Comparison of different measurement methods for a nacelle-based lidar power curve

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Abstract. In this study, different methods are used to determine a nacelle-based lidar power curve. The methods used have already been published in other studies. However, these studies differed in environmental conditions, rated power, hub height, rotor diameter and in the evaluation criteria of the power curve. In this study, the published methods for the determination of nacelle-based lidar power curves will be used and evaluated with uniform criteria. The basis for this is provided by measurements of ground- and nacelle-based lidar and met mast measurements at an IEC-conform site. The results show that some methods significantly reduce scattering in the performance curve and that the choice of measurement distances used has a significant influence on the quality of the results.

1. Introduction
Current plans provide that the power curve standard (IEC 61400-12 [1]) is to be restructured. In this context, there will also be a separate standard for the power curve with nacelle-based lidar systems. This is a right and important step: the hub height reaches heights where the erection of a meteorological mast (met mast) requires large financial resources. The rotor diameters of wind turbines become larger, and thus the influence of shear during energy conversion is higher. This development was counteracted by the introduction of the rotor equivalent wind speed (REWS) [2]. The REWS can be calculated for met mast and for ground-based lidar measurements. The REWS procedure is part of the valid standard IEC 61400-12. Nonetheless, nacelle-based lidar systems have advantages over met masts or ground-based lidar systems:

- The nacelle-based lidar system sees the inflow of wind towards the turbine.
- Potentially information about the flow conditions at several distances ahead of the turbine if several distances ahead of the turbine are used.
- Information of the wind field over the whole rotor area can be acquired.
- Combination of high temporal and spatial resolution of the wind field compared to classical wind measurements with met masts.

Several analyses of nacelle-based lidar power curves have already been published: Rettenmeier [3] has selected from a trajectory (7x7 grid in regular arrangement), different points such as only the vertices (Diamond) or only the outer points of the vertical and horizontal plane (BigCross) of the trajectory points averaged to a REWS. Furthermore, in [3] the method of Wagner [4] was adapted to nacelle-based measurements. Hofsäss [5] went one step further and not only
subdivided the measurement grid horizontally, but also summarized each trajectory point into a REWS weighted by its area portion. Two different methods were used to determine the weighting factors: Cartesian with even distribution (rectangular) and polar along the rotor radius (circular discs). A further approach for the determination of a power curve is the use of the rotor effective wind speed $v_0$ \[6\]. The averaged wind speeds per measurement distance are summarized to one averaged velocity under the consideration of Taylor’s frozen turbulence hypothesis \[7\]. This method was used by Rettenmeier \[8\] and Würth \[9\]. Borraccino \[10\] has combined the lidar measurements with a numerical model which takes induction into account. This makes it possible to calculate an undisturbed wind speed from disturbed measurements in the induction zone.

With all the mentioned methods, nacelle-based lidar power curves can be created, but there is no uniform evaluation criterion to compare the results of the studies with each other. The aim of this study is to compare as many different approaches as possible with each other using a uniform set of measurement data from a pulsed lidar system and uniform evaluation criteria. The investigated method represents generic lidar systems as well as real pulsed and continuous nacelle-based lidar systems.

2. Campaign Setup and Data analysis

The measurement campaign took place at an IEC-compliant test site near Wismar, Germany. The test wind turbine (WT) is a 2.5 MW pitch controlled turbine with 95 m hub height and a rotor diameter of 109 m. A met mast with a top anemometer at 95 m height was placed at a distance of 295 m towards the prevailing wind direction. The schematic structure is shown in Figure 1. The met mast was equipped with 1st Class cup anemometers, vanes, temperature and pressure sensors according to the IEC 61400-12\[1\]. A Leosphere Windcube V2 ground-based lidar (Sep 2013 - Apr 2014) was placed next to the met mast in order to allow for a direct comparison with the hub height cup anemometer. The ground-based lidar measured at eleven heights up to the upper tip height of the WT. The SWE lidar scanner \[11\] was installed on the nacelle of the WT approx. 2 m above hub height, looking upwind.

The lidar scanner measured five distances simultaneously at 81.8 m, 109.0 m, 136.3 m, 163.5 m and 190.8 m in front of the hub. The duration to measure one trajectory (5x5 regular grid) is 6.25 s and each line-of-sight velocity $v_{los,i}$ was estimated with 3000 laser pulses. The setting of the trajectory was a trade off between minimizing the duration time and maximizing the measurement distance. The lidar data had to be filtered and processed. For this purpose, a

Figure 1. Measurement setup with two lidar systems marked with ■, one nacelle and one ground-based system with their measurement planes (green) / heights (blue).
horizontal wind speed component $u_i$ was calculated from $v_{los,i}$ under the assumption that the vertical velocity $w$ and lateral velocity $v$ are zero. With these assumptions, the wind component $u_i$ corresponds to the horizontal wind speed $v_{hor,i}$. For each trajectory point, the 10-min statistics were calculated considering that the carrier-to-noise (cnr) ratio was between $-22$ dB and $-5$ dB and the measuring point was not influenced by a rotor blade (hard target). For each method, the REWS was calculated according to the required weighting and the used trajectory points.

2.1. Methods
The description of the methods is based on the assumption that the scan pattern is a regular rectangular grid with odd grid points (possible usable scan pattern are 3x3, 5x5 or 7x7) in both coordinate directions. Figure 2a shows an example of such a grid. The selection of the points is crucial to capture appropriate effects such as vertical shear. For averaging the wind speeds the approach of kinetic energy flux is used:

$$v_{REWS} = \left( \frac{1}{N} \sum_{i} v_{hor,i}^3 w_i \right)^{1/3}$$

*Bigcross*

The *Bigcross* method uses the 4 outer points on the central horizontal and vertical axis including the grid origin. By the 2 points on the vertical axis, vertical shear (speed gradient) is taken into account. For the 2 horizontal points, this also applies to the horizontal shear. The REWS is calculated according to Equation (1) with $N = 5$ and equally weighted with $w_i = 1$. If the points are connected to each other it would look like a cross.

*Diamond*

The *Diamond* method is very similar to the *Bigcross* variant. This method uses the same points on the horizontal and vertical axis, but the center point is not used. The rotor equivalent wind speed is calculated with $N = 4$ and weighted with $w_i = 1$. The name is again derived from the resulting pattern if the points are connected to each other.

*Corner4points / Corner4p1points*

The method emulates the measurement configuration of several commercial manufacturers offering nacelle-based lidar systems. The border points / corners are used. In the experiment 9.46° as opening angle for the farthest measuring distance and for the nearest measuring distance an angle of 18.43° was used. In addition to this approach the method *Corner4p1points* was used. This also uses the center of the grid as additional information. All points are equally weighted with $w_i = 1$.

*Twobeam*

In this method, again a commercial system is emulated. It uses two points on a horizontal line to determine the wind speed. The half opening angle is 15° and the points are equally weighted.

*Cartesian*

The method adapts Wagner’s [4] method of rotor equivalent wind speed for ground-based lidar measurements on nacelle-based measurements. The rotor area is divided into square segments, so that the measuring points are located in the center of these segments and the segment boundaries are between two measuring points. The wind speed is weighted with this resulting area share $w_i$. These procedures are described in detail in [5].
Polar
This procedure is very similar to the Cartesian method. Instead of dividing the area into rectangular segments, this method divides the rotor area into circular rings. The idea is that wind speeds are summarized, which cover the same blade position and thus extract a similar amount of energy. The weighting factors $w_i$ of the wind speeds are calculated from the areas of the circular rings. The circle rings are limited by the mean distance of the point radii. These procedures are also described in detail in [5].

V2
The name of this method comes from the used ground-based lidar system V2 from Leosphere.
The method according to Wagner [4] is used for the ground-based measurements. This method serves as an additional orientation for the correct assessment of the results of the nacelle-based procedures. We used in this campaign eleven measurement heights which are between 43 m and 150 m. This setup is shown in detail in Figure 1.

**WFC**

The wind field characteristics (WFC) method does not directly determine a comparable wind speed from the measurements, but determines the wind field characteristics (WFC) from the lidar data using a wind field reconstruction (WFR) model. The model used here (Equation (2)) was developed by Borraccino et al. [10] and is described in detail in his study. The schematic of the method is shown in Figure 2c. The idea is to describe the wind field with some quantities like the induction factor $a$, the vertical wind profile exponent ($\text{Power Law}$) $\alpha$, the linear horizontal shear gradient $\delta_h$ and an average wind speed $v_0$. The different coordinate systems (lidar with index $L$, Hub with index $H$ and the wind field with index $W$), which are visible in Figure 2c, are rotated and translated against each other. By transforming the original lidar measurements from the lidar coordinate system to the hub coordinate system the mounting position of the lidar as well as the pitch and roll of the lidar are compensated. By the second transformation from the hub to the wind coordinate system, the horizontal (and vertical) inflow angle, which corresponds to the yaw misalignment of the turbine, is inherently considered. The wind field is abstracted in the wind coordinate system by a plane inclined in space.

The induction factor $a$ is depending on the dimensionless distance $\xi$. This $\xi$ is related to the rotor radius $R_{\text{rot}}$ (Equation (3)). The horizontal shear is related to the horizontal direction in the wind coordinate system $y_W$ and the exponential law is used for the vertical direction $z_W$. The parameters of the wind field model (Equation (2)) are determined numerically for each 10-min data. This is done with the help of an optimization method like the Levenberg-Marquardt algorithm [12]. All 25 points per measuring distance are used as input. The parameters are optimized to minimize the error between the lidar measurements and the reconstructed wind speeds. At least two measuring distances must be used for the optimization, otherwise the induction factor cannot be determined.

$$v_{WFC} = v_0 \left(1 - a \left(1 + \frac{\xi}{\sqrt{1 + \xi^2}}\right)\right) \left(\frac{\bar{v}_W + \bar{h}_{hub}}{\bar{h}_{hub}}\right)^\alpha + \delta_h y_W$$ (2)

$$\xi = x_W / R_{\text{rot}}$$ (3)

Furthermore, the measuring planes, which have been used as inputs in this study for the determination of the parameters were varied. To determine the WFC for each 10-min time step, the WFR model has been numerically fitted to minimize the error. After the parameters for each time step were known, the mean horizontal wind speed $v_{2.5D}$ was determined from the model at a distance of 2.5 rotor diameters $D$. This distance corresponds to the optimum distance of a met mast measurement according to the IEC 61400-12 standard and can therefore be compared with it. This calculated wind speed is used to determine the power curve.

### 2.2. Calculation of the power curve

The calculation of the power curve ($P$-$v$) is based on the IEC 61400-12 standard. The data was filtered according to the valid free sector ($142.7^\circ$ - $355.17^\circ$). Furthermore, only temperatures above $2^\circ$C were taken into account in the evaluation. The wind speed was normalized to standard air density ($\rho_0 = 1.225 \text{kg m}^{-3}$) according to the pitch regulated turbine type. To quantify the estimated power curves, the annual energy production (AEP) is calculated. Only complete bins (minimum three 10-min values per bin) were considered for the AEP calculation. The AEP is
Table 1. Result of the OLS of the different methods with different input distances and the met mast.

| Method          | Distance [m] | Slope [-] | Offset [m s⁻¹] | R²   | Mean | Std | AEP |
|-----------------|--------------|-----------|----------------|------|------|-----|-----|
|                 | 81.8         | 109       | 136.3          | 163.5| 190.8|     |     |
| Big-cross       | -            | -         | -              | 0.991| -0.220| 0.980| 1.138| 0.643| 1.090|
|                 | -            | -         | -              | 1.010| -0.185| 0.978| 1.062| 0.921| 1.079|
|                 | -            | -         | x              | 1.027| -0.187| 0.975| 1.024| 0.947| 1.044|
|                 | -            | -         | x              | 1.041| -0.205| 0.970| 1.001| 1.001| 0.974|
|                 | -            | -         | x              | 1.009| -0.138| 0.981| 1.033| 0.728| 1.020|
| Corner4-points  | -            | -         | -              | 0.986| -0.252| 0.981| 1.160| 0.579| 1.110|
|                 | -            | -         | -              | 0.998| -0.215| 0.978| 1.107| 0.664| 1.068|
|                 | -            | -         | x              | 0.973| -0.171| 0.983| 1.139| 0.518| 1.061|
|                 | -            | -         | -              | 1.056| -0.162| 0.977| 0.940| 1.010| 0.916|
|                 | -            | -         | -              | 1.017| -0.171| 0.977| 1.033| 0.912| 1.013|
| Corner4-        | x            | -         | -              | 0.990| -0.267| 0.979| 1.159| 0.608| 1.103|
| points          | -            | -         | x              | 1.004| -0.241| 0.972| 1.107| 0.725| 1.063|
|                 | -            | -         | -              | 0.971| -0.188| 0.981| 1.167| 0.513| 1.072|
|                 | -            | -         | x              | 1.072| -0.182| 0.972| 0.921| 1.661| 0.991|
|                 | -            | -         | x              | 1.023| -0.192| 0.973| 1.036| 0.950| 1.008|
| Diamond         | x            | -         | -              | 0.996| -0.225| 0.978| 1.131| 0.713| 1.079|
|                 | -            | -         | x              | 1.018| -0.198| 0.975| 1.049| 0.975| 1.066|
|                 | -            | -         | -              | 1.037| -0.212| 0.969| 1.014| 0.999| 1.029|
|                 | -            | -         | x              | 1.055| -0.241| 0.962| 0.996| 1.079| 1.001|
|                 | -            | -         | x              | 1.013| -0.148| 0.978| 1.034| 0.974| 1.016|
| Two-beam        | x            | -         | -              | 1.007| -0.224| 0.980| 1.093| 0.832| 1.098|
|                 | -            | -         | x              | 1.031| -0.178| 0.979| 1.006| 1.249| 1.072|
|                 | -            | -         | x              | 1.052| -0.172| 0.976| 0.953| 1.269| 1.026|
|                 | -            | -         | x              | 1.072| -0.182| 0.972| 0.921| 1.661| 0.991|
|                 | -            | -         | x              | 1.007| -0.224| 0.980| 1.093| 0.832| 1.098|
|                 | -            | -         | -              | 1.031| -0.178| 0.979| 1.006| 1.249| 1.072|
|                 | -            | -         | x              | 1.052| -0.172| 0.976| 0.953| 1.269| 1.026|
|                 | -            | -         | x              | 1.072| -0.182| 0.972| 0.921| 1.661| 0.991|
| Cartesian       | x            | -         | -              | 0.980| -0.239| 0.981| 1.178| 0.588| 1.120|
|                 | -            | -         | -              | 0.992| -0.194| 0.979| 1.117| 0.620| 1.076|
|                 | -            | -         | x              | 1.003| -0.179| 0.978| 1.078| 0.712| 1.047|
|                 | -            | -         | x              | 1.013| -0.171| 0.977| 1.048| 0.733| 1.024|
|                 | -            | -         | x              | 1.019| -0.166| 0.977| 1.029| 0.943| 1.095|
| Polar           | x            | -         | -              | 0.985| -0.248| 0.980| 1.165| 0.587| 1.111|
|                 | -            | -         | -              | 0.996| -0.198| 0.979| 1.109| 0.640| 1.070|
|                 | -            | -         | x              | 1.007| -0.178| 0.978| 1.069| 0.724| 1.039|
|                 | -            | -         | x              | 1.020| -0.172| 0.977| 1.032| 0.937| 1.008|
|                 | -            | -         | x              | 1.017| -0.165| 0.977| 1.036| 0.936| 1.012|
| v2              |              |           |               | 1.001| -0.022| 0.994| 1.005| 0.865| 1.005 |

based on the Rayleigh distribution according to the IEC 61400-12 and was determined for the annual mean speeds from 4 m s⁻¹ to 11 m s⁻¹. As criteria for the power curve, the mean value and the standard deviation per bin are evaluated and also the AEP.

3. Results & Summary
The calculated power curves for the investigated methods and combinations of input variables are set in relation to the top height met mast power curve. The two power parameters of the P⁻v
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Table 2. Result of the OLS of the WFC methods with different input distances and the met mast.

| Method | Distance [m] | Slope [-] | Offset [m s⁻¹] | $R^2$ | Mean | Std | AEP |
|--------|-------------|-----------|----------------|------|------|-----|-----|
|        | 81.8        | 109       | 136.3          | 163.5| 190.8|     |     |
| WFC    |             |           |                |      |      |     |     |
| x x x - | 0.958 | -0.603 | 0.779 | 1.820 | 2.528 | 1.225 |
| x x x x | 1.002 | -0.448 | 0.931 | 1.283 | 1.288 | 1.088 |
| x x x x x | 0.997 | -0.418 | 0.941 | 1.282 | 1.288 | 1.090 |
| x x x - x | 0.998 | -0.398 | 0.947 | 1.250 | 1.114 | 1.080 |
| x x - x | 1.008 | -0.416 | 0.945 | 1.229 | 1.103 | 1.064 |
| x x - x x | 1.003 | -0.430 | 0.946 | 1.250 | 1.155 | 1.080 |
| x x - - x | 1.001 | -0.396 | 0.948 | 1.216 | 1.052 | 1.072 |
| x - x - x | 1.006 | -0.456 | 0.927 | 1.326 | 1.382 | 1.081 |
| x x - x x x | 0.995 | -0.442 | 0.933 | 1.311 | 1.390 | 1.103 |
| x x - - x - | 1.001 | -0.430 | 0.944 | 1.262 | 1.194 | 1.084 |
| x x - x - x | 1.014 | -0.429 | 0.943 | 1.262 | 1.194 | 1.084 |
| x - x x x | 1.004 | -0.473 | 0.936 | 1.316 | 1.381 | 1.093 |
| x - - x x | 1.007 | -0.456 | 0.939 | 1.257 | 1.240 | 1.078 |
| - x x - - | 0.823 | -0.144 | 0.731 | 2.054 | 2.847 | 1.343 |
| - x x - x | 0.919 | -0.315 | 0.842 | 1.650 | 2.190 | 1.187 |
| - x x x x | 0.929 | -0.243 | 0.885 | 1.494 | 1.914 | 1.142 |
| - x x - x x | 0.959 | -0.327 | 0.910 | 1.396 | 1.650 | 1.152 |
| - x - x - x | 0.965 | -0.403 | 0.885 | 1.733 | 1.856 | 1.162 |
| - x - x x x | 0.940 | -0.300 | 0.887 | 1.482 | 1.864 | 1.134 |
| - x - x - x | 0.977 | -0.405 | 0.913 | 1.358 | 1.592 | 1.131 |
| - - x x - x | 0.702 | 0.295 | 0.663 | 2.475 | 3.362 | 1.427 |
| - - x - x x | 0.813 | 0.081 | 0.801 | 1.883 | 2.598 | 1.313 |
| - - x - x x | 0.862 | -0.088 | 0.819 | 1.731 | 2.435 | 1.249 |
| - - - x x x | 0.609 | 0.697 | 0.493 | 2.883 | 4.126 | 1.265 |

- The mean value per bin and the standard deviation per bin - are set in relation to the bins of the met mast power curve. The average values are calculated from these relative values (Equation (4) and (5)). In order to be able to compare the AEP, the relative values were determined for all calculated annual wind speeds and the average value was also calculated (Equation (6)). The results for the different methods are shown in Table 1, the results for the WFC are listed in Table 2. In total 57 different combinations were examined, 26 for the WFC method and 31 for the different averaging methods. Values above one indicate that the examined method is larger than the reference, smaller one indicate correspondingly smaller. If the mean value is greater than one, this means that there is more power in the bins (shift of the power curve to lower wind speeds). For the values for the standard deviation, values smaller than one mean that the fluctuations within the bins have been reduced, which means a reduction in uncertainties. The values of the power curve have a direct influence on the AEP. Values greater than one mean that more energy is be generated as with the reference power curve.

\[
\text{Mean} = \frac{1}{N_{\text{bin}}} \sum_{i} \left( \frac{P_{\text{REF},i}}{P_{\text{IEC},i}} \right)_{\text{mean}}
\]  

(4)
\[
\text{Std} = \frac{1}{N_{\text{bin}}} \sum_{i} \left( \frac{P_{\text{REWS},i}}{P_{\text{IEC},i}} \right)_{\text{std}} \\
\text{AEP} = \frac{1}{N_{\text{AEP}}} \sum_{i} \left( \frac{\text{AEP}_{\text{REWS},i}}{\text{AEP}_{\text{IEC},i}} \right)
\]

Tables 1 and 2 contain the following information: The first column contains the name of the used method, followed by the lidar measurement distances (’x’ means is used), which were used as the basis for the power curve determination. The values in the columns Slope, Offset and \( R^2 \) refer to the parameters of an ordinary least square fit (OLS) to the averaged lidar REWS and the met mast wind speed. An example of the OLS is shown in Figure 2b, the x-axis represents the horizontal wind speed from the met mast and the y-axis represents the REWS of the lidar measurement. The last three columns \( \text{Mean}, \text{Std}, \) and \( \text{AEP} \), represent the relative averages of bin mean power values and bin standard deviation of the power of performance curves and the averages of AEP. Positive comparisons are highlighted in green, negative comparisons are highlighted in red.

When comparing the different methods with the wind speed measurement at the met mast, the ground-based nacelle \( V2 \) shows the best matches, there are only very few differences. The methods for the nacelle-based lidar measurements reveal a clear dependence on the measurement distance in the OLS comparison with the met mast. The Slope increases with the measuring distance, the Offset also decreases in the trend. In case of close distances in front of the rotor, the wind speed is reduced. The influence within the induction zone on the deceleration of the wind speed can be seen, the Offset increases with the distance. The coefficient of determination \( R^2 \) of each method is not very different, these values are relatively constant around a value of 0.98.

If the characteristic values of the power curves are compared with each other, the parameters differ considerably in some cases. Again, an influence of the measurement distance can be detected, the average values of the bins decrease with the measurement distance. This in turn is a consequence of the induction, which causes a deceleration of the wind speed and shifts the power curve to the left. A further effect to be considered here is the significance of the averaging over the complete rotor area. This also takes into account the vertical shear. This can be clearly seen in the method \( \text{Twobeam} \): While the average power is almost identical to the mast measurements, the average standard deviation is clearly increased by up to 25\%. In comparison, the methods considering how the measuring points are distributed over the height show a significant reduction in scatter per bin. This is most obvious for the method \( \text{Corner}4\text{p1points} \) for measuring distance 136.3 m and for method \( \text{Cartesian} \) for measuring distance of 81.8 m. At all methods except for the two methods \( \text{Cartesian} \) and \( \text{Polar} \), the standard deviation in measurement distance of 163.5 m increases. No abnormalities were found in the measured data, therefore it is assumed that the points are distributed unfavorably in the rotor area to represent the real power consumption. In comparison, the measurement with the ground-based lidar shows no difference in the mean value of the power curve, but a reduction of the dispersion in the bins by about 13.5\%. This is only achieved by averaging the wind speed over the rotor area.

From the results of the \( \text{WFC} \) method, it can be clearly seen that the selection of the measuring distances used is decisive for the quality of the wind field reconstruction. The worst correlation is found in the reconstruction with the two farthest measuring distances (163.5 m, 190.8 m). The statistical values are 40\% percent lower and the dispersion is very large compared to the met mast with \( R^2 = 0.493 \). The other three combinations show a similar behaviour where the distances used lie directly next to each other (81.8 m and 109 m; 109 m and 136.3 m; 136.5 m and 163.5 m). If there is a larger distance between the used layers, the result will be better. In comparison, the combination with the measurement distances 81.8 m and 163.3 m correlate good
with the reference data: the $R^2$ is 0.95 and the Slope is 1.014, but the Offset of $-0.429$ is about twice as high as with the methods in Table 1.

The power curves created with the wind speed from the WFC method (same distance as the mast) show significantly higher values than the power curve based on the mast data. For combinations with reasonable match ($R^2 > 0.92$) when compared to the mast, the averages of the power curve showed values up to 32% higher than the mast power curve. The values for the standard deviation are significantly higher. The values for the AEPs are also increased according to the power curve. However, there are two exceptions where the three parameters are in the range of the met mast power curve. These are the combinations with the distances 81.8 m, 109 m, 190.8 m and 81.8 m, 163.5 m.

Compared to the results of Borraccino [10], the results of this study are significantly worse. One reason for this could be that Borraccino has used 6 points per measurement distance and the data were filtered significantly more strictly. If only 5 points (the four corners and the center point) per measuring plane are used instead of the 25 points, the result for combining the first two measuring distances with the measuring mast improves to an Offset of $-0.3901$ and Slope of 1.002 and $R^2$ of 0.9372. This represents a significant improvement of the result.

4. Conclusion
This study investigated several different approaches to averaging nacelle based pulsed wind lidar measurements. No method has proven to be the measure of all things. What became clear is that it is important to detect the vertical shear. In addition, the data show a significantly lower standard deviation for closer measuring distances than for farther measuring distances. For this test site, the methods Cartesian (at 81.8 m), Corner4p1points (at 81.8 m), and Corner4points (at 136.3 m) showed the best combination of the highest mean, lowest standard deviation and highest AEP values. In the WFC method used, the values showed considerable deviations from the measurement mast, also with respect to the measurement mast performance curve. The selection of measurement distances as input variables for the WFC model has a considerable influence on the results. At this test site, the best combinations were 81.8 m, 109 m, 190.8 m and 81.8 m, 163.5 m. A reduction of the dispersion in the bins and thus a reduction of uncertainties could not be achieved with the WFC method. A possible cause for the bad matches, also in comparison to Borraccino [10], is the large number of measuring points (25 points per measuring distance) that were used. The results could be improved by a reduction to a significant selection (5 points; 4 corner points plus center point). In comparison to the “simple” methods, where the measuring points are combined into a REWS, the WFC method performs worse. For this method the selection of the measuring points plays a significant role, which should be investigated in a further work.

For this purpose, it is more appropriate to use the measurement data averaged over the rotor area for averaging and power curve determination. However, the future of power curve determination will be the nacelle-based remote sensing methods. The mere fact of capturing the wind field directly in front of the turbine and thus obtaining detailed flow information, which is also seen by the wind turbine, has been shown to lead to a reduction of uncertainties.

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References

[1] International Electrotechnical Commission 2017 *Wind energy generation systems. Part 12-1*,

[2] Wagner R 2010 *Accounting for the speed shear in wind turbine power performance measurement* Ph.D. thesis

[3] Rettenmeier A, Klausmann P, Hofsiä M, Bischoff O, Schlipf D, Siegmeier B and Kühn M 2011 *EWEA 2011, Brussels*

[4] Wagner R, Cañadillas B, Clifton A, Feeney S, Nygaard N, Poodt M, Martin C S, Tüxen E and Wagenaar J W 2014 *Journal of Physics: Conference Series* **524** 012108

[5] Hofsiä M, Kozlowski D, Siebers T and Cheng P W 2015 *Proceedings of the 13th German Wind Energy Conference DEWEK 2015, 19th-20th May 2015 in Bremen, Germany*

[6] Schlipf D, Schlipf D J and Kühn M 2013 *Wind Energy* **16** 1107–1129

[7] Taylor G I 1938 *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **164** 476–490

[8] Rettenmeier A, Schlipf D, Würth I and Cheng P W 2014 *Journal of Atmospheric and Oceanic Technology* **31** 2029–2034

[9] Würth I, Rettenmeier A, Schlipf D, Cheng P W, Wächter M, Rinn P and Peinke J 2012 *Proceedings of the 11th German Wind Energy Conference DEWEK 2012, 7th-8th November 2012 in Bremen, Germany*

[10] Borraccino A, Schlipf D, Haizmann F and Wagner R 2017 *Wind Energy Science* **2** 269–283

[11] Rettenmeier A, Bischoff O, Hofsiä M, Schlipf D and Trujillo J J 2010 *EWEC 2010, Warsaw*

[12] Newville M, Stensitaki T, Allen D B and Ingargiola A 2014 *LMFIT: Non-Linear Least-Square Minimization and Curve-Fitting for Python*