignment of the Lidar to rotor is important (direction of wind is relative to Lidar orientation) and more advanced systems use feedback from the rotor to confirm this to precision accuracy.

The loss of production is calculated at between cos^2 and cos^3 of the misalignment. The example shown in Figure 5 identifies a 6.4 degrees yaw misalignment equating to ~1.5% AEP loss and this can be corrected by inputting an offset in the turbine controller if access is available, or by rotating the nacelle wind direction sensor.

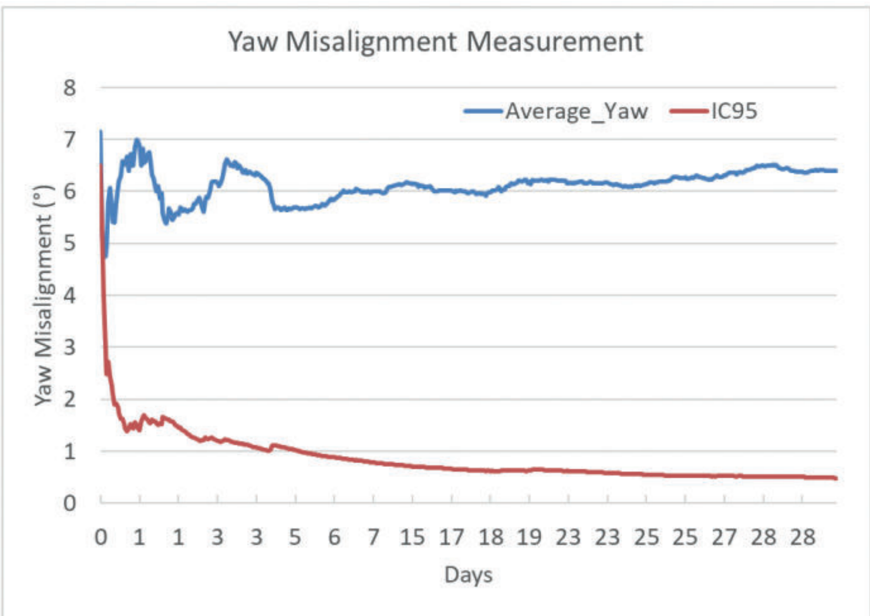

Figure 5: Example of a Lidar measured wind yaw misalignment

The misalignment is removed and the power curve improvement is confirmed via the Lidar. Misalignments are often wind speed dependent also as shown in Figure 6 and where possible an adaptive controller solution should be implemented.

It is important to note that Lidars measure the wind yaw misalignment relative to the Lidar axis. If the Lidar is installed poorly, the Lidar axis itself can be misaligned with the rotor axis. To mitigate this source of uncertainty, circular scan Lidars have the ability to continually measure Lidar to rotor misalignment, thereby removing that potential source of error.

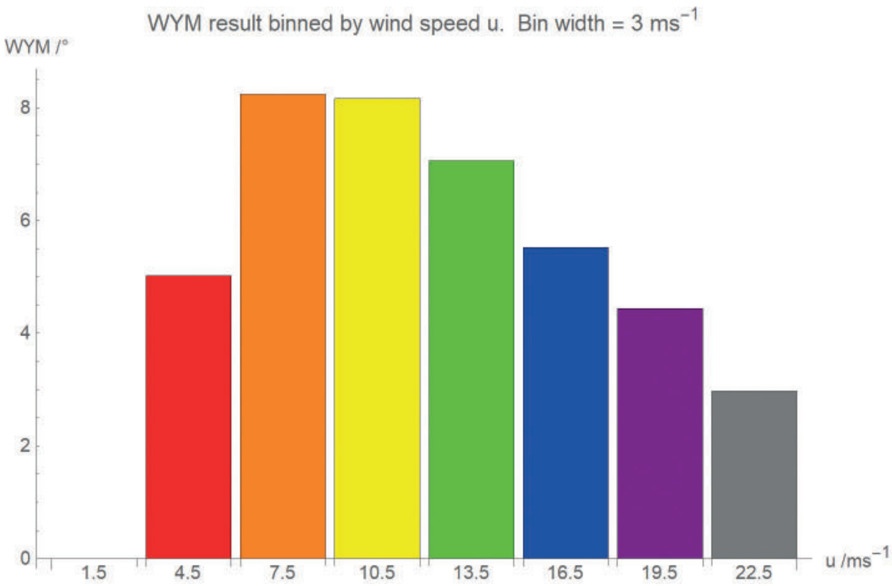

Figure 6: Wind yaw misalignment as a function of wind speed at 0-3m/s, 3-6m/s, 6-9m/s etc. (Left to Right)

Wake detection and complex flow

Wakes from neighbouring turbines, or complex flow caused by terrain may impact turbine performance and are challenging to identify. While some Lidars measurements can be adversely affected by the presence of wakes, e.g. identifying the phenomena as being yaw misalignment, a circular scanning Lidar provides a complex flow parameter to identify such conditions.

Through the identification of such events as shown in Figure 7, power curves can be generated to calculate energy losses from individual turbines that are subject to wake effects and sectors identified to pinpoint the origination of the wake. A wind sector management strategy can be defined to manage wakes across a site to allow for increased site production where possible.

The area of wind turbine and wind farm optimisation is a complex one but offers the potential benefits that justify exploration in the methods described above. Appropriate choice of Lidar with the right measurement capabilities and an appropriate user interface will help but collaboration is paramount. The inclusion of Wind Turbine OEMs, Engineering Consultants and Lidar OEMs in any such project can ensure the optimal outcome.

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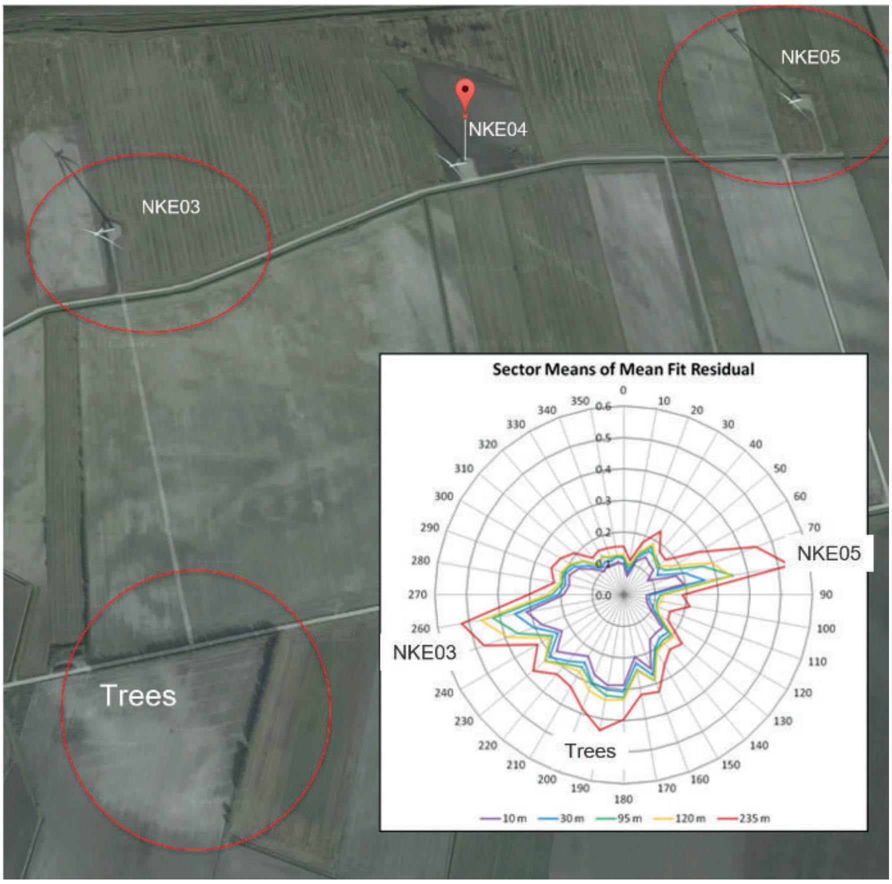

Figure 7: Example of Nacelle Based Lidar on turbine NKE04 detecting complex flow from turbine wakes and terrain (trees)

Some common questions on the use of nacelle based lidars

How do you ensure the alignment between the Lidar and the nacelle?

What is total uncertainty of the Lidar measurement?

What is the accuracy of data?

Is a Ground Based Lidar more accurate as compared to Nacelle Based Lidar?

Is there something like maintenance needed for the Lidar during the measurement campaign? or just mounting and dismantling? (and analysing the data of course).

Can you perform non-contractual power curve tests with nacelle-Lidar in complex terrain?

These questions, and more, are answered alongside a 1hr webinar on the topic available here:

https://www.zxLidars.com/ul-and-zx-Lidars-place-industry-focus-on-wind-farm-performance-validation/