can the wind industry bank on wind lidar?

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This article is sponsored by: ZephIR Lidar

What does that mean? ZephIR Lidar promotes advancement in wind measurement technologies to the wind energy industry. There are a number of solutions with Lidar, and ZephIR Lidar being only one. This article does not seek to compare or contrast solutions, and acts only as an advocate of any solution that offers the opportunity for advantages over current methodologies.

introduction

01 Can you use wind lidar to provide quantitative data for the annual energy prediction (P50, P75 and P90) of a modern scale wind farm, allowing developers to raise the necessary finance to progress and construct full-scale developments? Since the introduction of wind lidar in 2003 for wind measurements within the wind energy industry this ultimate question has always been raised.

Why is this question so important? In order to take advantage of the many benefits remote wind sensors offer to the wind industry, use of a system becomes even more cost-effective when it can be used in isolation of any other sensor.

However, to achieve acceptance of stand-alone operation within the industry (that is, without the use of traditional mast mounted cup anemometers), key technical acceptance criteria have to be met and a body of evidence provided to demonstrate performance against these milestones.

why does the industry seek to improve wind measurements?

02 In order to address this question we need to look first at the motivations behind a wind measurement campaign and the resulting outputs of a wind resource assessment process, as outlined below.

A wind resource assessment programme is primarily required for the following reasons:

- To determine the long-term wind resource and flow characteristics across the project site so that wind turbine siting, specification and suitability studies can be performed
- To determine the long-term wind resource so that accurate annual and life-time energy yield predictions can be made, including an assessment of the uncertainty in such calculations, accounting for all sources of data collection and modelling errors and also the inherent variability in the wind resource on differing temporal scales

The typical steps in such a process are:

1. On-site wind speed data collection
2. Correlation of short-term wind data with a suitable long-term reference source in order to determine a long-term wind climate
3. Flow modelling from the point of data collection across the extent of the wind farm site, to consider variations in wind resource due to changes in elevation, topography and land cover
4. Consideration of the changes in wind climate due to height above ground level (wind shear)
5. Calculation of the gross yield of the wind farm, accounting for specific wind turbine performance
6. Consideration of losses, including wake, system losses & availability, and turbine performance

The principle outputs of a wind resource assessment campaign are therefore:

- Site design wind conditions (gust wind speeds, vertical shear values, turbulence values)
- Net Annual Energy Predictions (AEP) – P50
- Energy production uncertainty analysis for different probability levels and timescales, for example:

  - P90 10 year
  - P90 1 year

The industry routinely compares the measured energy yield of constructed wind farms with energy yield prediction from the pre-construction analysis based on the measured wind speeds, using the method described above. This feedback cycle for such a comparison is of the order of 5 years from the point of on-site wind resource measurement.

Results from these comparisons show a general over-estimate in pre-construction energy yield predictions. Typical results from consultants have recently been published showing approximately 10% over-estimation reducing to 7% over-estimation after availability and windiness normalisation.

A number of items have therefore been highlighted that may contribute to this over-estimation:

- Poor wind measurement strategy:

  i) Measurement below hub-height due to increasing cost to go higher, H&S increased risk, and structures distorting wind flow when larger ii) data at higher heights is extrapolated iii) measurement at single / minimal location(s)

- Lack of sufficient 'real' data points to reduce the uncertainty of flow models
- Use of unsuitable flow models for site flow environment (i.e. presence of complex terrain and forestry)
- Poor wind measurement quality; anemometer type/calibration, mounting/maintenance issues
- Poor performance of turbine wake models
- Use of unrepresentative reference data
- Power curves based on hub-height only rather than full rotor measurements

guidelines for improving and delivering more accurate annual energy predictions

03 A number of the key items in the previous section are directly linked to limitations posed by traditional anemometry where, as a general rule, the taller the structure holding the anemometry sensors, the greater the economic, logistical and planning / permitting investment required.

With the ever-increasing hub height of wind turbines and also the size of their rotor diameters, particularly in offshore applications, coupled with the limitations highlighted in the pre- and post- energy calculation review, it is a logical evolution for an industry focused on reducing risk to embrace an alternative measurement methodology – remote sensing.

Remote sensing is the acquisition of information about an object or phenomenon without making physical contact with the object. In contrast to conventional cup anemometry, which infer a wind speed by way of counting rotations of a calibrated rotor, remote sensing devices derive a wind speed that directly measures the fluid flow. In relation to the wind industry two forms of remote sensing technologies are available commercially:

- Sodar (Sonic Detection and Ranging) using sound waves, and
- Lidar (Light Detection and Ranging) using light waves

Both techniques generally employ the Doppler effect to detect the movement of air in the Atmospheric Boundary Layer (ABL) and infer wind speed and direction:

In the case of Lidar, electromagnetic radiation (light) is reflected off particles, whereas with Sodar an audible pulse of sound is reflected off the varying temperature structures in the atmosphere.

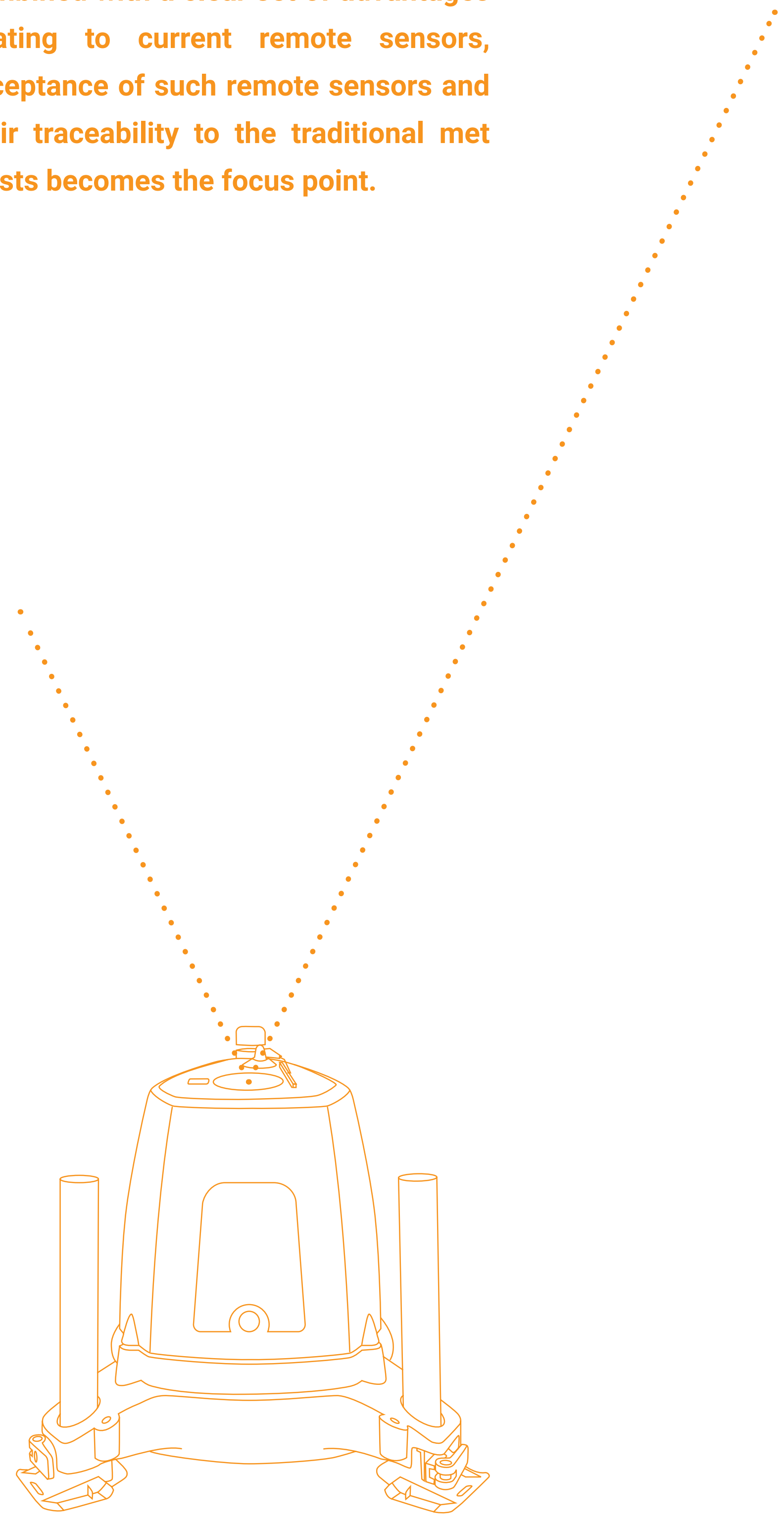
Remote sensing in principle delivers many benefits above and beyond traditional anemometry including:

Measurements at hub height (and above): Wind data can be captured across the entire turbine rotor confirming hub-height resource as well as wind shear and turbulence across the rotor. Shear extrapolation bias and uncertainty is therefore greatly reduced.

Combination with advanced flow models that correctly account for forestry & topography: Advanced flow models provide significantly improved horizontal and vertical extrapolation of measured wind resource, especially in complex and forested terrain. Flow model accuracy is improved through the use of multiple spatially separated measurement points on the site for model verification and tuning.

Measurements at multiple points, especially on a complex site: Remote sensors are re-useable, portable and do not require lengthy planning applications before installation. Data can be collected easily at multiple points on a site to provide representative measured data for all turbine locations and tuning/verification points for flow models.

With a clear set of disadvantages relating to traditional measurement methodologies using tall met masts, combined with a clear set of advantages relating to current remote sensors, acceptance of such remote sensors and their traceability to the traditional met masts becomes the focus point.



traceability & accuracy

04 Cup anemometers have been the industry standard for measuring wind speed at wind farm sites and therefore are considered to be the incumbent technology against which any alternative measurement approaches must be judged.

The current foundation of any remote sensing device accuracy is therefore demonstrated by being equal to traditional meteorological masts and cup anemometry across a range of applications, described later in this report. A number of independent wind engineering and certification organisations now provide specific offerings to validate a remote sensing device at a number of IEC 61400-12-1 (Power Performance Measurements of Electricity Producing Wind Turbines) compliant met mast sites globally. These include but are not limited to:

- Carrot Moor Test Facility, UK
- UK Remote Sensing Test Site, UK
- Test Site Lelystad, the Netherlands
- Hovsore and Osterild Test Sites, Denmark
- Schleswig-Holstein Test Site, Germany
- LIDAR-Test Field Georgsfeld, Germany

The largest batch of single device verifications to date have been performed on ZephIR 300 units in more than 170 separate campaigns, using an industry accepted process. The lidar performance is validated against a 91.5m met mast at the UK's Remote Sensing Test Site consisting of a meteorological mast constructed to conform with the recommendations for mast anemometry in IEC 61400-12-1, which has been approved for use by technical and engineering services providers including Natural Power and DNV-GL.

The terrain in the vicinity of the mast is flat and covered with sparse low-growing vegetation, and is therefore of low flow complexity. On a wider scale the site is surrounded by flat arable land that is devoid of any dense closed-canopy forest. The site meets the IEC requirements for maximum terrain variation in all sectors.

Wind speed comparisons are carried out from ground-based ZephIR units, operating in their standard mode with the conical scan aligned vertically, at 4 heights: 91m, 70m, 45m and 20m. The units are located between 3m and 8m from the base of the mast.

Each test consists of a cross-correlation of 10-minute averaged wind speeds at each measurement height over a period of 2 to 3 weeks. The results from the 170 verifications undertaken in a recent production batch are summarised below for wind speed and turbulence:

Combined results from >170 ZephIR 300 performance verifications
Horizontal Wind Speed

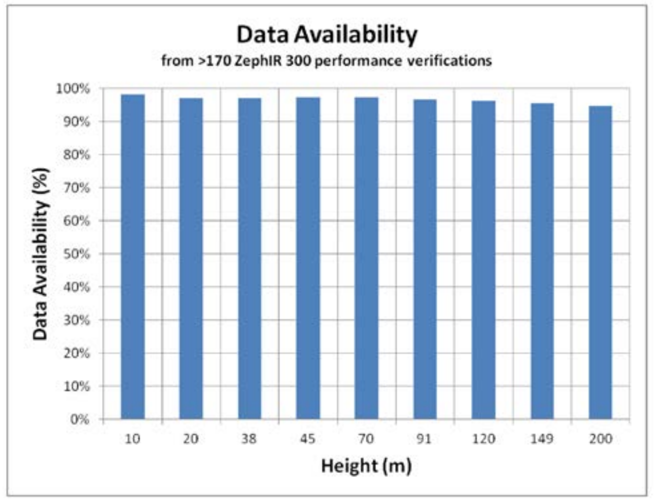
Height (m)	Gradient		R^2		Avail (%)	
	Mean	Std	Mean	Std	Mean	Std
91	1.004	0.007	0.988	0.007	96.66	2.61
70	1.002	0.005	0.991	0.008	97.20	2.22
45	1.002	0.004	0.991	0.006	97.37	2.10
20	0.999	0.005	0.992	0.005	97.15	2.66

Combined results from >170 ZephIR 300 performance verifications
TI

Height (m)	Gradient		R^2	
	Mean	Std	Mean	Std
91	0	0	0	0
70	1.036	0.050	0.731	0.105
45	1.011	0.037	0.756	0.092
20	1.005	0.021	0.753	0.094

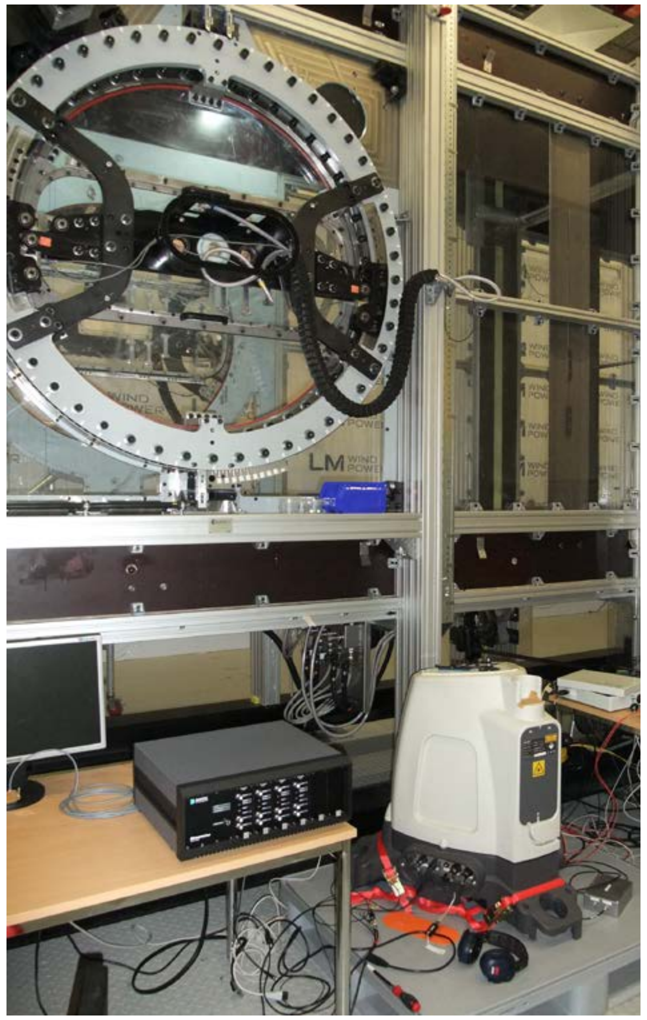
(91m instrumentation on the met mast does not provide TI data and therefore is ignored in the above table).

The results shown are not filtered beyond the standard device data output and practices used for remote sensing devices. The data availability across the batch of 170 verifications identifies high availability across all heights up to 200 metres with no significant change in performance:



In a further verification of absolute lidar performance, a modified ZephIR 300 was tested against a calibrated wind tunnel as part of a Danish National Advanced Technology Foundation (DNATF) project with Denmark's National Laboratory for Sustainable Energy, DTU Wind Energy (formerly Risø), LM Wind Power (global manufacturer of wind turbines blades) and optical and laser solutions provider, NKT Photonics.

ZephIR 300 was deployed in LM Windpower's wind tunnel in Denmark and successfully measured wind speeds from 5 m/s to 75 m/s with an averaged difference of just 0.4% for a sustained period of time and across all measured speeds. This is well within the tolerance of the pitot tube used to calibrate the wind tunnel itself. To the company's knowledge, these are the first and only reported tests in the world to accurately measure the performance of a lidar in a wind tunnel and help demonstrate lidar's ability to measure low and high wind speeds for wind resource campaigns in the renewable energy sector.



applications

05 With traceability of system accuracy achieved, and in order to chart the industry acceptance of remote sensing devices, it is essential that significant technical organisations, for example the International Electrotechnical Commission (IEC) and International Energy Agency (IEA) committees, assess and communicate technical and commercial progress with any such remote sensing device. In turn this helps to assure or indeed deny compliance with any standards produced by the committees.

In addition, the use of each remote sensing device should be considered in specific modes of applications with differing demands. These applications can be designated as follows, each with increasingly demanding conditions relative to them:

- Onshore, benign site
- Offshore, fixed platform
- Onshore, complex site
- Offshore, floating platform

In each case this paper compares the wind industry's original wind lidar system, ZephIR, which has the longest operational track record of all commercially available lidar systems in this application.

ZephIR is uniquely a continuous wave lidar which offers specific advantages in all applications noted and therefore, being the broadest in its remit, acts as a good comparison.

There are a number of significant remote sensing devices currently in operation, and all sensors should be considered by readers – this paper aims to capture all areas associated with the subject of delivering finance-grade wind measurements, but not compare sensors in each application.

These sensors include:

- ZephIR 300 / ZephIR Lidar / Lidar - continuous wave [reference case]
- AQ510 / AQSystems / Sodar
- WindCube V2 / Leosphere / Lidar - pulsed

onshore: benign site

06 DNV GL has been widely acknowledged as a leading technical authority on wind energy for nearly three decades. Over the past ten years the company has applied this authority to remote sensing, specifically its use in the context of the development, design and financing of wind farm projects. Their analysis notes that cup anemometers have been the industry standard for measuring wind speed at wind farm sites and therefore they must be considered the norm against which any alternative measurement device must be judged.

DNV GL proposes a clear and auditable staging process for remote sensing devices which cover both lidars and sodars, when operating in benign environments:

Stage 1 & Milestone 1: Limited validation of a commercial device moving to some successful testing against conventional met masts over a range of heights (50m – 120m), achieving a similar level of accuracy in measurement. Results should be published in suitable technical papers.

Stage 2 & Milestone 2: Increasing range of site measurements made under a range of meteorological conditions, moving to formal wind speed and energy assessments being provided based in part on data from the device, but only with site-specific validations against conventional anemometry.

Stage 3: A device is considered proven for use in the assessment of wind farm sites. The data may be used quantitatively within formal wind speed and energy assessments with only limited or no site-specific validations against conventional anemometry.

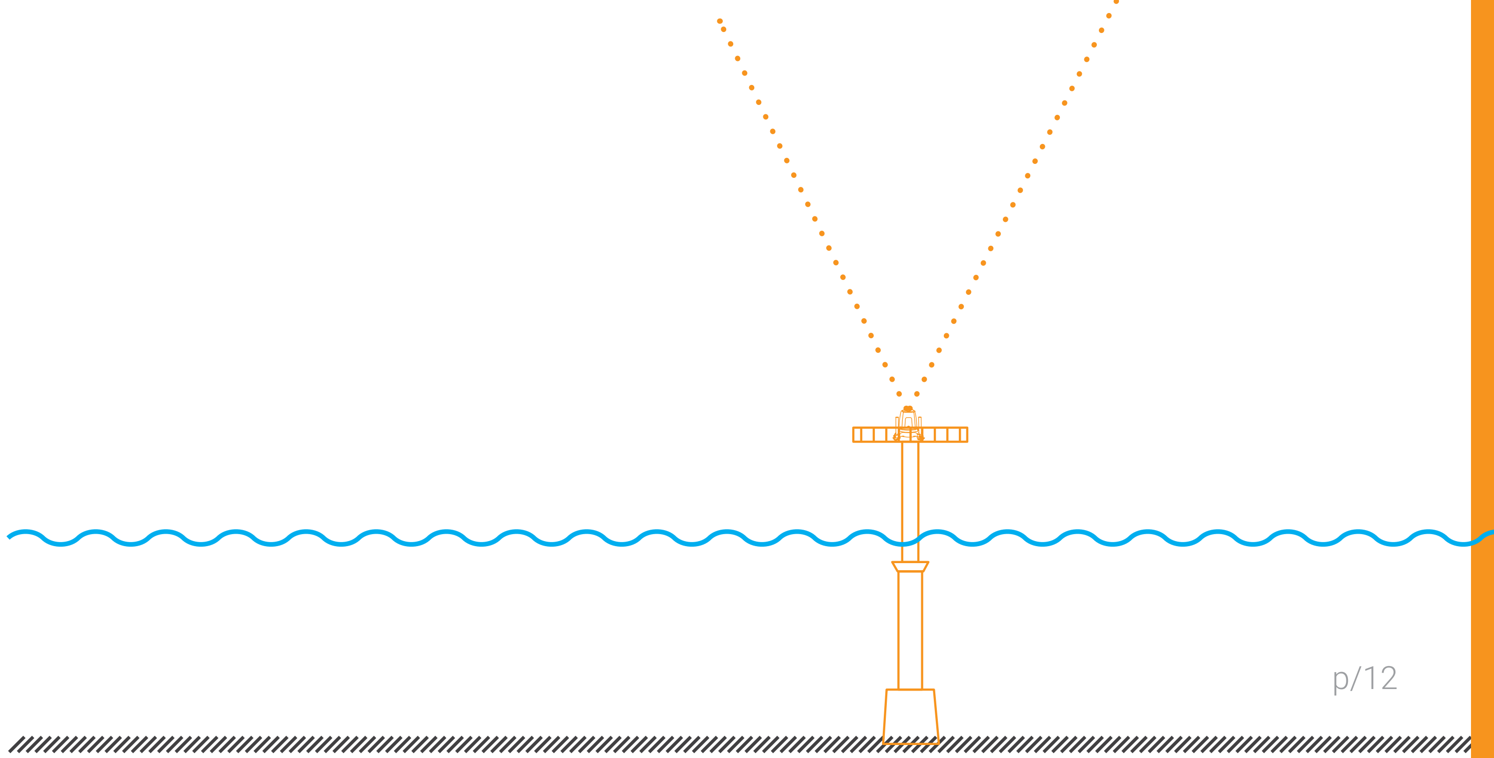
DNV GL considers ZephIR 300 to be at Stage 3 under "benign" conditions - accepted for use in bankable / finance-grade wind speed and energy assessments with either no or limited on-site met mast comparisons. In October 2012 ZephIR was the first commercial wind lidar system to achieve acceptance at this level.

offshore: fixed platform

07 Offshore, DNV GL generally considers Stage 3 Lidars operated on a stationary platform as being comparable to a benign scenario as noted in the previous section provided that enough evidence is given to ensure no significant flow distortion from the platform or its components might affect the measurements.

Given the importance of measurements when considered against the substantial economic investment in offshore wind energy development, validation of the specific device should be made at an appropriate onshore flat terrain test site before and after the offshore measurement campaign. Comparison with a met mast provides traceability back to traditional anemometry, so the onshore validation should be made against a tall IEC compliant meteorological mast.

Under specific conditions advised and audited by DNV GL, it is anticipated that equivalent accuracy and uncertainty results would be obtained from an energy prediction based on data from ZephIR 300 mounted on a stationary platform as from an energy prediction based on data from a conventional offshore hub height met mast. Economic savings can also be realised in the area of offshore wind resource assessment in addition to overcoming practical challenges where met masts are not a viable option.



ZephIR 300 mounted on a platform on the north east of a lighthouse using a specially designed support frame, measuring wind direction and wind velocity, augmenting wind measurements from onshore sources.

ZephIR's wind data provides real opportunity to enhance the energy assessment and revenue forecasting, which becomes an essential part of the overall business case for the project.

onshore: complex site

08 In the area of complex flow environments i.e. where the wind flow displays complex flow characteristics as a result of topography, surface roughness and other physical or environmental effects, additional technical issues must be considered, above and beyond the benign conditions of an onshore site or those of a fixed platform offshore.

This is due to the difference in the nature of measurements taken by a cup anemometer (referred to as point data; a single point of data at the cup centre) and a remote sensor (referred to as volume data; a volume of data averaged from the 3 dimensional space interrogated by the sensor).

The accuracy of each type of sensor is not in question here, but rather that the traceability of a newer technology (remote sensing) is understandably compared to the older technology (cup anemometry), and so a conversion in data is required to permit a direct comparison.

The new FGW TR 6 standard (Technical Guidelines for Wind Turbines, Part 6: Determination of Wind Potential and Energy Yields, published by FGW e.V. - Fördergesellschaft Windenergie und andere Erneuerbare Energien), which came into force at the end of September 2014, is one of the first wind industry guidelines to allow stand-alone wind measurements by remote sensing devices in order to derive the wind resource in complex terrain. It refers to the draft of the new IEC 61400-12-1 for any verification purposes as outlined above.

tb engineers, an engineering company dedicated to measurements and consultancy for the wind industry, is based locally in Germany where the new standards have been approved. With the special focus of tb engineers on power, load and wind measurements, and on the application of new methods and devices, they are well placed to provide commentary on the new standards:

- For complex sites, FGW TR 6 allows the assessment of the uncertainty caused by the terrain to be measured by a remote sensing device and then converted through a 3-dimensional flow model or a simplified estimation described in the IEA recommendations.
- Any device-internal conversion algorithm applied in complex terrain (i.e. over and above those used and by DNV GL in Stage 3 acceptance) should be known to the user of the device and taken into account.
- Specific care should be taken with respect to the application of the remote sensing device, which may have an influence on the uncertainty e.g. distance to forests, sources of noise, buildings.
- Any data, which is uncertain in relation to quality should be excluded, however, operators and analysts need to be sure that no systematic error is introduced through this method, for example if data is always excluded in similar meteorological situations.

FGW TR 6 also describes the use of remote sensing devices for height extrapolation as a relative analysis to transfer traditional met mast anemometer measurements to greater heights. Minimum requirements are defined such as overlapping times and the number of parallel measurement heights at the mast and at the remote device.

Last but not least, FGW TR 6 proposes the use of remote sensing devices for wider areas within future wind farms in order to identify the spatial variation of the wind regime. With the conditions above, wind measurements from remote sensing devices may be used to construct the wind regime from a correlation to a longer measurement on site (whether by remote sensor or cup anemometry).

ZephIR 300 utilises wind consultancy Natural Power's fully parameterised and automated computational fluid dynamics (CFD) model, VENTOS®, to analyse air flow at the measurement site. The VENTOS results are combined with the front-end software tool Dynamics™ to convert ZephIR wind speed measurements into point measurement equivalent flow data, emulating what a single point cup anemometer would measure on such a site. Dynamics splits the 360° ZephIR scan into 36 sectors of 10° and calculates a conversation factor for each of these sectors at every measurement height.

This validated method therefore provides a location-specific conversation factor for all wind directions that takes into account flow characteristics of the surrounding terrain.

The Dynamics conversion factors applied are provided to the end user in full allowing for further wind analysis, whilst also providing a clear audit trail for project financing and/or due diligence. This satisfies the requirements of FGW TR 6 standards and allows for the use of ZephIR 300 in a complex site.

offshore: floating platform

09 As part of the Offshore Wind Accelerator programme The Carbon Trust, along with a consortium of industrial partners, are investigating the potential of floating Lidar technology in the context of wind resource assessment for the offshore wind industry.

Floating lidar has the very real opportunity to replace both meteorological met masts and fixed platforms / existing infrastructure deployed with remote sensors, for the measurement of wind resource for a fraction of the current cost.

The Carbon Trust Offshore Wind Accelerator has published a roadmap for commercial acceptance of floating lidar technology – The Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology - which highlights three stages of commercialisation, in terms of defined accuracy and availability Key Performance Indicators (KPIs).

According to the roadmap, measurement uncertainties decrease as a floating lidar device progresses through the following stages:

- Baseline: As a pre-requisite, the lidar measurement unit itself should have achieved wide-spread acceptance within the onshore wind industry as "proven" in the field of wind resource characterisation for non-complex terrain sites at least.
- Pre-commercial: Following a successful pilot validation trial, the floating Lidar technology may be utilised commercially in limited circumstances - specifically in conditions similar to those experienced during the trial. Elevated measurement uncertainty assumptions may be expected for such an application, when benchmarked against the deployment of a conventional fixed offshore meteorological mast.
- Commercial: Following successful further trials and early commercial deployments covering a range of site conditions, a sufficient body of evidence is accumulated to relax the elevated uncertainty assumptions.

There are a number of floating lidar devices that are likely at some stage to be assessed by The Carbon Trust Offshore Wind Accelerator, however at the time of publication of this report, few findings have been presented formally within this framework. Therefore assessment of floating remote sensing devices lies more in the theoretical make-up of the sensor, notwithstanding the chosen platform technology of which there are also many options.

Doppler lidars measure the wind by detecting the line-of-sight Doppler shift caused by scattering of laser light from aerosols. Depending on the lidar type, significant motion of the lidar can affect the relative line-of-sight velocity and can lead to unreliable wind data.

However, continuous wave (CW) lidars such as ZephIR 300 can deliver exceptional sensitivity, achieved by focussing all the energy from the onboard laser at the chosen range, and this permits high data rates by scanning at 50Hz / 50 data points per second / measurements every 20ms. Any motion is frozen over this short integration time, so that in many high motion applications, such as those found on floating platforms or when mounted on the nacelle / in the spinner of wind turbines, high quality wind measurement can be carried out without motion-compensation.

Providers of platform technology have also made independent assessments of all remote sensors available and they are summarised below where available. Interested readers should conduct a thorough review of all options available as some prototype platforms are not yet in the commercial domain; the information shown below is correct at time of publication.

Manufacturer	Product name	Lidar technology
SeaRoc	SeaZephIR	ZephIR
Fugro Oceanor	SeaWatch	ZephIR
Babcock	FORECAST	ZephIR
3E	Flidar	WindCube
Axys	Sea Sentinel	Vindicator / ZephIR
EOLUS (IREC / Neptune)	EOLUS BUOY	ZephIR
FloatMast	FloastMast	ZephIR
Fraunhofer IWES	Wind Lidar Buoy	ZephIR

Fraunhofer IWES has recently successfully finished the validation of their Wind Lidar Buoy at FINO1 which confirms the commercial acceptance of wind data from the on-board ZephIR 300 lidar for use in floating offshore energy assessments, adhering to criteria within the Carbon Trust Offshore Wind Accelerator roadmap.

An offshore verification test was performed for and with the Fraunhofer IWES Wind Lidar Buoy now equipped with a ZephIR 300 Lidar next to the FINO1 met mast, in the German North Sea about 45km north of the East Frisian island Borkum. Both the availability and the accuracy of the floating lidar system were assessed against the offshore test site which was set up as a lidar-mast comparison adhering to IEC 61400-12-1 ed.2 CD where wind measurements from the lidar and the mast are compared with each other for different corresponding height levels and reference conditions.

Results of the trial demonstrate that the Fraunhofer IWES system based on the ZephIR 300 lidar delivers excellent correlations and extremely high data availability when compared to a traditional tall met mast structure, well within the Offshore Wind Accelerator criteria.

summary & conclusions

10 Through the provision of extensive field testing verifying remote sensing systems against traditional anemometry, and working within well-defined roadmaps implemented by leading organisations, a number of devices such as ZephIR 300 are being accepted for use in finance-grade wind farm energy analyses.

This advancement in measurement methodology allows project developers to increase the project Net Present Value (NPV), as demonstrated in a recent deployment of ZephIR 300 which saw the P90/P50 ratio increase by 2% at wind energy developer Gaelectric's 42 MW Dunbeg Wind Farm, with the energy assessment performed by DNV GL.

Further studies by leading consultancy Ecofys have highlighted the anticipated Net Present Value differentials for a variety of measurement methodologies, with the most advantageous being a 'roving' lidar which reduces the uncertainty in energy yield by up to 3.2% on a typical 20 MW European onshore wind farm compared to a met mast only, as shown in the table below. This equates to an increase in NPV of €600,000 or €30,000/MW installed. The second scenario shown, Lidar beside a met mast, is based on a one year met mast campaign with the Lidar beside the mast for 3 months, primarily to acheive a better vertical extrapolation. Thus, the costs are lower than scenario 1, with just Lidar costs for one year.

Cost-benefit analysis	Reference: Climate-based	Met mast only	1. LiDAR stand-alone	2. LiDAR next to mast	3. LiDAR moved around site
Approximate measurement costs [k€]	5	35	95	65	120
Uncertainty in energy yield [%]	17.0%	14.0%	12.0%	12.0%	10.8%
P_{90} / P_{50} ratio	78%	82%	85%	85%	86%
Leverage [%]	80%	82%	83%	83%	84%
Equity investment [k€]	5,400	4,800	4,400	4,400	4,200
Return on Equity [%]	9.7%	11.8%	13.4%	13.4%	14.5%
Increase in Net Present Value [k€] compared to reference case	-	700	1,100	1,100	1,300

The full report, courtesy and copyright of Ecofys, is available here:
http://www.ecofys.com/files/files/ecofys-2013-position-paper-on-lidar-use_02.pdf

Building on these financially-driven opportunities, additional benefits through the use of remote sensing include:

- Avoiding lengthy planning permission for masts
- Acceleration of multiple sites at once with no detrimental impact on financing terms e.g. two short masts at two sites, and a roving lidar moving between.
- The ability to take measurements under a low public profile during the feasibility stages of a wind energy project.
- The avoidance of working at height / H&S implications of tall structures

In conclusion, wind lidars such as ZephIR 300 have demonstrated their ability for providing quantitative wind speed measurements, to an industry-approved standard. ZephIR 300 is now accepted within a Technical Advisor / Bank's Engineers formal energy assessment of a modern scale wind farm with specific site conditions forming part of the appropriate measurement methodology chosen.

With a modern lidar system such as ZephIR 300 now costing as little as an 80 metre met mast over a 3 year measurement campaign, there is also economic benefit in using wind lidar - the reduction in energy yield uncertainty provides a significant increase in project Net Present Value and Return on Equity.

A full list of financing parties and associated Technical Advisors that already accept ZephIR 300 data as part of a formal energy assessment is available by request to: research@zephirlidar.com

Further information and reading:

www.dnvgl.com
www.tb-engineers.de
www.zephirlidar.com
www.wind-fgw.de
www.naturalpower.com
www.leosphere.com
www.aqsystems.com
www.ecofys.com