Power Performance Testing with Stand-alone WINDCUBE® Lidar

An alternative approach to accurate turbine performance assessment

Authors:
Guillaume Coubard-Millet
Evan Osler
Steve Clark
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1. INTRODUCTION

An understanding of individual wind turbine performance at any modern wind farm is critical. The characterization of turbine efficiency is a necessary first step for detecting underperformance, evaluating turbine upgrades, refinancing or reselling a project, identifying degradation in performance over time, and increasingly for wind farm owners trying to decide whether to invest in contractual power performance testing within the first year of plant operations per the IEC 61400-12-1:2005 standard (1).

It is well known that the IEC -12-1:2005 methodology requires the use of a hub height meteorological mast to measure the wind conditions upwind of the turbine(s) being tested. In this white paper, it is argued that ground-based WINDCUBE Lidar technology provides a very similar input for assessing wind turbine performance in simple terrain sites, mimicking the role of an IEC met mast but with a much higher degree of flexibility and at a much lower cost. This argument is laid forth in Section 2 as a WINDCUBE-based operational power curve test along with its typical resultant uncertainties are characterized in the spirit of the IEC standard. We then show that results of such a test give wind plant owners very similar benefits in understanding whether turbine performance meets, underwhelms, or exceeds expectations, and just as importantly whether far more costly and time-intensive actions such as formal IEC 61400-12-1 testing will pay off.

The value and typical procedure of WINDCUBE-based operational power performance testing are illustrated in Section 3 with a case study example of a turbine performance test undertaken in the Midwest USA. The wind farm owner’s objective in this case was to rapidly and economically assess the performance of a targeted turbine installed just a few months prior, both to confirm suspected underperformance and to determine whether to invest in more expensive, contractual testing as a basis for warranty claims and possible liquidated damages payments from the turbine OEM. The turbine was selected because initial SCADA data analysis indicated an overestimation of the calculated energy produced based on the nacelle anemometer power curve when compared to the real energy produced (Calculated > Real production). A WINDCUBE Lidar was chosen to serve as the reference wind measurement device for the test due to its ease of installation (Figure 1), proven accuracy and wide industry acceptance. This data was combined with turbine SCADA data and ground level atmospheric measurements to provide an accurate and meaningful understanding of the turbine’s performance relative to its reference power curve.

Figure 1: The exceptional portability of WINDCUBE makes it well-suited to rapid deployment and turbine testing. Photo credit: Leosphere SAS
2. THE “OPERATIONAL” POWER CURVE

A calculated turbine power curve is the most common method for assessing wind turbine performance. An ideally calculated power curve is derived from the relationship between the wind that would exist at the position of the center of the turbine’s rotor if the turbine was not present to obstruct the wind (called free wind speed), coupled with the turbine power output at that wind velocity. Measurements of the power output of a wind turbine are performed by a power meter and are available in every SCADA system. In contrast, measuring the wind speed at hub height at the location of the turbine as if the turbine were not present at all is a significant challenge. The goal is to measure an undisturbed wind flow upwind of the turbine, in a location close enough to be representative of what the wind speed would be at the position of the turbine. The IEC 61400-12-1 standard provides very complete guidelines for this procedure, starting from the location of the wind measurement to the calculation of the power curve uncertainty.

“Operational” power curves (OPCs) are defined as power curves established by following a simpler process and/or by measuring the wind speed with a different device than an IEC meteorological mast. In the case of a WINDCUBE-based operational power curve, the suggested methodology follows the most important guidelines to enable selection of high quality and meaningful measurements, as outlined in Table 1.

<table>
<thead>
<tr>
<th>IEC Recommendation</th>
<th>Reason</th>
<th>Does the OPC methodology follow this?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed sampling rate of 1Hz</td>
<td>a- To statistically collect enough data samples over a 10 minute average</td>
<td>Yes</td>
</tr>
<tr>
<td>Wind measurement location</td>
<td>b- To assess the variability of the wind, especially turbulence intensity and gust.</td>
<td></td>
</tr>
<tr>
<td>a- 2 to 4 rotor diameters in front of turbine</td>
<td>a- To avoid the wind speed decrease when the wind flow approaches the turbine rotor (also known as blocking effect or induction effect - see Figure 2).</td>
<td>Yes</td>
</tr>
<tr>
<td>b- At hub height</td>
<td>b- To measure at the center of the turbine’s rotor</td>
<td></td>
</tr>
<tr>
<td>Data synchronization between sensors</td>
<td>To associate measurements from different sensors together</td>
<td>Yes</td>
</tr>
<tr>
<td>Data filtering</td>
<td>To keep meaningful measurements only</td>
<td>Most important filters</td>
</tr>
<tr>
<td>Wind speed normalization</td>
<td>To remove the impact of atmospheric conditions</td>
<td>Yes</td>
</tr>
<tr>
<td>Binning the scatter plot</td>
<td>To assess the measured power curve</td>
<td>Yes</td>
</tr>
<tr>
<td>Uncertainty calculation</td>
<td>To characterize the level of confidence in the measured power curve</td>
<td>Partially, via inference (see p. 6)</td>
</tr>
<tr>
<td>Minimum number of data points</td>
<td>To ensure the validity of the result</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Figure 2: An illustration of the wind speed deficit that occurs in the turbine induction zone, and therefore of the importance of measuring at 2.5 rotor diameters upwind. Actual data presented here was collected using a Wind Iris nacelle Lidar pointed upwind of the turbine, and fit to a curve (2).

As introduced earlier, instead of using a hub height met mast as the standard requires, the wind speed measurement in this example was performed by a WINDCUBE ground-based Lidar.

More than 500 WINDCUBE Lidars are used globally today for wind resource and wind turbine performance assessment. WINDCUBE records 10-minute average wind speed data at 12 user-selectable heights of measurement, allowing for flexibility to measure not only at turbine hub height but across the entire rotor swept area if desired. According to independently issued statements from a leading wind energy consultancy (3), its measurement uncertainty is within the uncertainty of calibrated Class 1 anemometry. Also, every unit is tested and validated in such a way that its performance can be traced back to a reliable reference. The quality of measurement and performance stability and traceability (4) allows WINDCUBE data to be “bankable” with limited if any on-site verification, in contrast to commonly used Sodar technologies.

Figure 3: WINDCUBE measurements at 12 heights from 40m - 200m

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1 Each WINDCUBE is verified against a “golden” reference WINDCUBE Lidar at the time of manufacturing and again following extended field campaigns or significant repairs. The reference Lidar is in turn periodically calibrated by the Danish Technical University (DTU) to a 116m IEC met mast located at the Høvsøre Test Site. The verification test requires that the Lidar agree within very narrow margins to the golden WINDCUBE. A verification report accompanies each WINDCUBE shipment and guarantees traceable accuracy at multiple measurement heights. A sample verification report including standard pass/fail criteria of this test can be shared upon request.
Uncertainty of a WINDCUBE-measured Operational Power Curve

The objective of a power curve test of any kind is to calculate a result with sufficient confidence upon which decisions can be made. The confidence in the result is stated by computing the test uncertainty (the lower the uncertainty the greater the accuracy). The uncertainty of a power curve test takes into account the dispersion (i.e. scatter) of the measurement and the calibration uncertainty of every sensor, especially the uncertainty of the wind speed sensor, which has a large impact on the overall uncertainty evaluation. Background literature on the topic of horizontal wind speed uncertainty measured by WINDCUBE Lidar in simple terrain is useful for informing what the uncertainty of a measured power curve would be relative to what would be expected from a hub height IEC calibrated mast, the current gold standard in terms of accuracy.

One background example of the typical standard uncertainty of hub height wind speeds measured by WINDCUBE was published in a study by Deutsche WindGuard, an independent wind consultancy based in Germany that has extensive experience testing and calibrating remote sensing devices (5). This study compared uncertainty of hub height wind speed measured by a hub height met mast with calibrated Class 1 anemometers, a Lidar (in this case a WINDCUBE although it was not specifically identified in the chart) and an unnamed Sodar. The total uncertainty ($u_{\text{total}}$) is calculated as the root square of the sum of the squares of the identifiable measurement uncertainties sources ($u_{n,i}$):

$$u_{\text{total}} = \sqrt{\sum (u_{n,i})^2}$$

Both remote sensing devices exceed the mast in magnitude of verification uncertainty. The Sodar technology suffers significantly from sensitivity to changes in shear driving its total uncertainty to greater than 5% at hub height versus 2.5% for the WINDCUBE. The Sodar’s high sensitivity to shear implies that the accuracy at a given height will vary based on shear conditions far more than what the WINDCUBE has been shown to experience.

In the case of WINDCUBE, the uncertainty is driven more so by its verification to an already uncertain reference (a calibrated cup anemometer) than by any flaw in its measurement performance such as shear-based sensitivity.

Figure 4: Hub Height wind speed uncertainty in simple terrain for an IEC met mast, WINDCUBE Lidar and unnamed Sodar system. (5)
The low uncertainty of WINDCUBE wind speed measurement translates directly into a low power curve uncertainty and a low AEP uncertainty. When IEC Met mast and WINDCUBE power curve uncertainty are compared, Deutsche WindGuard noted that “The power curve gained with the WINDCUBE agrees very well with the power curve evaluated from the mast measurement, with the deviations (i.e. the difference between power curve and mast measured power curve) being smaller than the standard uncertainty of the cup anemometer measurement” (6).

**Striking a balance between Economics, Practicality and Uncertainty**

A WINDCUBE-based operational power curve test is one of many such methods available to wind farm operators currently. Each method strikes a unique balance in terms of economics, practicality and resulting AEP uncertainty.

The most economical choice for wind speed input to an OPC is from a nacelle anemometer, which is preexisting and is effectively a zero cost input. Unfortunately the measurement uncertainty from nacelle anemometry is significant, making nacelle anemometers which have not been individually calibrated *in situ* per the IEC 61400-12-2 recommendations (or similar) to be of little use in deriving absolute power curve measurements. This makes even the most accurate nacelle anemometers useful for assessing turbine performance in a relative sense at best. Ground-based measurement methods such as those from an industry-standard Sodar and WINDCUBE Lidar will typically differ in price by a factor of 2 to 2.5x when considering average monthly rental fees for each device, with both methods falling well below of the cost of a hub height met tower, especially with the assumption of short (e.g. 3 month) campaign durations. A purchased Sodar or WINDCUBE can be cost-amortized relatively rapidly when considering the low cost of relocations compared to repeated hub height met tower installation and decommissioning.

The remote sensor option is less practical in general than a nacelle anemometer would be by virtue of the need to install the device separately at a unique location upwind of the turbine(s) being evaluated\(^2\), but far more practical than a met tower installation given the typical lack of permit or soil disturbance required.

AEP uncertainties typical of mast-, WINDCUBE- and Sodar-based power curve tests are illustrated in a relative sense along with cost in Figure 5. Based on its favorable nexus of cost, practicality and accuracy, a WINDCUBE-measured power curve will typically offer significantly more confidence on which to make actionable and defendable business decisions when compared to a nacelle anemometer (7) or Sodar-based test, and still at a small cost compared to an IEC met mast.

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\(^2\) A nacelle Lidar based power curve test, such as one performed with a Wind Iris Nacelle Lidar, eliminates the requirement of installing anything on the ground at all but does involve the logistics of an installation atop a nacelle. This method presents a separate set of pros and cons, practicality and uncertainty relative to the more conventionally-minded approaches discussed in this white paper. See (2) for further information on the topic.
3. A REAL WORLD EXAMPLE

The following section provides a real world example of an operational power curve measured utilizing a WINDCUBE, including the measurement layout as well as the relatively simple and straightforward methodology used to extract full value from the measurement campaign (see Table 1).

**Project Overview**

The wind farm project under study is located in a Midwest USA location with simple terrain per IEC terrain classification guidelines. The turbine layout consists of rows of several tens of wind turbines oriented in west to east strings. As is typical for the Midwest, the site features a bimodal wind direction distribution, with prevailing winds from the north and south. The studied turbine is located on an outer row of the wind farm and frequently experiences unwaked winds as a result. Further details related to the wind farm layout, specific turbine type, owner, etc. are omitted in order to maintain confidentiality. All turbine performance data is normalized.

![Figure 5: Cost and uncertainty comparisons of various methods for measuring the wind speed as part of an operational power curve test in simple terrain.](image)

![Figure 6: Site layout during operational power performance test.](image)
The measurement campaign lasted 8 months, from August 2014 until end of March 2015, a duration typically well beyond what is required but which provided a rich dataset for analysis purposes. During this period 33,552 10 minutes averaged measurements were collected.

The wind turbine is equipped with a standard SCADA system and a meteorological station. As recommended by the IEC standard, 10 minutes averaged data were used. The data available for the analysis are summarized in Table 2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output</td>
<td>kW</td>
</tr>
<tr>
<td>Nacelle wind speed</td>
<td>m/s</td>
</tr>
<tr>
<td>Nacelle yaw orientation</td>
<td>°/nacelle yaw reference</td>
</tr>
<tr>
<td>Blade Pitch</td>
<td>°</td>
</tr>
<tr>
<td>Turbine LOG</td>
<td>Binary</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>hPa</td>
</tr>
</tbody>
</table>

*Table 2: SCADA data used during OPC computation*

A WINDCUBE was installed in the field upwind of the turbine with respect to the dominant wind direction, beyond the turbine induction zone. The Lidar, here in its standard configuration, measured the wind speed (horizontal and vertical components) at 12 different heights, from 40m to 220m, including the hub height measurement at 80m. This configuration met the IEC standard requirement in term of wind speed measurement height (i.e. turbine hub height) and distance to the turbine. Prior to the deployment, the Lidar was tested and validated at RNRG against a calibrated reference WINDCUBE.

The available data from the Lidar is shown in Table 4. The Lidar data was downloaded via the WINDCUBE web portal, Wind Web.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heights of measurement</td>
<td>Hub height + 11 other heights, ranging from 40m – 220m AGL</td>
</tr>
<tr>
<td>Horizontal wind speed</td>
<td>m/s, for every height of measurement</td>
</tr>
<tr>
<td>Vertical wind speed</td>
<td>m/s, for every height of measurement</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Degrees (°), for every height of measurement</td>
</tr>
<tr>
<td>Turbulence intensity</td>
<td>%, for every height of measurement</td>
</tr>
<tr>
<td>Measurement availability</td>
<td>% 1Hz valid data over 10 minutes</td>
</tr>
</tbody>
</table>

*Table 3: WINDCUBE data used during OPC computation*

Data Analysis Step 1 - Data Synchronization

As the wind turbine and WINDCUBE data sets are merged for analysis, the synchronization between the two sets is a critical first step towards providing meaningful results. To do so efficiently, the horizontal wind speed values (available in both datasets, from different sensors) can be used for synchronization (Figure 7).
In this dataset, a 4 hour, 50 minute offset was found, corresponding to the sum of time zone differences, presence/absence of daylight savings time, and difference in whether the timestamp of each data set indicated the start or end of a 10 minute interval.

![Figure 7: Synchronization analysis](image)

This analysis was conducted across the entire dataset to make sure no desynchronization happened randomly and affected the analysis.

**Data Analysis Step 2 - Data Filtering**

When performing wind measurements for power curve testing, the IEC61400-12-1 standard advises filtering out measurements performed in specific conditions. As explained in an earlier section, the objective is to screen for high quality wind measurements performed in undisturbed conditions and representative of the wind speed that should exist at the nacelle position if the wind turbine itself was not present. In order to produce a high quality dataset, it was necessary to develop a robust and simple data validation process via filtering on wind direction sectors, turbine LOGs and WINDCUBE measurement availability. This process is detailed below.

**Wind sector filtering**

Only wind measurements performed in undisturbed conditions and representative of what the turbine “sees” should be kept for the analysis. The wind sector filtering consists of selecting the wind directions where these two requirements are met.

Annex A of the IEC 61400-12-1 standard gives guidelines to define the wind sector that should be:
- centered on the axis defined by the turbine tower position and the wind measurement device;
- of a certain width that depends on:
  - the distance between the turbine and the measurement device;
  - potential adjustments, for example: exclusion of wind directions with disturbed flow, generated by wakes of neighboring wind turbines.

In this case, a 74° wind sector oriented north was defined as usable as the WINDCUBE was located at a 2.5D distance from the turbine, and no neighboring turbine wakes or obstacles disturbed the wind flow from the Lidar direction.
Figure 8: layout of the turbine under test and the upwind Lidar, showing waked directions, the Lidar-measured wind rose and the usable wind sector for power curve analysis.

The position of the WINDCUBE was determined prior to the installation, taking into account the both nearby wind turbines and the prevailing wind direction.

After wind sector filtering 11,153 data points (33%) remained available for the next filtering steps.

**Turbine LOG filtering**

It is advised to filter the dataset using the turbine’s status parameter (turbine LOG) in order to ensure that turbine data is used only from periods when the turbine runs in normal operation. This eliminates the influence of turbine curtailment or planned downtime.

Only timestamps with a LOG specifying normal operation mode were included in the dataset.

After wind sector and turbine LOG filtering 9620 data points (28%) remained available for the next filtering steps.

**WINDCUBE measurement availability filter**

The WINDCUBE used during the campaign utilized its standard 1Hz sample rate, meaning a new wind measurement was recorded roughly once every second. The 1Hz measurements were averaged over 10 minutes to derive the 10 minute average data used for the data analysis. The WINDCUBE measurement availability filter is applied to the 10 minute data to screen out data. Some measurements are invalidated by the Lidar itself, primarily due to atmospheric influences. The indicator “WINDCUBE measurement availability” is the percentage of valid 1Hz measurements over 10 minutes. For example, a measurement availability of 90% indicates that 90% of 600 1Hz

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3 Lidar measurements require the presence of aerosols – naturally occurring and/or anthropogenic – in the atmosphere for a backscatter media. Occasionally a very clean air mass or a heavily saturated air mass will limit signal backscatter at some or all measurement heights.
measurements (or 540 measurements) were deemed valid in the 10 minute sample. The dataset was filtered based on this indicator to keep representative measurements only.

Figure 9 shows scatter plots of WINDCUBE measurement availability at hub height as a function of the wind speed. It should be noted that the measurement availability is high on average, with a mean by wind speed bin (thick green line) of greater than 90% in all speed bins. For the power curve analysis, measurements with a 10 minute average availability greater than 80% were kept according to industry best practice.

After the availability filtering, the dataset available for power curve analysis consisted of 7149 data points (21%).

**Outlier data exclusion**

To exclude data that are not relevant or that create a bias in the results, obvious outlier data are excluded.

After the outlier data filtering, the dataset available for power curve analysis consisted of 7065 data points (21%).

**Dataset filtering summary**

<table>
<thead>
<tr>
<th>Source</th>
<th>Variable</th>
<th>Range</th>
<th>Comments</th>
<th>Data available after filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine SCADA</td>
<td>Wind sector</td>
<td>[260° ; 340°]</td>
<td>Remove disturbed wind flow</td>
<td>11153</td>
</tr>
<tr>
<td></td>
<td>Turbine LOGs</td>
<td>1</td>
<td>Turbine runs in normal mode over 10 minutes</td>
<td>9620</td>
</tr>
<tr>
<td>WINDCUBE Lidar</td>
<td>WINDCUBE measurement availability</td>
<td>&gt; 80%</td>
<td>Data availability over 10 minutes</td>
<td>7149</td>
</tr>
<tr>
<td>Undefined</td>
<td>outlier data</td>
<td>1</td>
<td>remove non-relevant data</td>
<td>7065</td>
</tr>
</tbody>
</table>

*Table 4: Dataset filter steps*
Data Analysis Step 2b – Turbulence intensity and Wind Shear considerations

Theoretical (8) and practical (9) (10) studies have shown that turbine performance is impacted by turbulence intensity (TI) and wind shear, two secondary factors that often inversely correlate with each other. In this case study, the available reference power curve made no mention of specific values for these two variables, meaning the dataset could not be filtered on them. As a result and to make sure the recorded measurements were from periods with equivalent atmospheric conditions, an analysis of TI and shear was performed. The ability of the WINDCUBE to accurately measure hub height TI in simple terrain (11) and wind speeds at heights both above and below hub height allows for this additional analysis with no inference or extrapolation required.

TI and shear index were calculated using the following equations:

\[ TI = \frac{\text{std}(HWS(\text{hub height}))}{HWS(\text{hub height})} \]

\[ \text{Shear}_{\text{index}} = \left( \frac{HWS(\text{hub height} + 20\text{m}) - HWS(\text{hub height} - 20\text{m})}{40\text{m}} \right) \]

The TI and shear index values were calculated for every 10 minutes measurement already validated with a wind speed greater than 5m/s, and then averaged per hour of the day.

Figure 10: Normalized Turbulence Intensity at hub height, Shear index and temperature variation by hour of day (local time).

Figure 10 shows that two distinct periods can be identified:
- Daytime (8:00am to 8:00pm): High Turbulence intensity and low wind shear
- Nighttime (8:00pm to 8:00am): Low turbulence intensity and high wind shear

As is typically the case in inland simple terrain, TI and wind shear are both strongly (negatively) correlated to each other as well as to daily temperature variation which is a proxy for solar gain and boundary layer mixing. Turbulence increases and shear decreases during the daytime in a less stable, well-mixed atmosphere as the boundary layer becomes thermally unstable.

At night, the opposite occurs as the thermal profile of the boundary layer stabilizes, with a decrease of turbulence intensity and increase of wind shear.
Turbine performance was additionally assessed under these two distinct periods (daytime and nighttime).

**Data Analysis Step 3 - Wind Speed Normalization**

It is well known that the energy available in a wind flow is a function of the air density, a quantity that depends mostly on the atmospheric temperature and pressure. Therefore, depending on the season a given wind velocity is more or less energetic, and that will influence the power curve itself and the resultant understanding of the turbine performance. The wind speed is normalized following the formula below in order to suppress the influence of air density fluctuations.

\[
HW_{S_{\text{normalised}10\text{min}}} = \frac{HW_{S_{\text{measured}10\text{min}}}}{\rho_{\text{10min}}} \frac{\rho_{\text{ref}}}{\rho_{\text{ref}}}^{\frac{1}{k}}
\]

With \(HW_{S_{\text{measured}10\text{min}}\text{}}\) the measured 10 minutes averaged horizontal wind speed, \(\rho_{10\text{min}}\) the air density over the 10 minutes period of the wind speed measurement and \(\rho_{\text{ref}}\) the reference air density (usually 1.225kg/m\(^3\), air density at sea level).

The normalization procedure returns wind speed values as if the temperature and pressure were the same for all measurements (1). This way, power curves measured in very different environments can be compared, regardless of climate, elevation, etc.

The objective of this analysis was to compare power curves calculated from WINDCUBE wind measurement to the reference power curve. Thus the measured wind speeds were normalized to the temperature and pressure indicated on the reference power curve definition.

**Data Analysis Step 4 – Power Curve Computation**

To obtain the scattered (non-bin averaged) power curve, the turbine power output was plotted as a function of the normalized wind speed, using the filtered dataset.

To obtain the measured power curve, the data are averaged by bin of wind speed. To do so, 10 minute wind speed and power measurements are averaged in 0.5 m/s speed bins (1). For example, for the bin 6.5m/s, the 10 min averaged power measurements measured for wind speed between 6.25m/s and 6.75m/s are averaged (here, 0.259 normalized power). Then, the 10 min averaged wind speeds between 6.25m/s and 6.75m/s are averaged (here, 6.51m/s). The pair \([P=0.259*P_{\text{nominal}}; 6.51\text{m/s}}]\) is then plotted as shown in Figure 11. The binned power curve is computed by applying this methodology to every 0.5m/s bin of wind speeds.

Figure 11 shows the turbine performance analysis per period of the day (day time and night time) with the reference power curve (dashed black line), the scatter power curve, the binned operational power curve and the statistical uncertainty (one standard deviation) (black bars).
Figure 11: ABOVE: Scattered power curve, binned power curve (Daytime: green; Nighttime: yellow) and the reference power curve (dashed black). BELOW: Comparison of binned power curves (Daytime and Nighttime) with reference power curve. Error bars represent the statistical uncertainty on the power (1 standard deviation).

As a means of assessing the representativeness of the measured power curve, the standard advises a review of the wind speed range covered, the overall number of data points, and the number of data points per bin of wind speed. A minimum of three points per bin are advised. Figure 12 shows the number of data plotted per bin of wind speed. In this example, 7065 data points were used, equivalent to 1177.5 hours of measurement, covering a range of wind speed from cut-in to 20m/s. This is more than sufficient to provide confidence in the result (180h required by the IEC standard).
Figure 12: Number of 10 min measurements per wind speed bin (green) and the minimum number of data per bin of wind speed required by the IEC standard (red). From 3m/s to 20m/s, there is enough data in each bin to consider the measured power curve statistically representative.

**Statistical uncertainty vs. overall uncertainty**
The uncertainty bars plotted on the power curve graph in *Figure 11* represent the statistical uncertainty. The total uncertainty specific to this real-world test was not computed in this case as the wind farm owner was comfortable with background documentation substantiating the accuracy of the WINDCUBE measurements as well as the value of the validation performed prior to the campaign.

### 4. CONCLUSION

During this example project, an operational power curve measurement was performed on a modern wind turbine in the Midwest USA with a WINDCUBE ground based Lidar, SCADA data, environmental measurements and a simple methodology derived from the IEC standard. Operationally, the success of the performance assessment is largely due to the location choice of the WINDCUBE relative to the wind turbine being assessed, the ease of installation, the high data availability (>90%), and industry acceptance of WINDCUBE as an acceptable surrogate for conventional met masts in simple terrain.

The straightforward methodology used in the analysis ensures that the measured wind speed meets the standard definition, the synchronization between SCADA and Lidar data is guaranteed and the irrelevant data filtered out. These easy-to-apply steps ensure trustful, consistent and accurate turbine performance assessment with acceptably low uncertainty on which to make important business decisions.

The measured power curve showed without any doubt that the turbine was underperforming when compared to the reference power curve in both convective (daytime) and nocturnal atmospheric boundary layer conditions. Following this internal test, the wind farm owner was able to confidently proceed with a formal IEC power curve test while the WINDCUBE was moved to another location to analyze additional wind turbines.
5. REFERENCES


