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Power curve measurement uncertainty – follow up comparative exercise for IEA Task 32

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Abstract. A comparative exercise for estimating the uncertainty associated with new methods for power performance measurements was coordinated by the International Energy Agency (IEA) Wind Task 32. Both IEA Task 32 and the Power Curve Working Group (PCWG) have identified the application of the new uncertainty guidelines as a problem area. One time series dataset from a wind turbine, hub height mast and vertical profiling lidar was provided to calculate the power curve using three different wind speed definitions. For each wind speed definition, participants had to estimate the wind speed measurement uncertainty based on the guidance provided by the June 2016 Final Draft International Standard (FDIS) of IEC 61400-12-1 Edition 2. The comparative exercise included three iterations over the course of one year to incrementally harmonize the calculations and assumptions. The exercise showed significant variability among participants reflecting difficulty with the interpretation and application of the informative guidance. It also demonstrated that when using current technology and the available calibration techniques the use of a standalone lidar with a short met mast resulted in a significantly higher uncertainty compared to only using a hub height mast (with some measurements of wind shear and wind veer in the lower rotor).

1. Introduction

The method for calculating a wind turbine's power curve using a Rotor Equivalent Wind Speed (REWS) was previously evaluated in a comparative exercise [1] coordinated within International Energy Agency (IEA) Wind Task 32. The focus of the exercise was the application and impact of using a REWS versus a Hub-Height Wind Speed (HHWS) under various inflow conditions using existing datasets. The scope of the exercise did not require an estimate of the measurement uncertainty but it did show variation in the application or interpretation of applying a REWS. Other work has been conducted to assess the impact of wind speed shear and to some extent the associated uncertainties [2][3][4][5]. In March of 2017, IEC 61400-12-1 Edition 2 [6] was released which included the option to apply REWS for power performance measurements and guidance for how to estimate the REWS uncertainty. For the purpose of this exercise, there was a limited focus applied to differences in the power curve and Annual Energy Production (AEP) as a result of the different wind speed definitions. Instead, the focus was comparing the measurement uncertainty both in the binned power curve and for the estimated AEP values. It should be considered that some variation in the uncertainty was expected.



Three iterations of the exercise were completed between August of 2016 and June of 2017 and therefore only the first exercise was truly ‘blind’ for the participants. For each iteration, more guidance was provided to harmonize the wind speed bins, apply filters for lidar availability, align uncertainty parameters, and finally to adjust some uncertainty estimates to be less conservative than the guidance provided in the IEC Standard.

IEA Task 32 and the Power Curve Working Group (PCWG) each invited all members to participate in the round robin. Approximately 40 participants initially expressed interest, however only 8 submitted complete results for the first round of the exercise. The number of complete results varied from 8 to 11 during the three iterations. Participants primarily included third party measurement laboratories but also consisted of wind turbine manufacturers and research institutions.

It should be emphasized that the results of the comparative exercise are based on a common dataset and only a subset of the uncertainty components were considered. Further, the exercise focused on the relative differences in the uncertainty without having a requirement that the input values, such as the binned power curve, was identical between participants. Both the absolute value of the uncertainty and the differences in uncertainty for a real-world test will vary based on many factors including variations in the binned power curve.

2. Methods

The comparative exercise was planned within the IEA Task 32 Advisory Board. Initial planning including identifying a dataset, creating a template for submission of results, and creating instructions for the exercise. Once these tasks were completed, the first round of the comparative exercise was launched in August of 2016.

2.1 Definitions

Wind Speed 1 (WS1):

In the following definition, all references to equations or Clauses refer to IEC 61400-12-1 Edition 2. This wind speed definition is known as REWS including veer ($v_{eq,final}$), meaning Clause 7.2.6 option a, using Eq 11, Eq 9, and Eq Q1. Or:

$$v_{eq,final} = f_{r,RSD} \cdot v_{h,MM} \quad (1)$$

where:

$v_{eq,final}$ is the final rotor equivalent wind speed;
 $f_{r,RSD}$ is the wind shear correction factor using a remote sensing device;
 $v_{h,MM}$ is the wind speed measured by the cup anemometer at hub height.

$$f_{r,RSD} = \frac{v_{eq,RSD}}{v_{h,RSD}} \quad (2)$$

where:

$f_{r,RSD}$ is the wind shear correction factor using a remote sensing device;
 $v_{eq,RSD}$ is the rotor equivalent wind speed measured by the remote sensing device;
 $v_{h,RSD}$ is the wind speed measured by the remote sensing device at hub height.

$$v_{eq,RSD} = \left[\sum_{m=1}^{n_h} (v_m \cos(\varphi_m))^3 \frac{A_m}{A} \right]^{\frac{1}{3}} \quad (3)$$

where:

$v_{eq,RSD}$ is the rotor equivalent wind speed measured by the remote sensing device;

n_h is the number of available measurement heights in area of the rotor;
 v_m is the wind speed measured at height m ;
 φ_m is the difference between the wind direction at hub height and the one at height m ;
 A is the rotor swept area;
 A_m is the area of the m th segment, i.e. the segment for which wind speed v_m is representative.

Wind Speed 2 (WS2):

This wind speed definition is the HHWS meaning Clause 7.2.7, option a. This is the ‘classic’ definition of HHWS from a cup anemometer on the met mast assuming the lidar data was not available.

Wind Speed 3 (WS3):

This wind speed definition is the lidar-based REWS including veer, meaning Clause 7.2.6 option b, using Eq Q1 (Eq. 3 above). Only the measurements from the 33 m measurement height from the met mast were assumed to be available for monitoring of the lidar.

2.2 Dataset

The 10-minute time series dataset provided for the exercise included wind turbine active power signals and meteorological (met) signals from both a hub height met mast and vertical profiling lidar. A summary of the available signals is provided in Table 1. The dataset allowed for a valid database of approximately 600 hours with complete winds peed bins from approximately 1.0 to the cut out winds speed of 25.0 m/s.

Table 1. Summary of time series data available to participants.

Height above ground level (m)	Instrument type	Manufacturer/Model	Mounting arrangement
100	MEASNET Calibrated Anemometer	Windsensor P2546A	Single top mount
96	MEASNET Calibrated Anemometer	Windsensor P2546A	Side mount
33	MEASNET Calibrated Anemometer	Windsensor P2546A	Side mount
96	MEASNET Calibrated Wind Vane	Thies First Class Wind Direction	Side mount
33	MEASNET Calibrated Wind Vane	Thies First Class Wind Direction	Side mount
2	Data logger	Campbell Scientific CR1000	Base
NA	Lidar	Leosphere Windcube V2 (window height 0.5m), measurement heights at 37, 55, 69, 84, 99, 113, 127, 141 and 158m with respect to the window height	NA

2.3 Uncertainty parameters

In order to limit the variability of results only a narrow set of wind speed and method uncertainty parameters were considered in the exercise. The parameters were selected to focus the comparison between a met mast versus lidar measurement method. Also, the wind speed uncertainty is typically the dominant part of the total uncertainty budget and while there will be some additional uncertainty for a full analysis according to the IEC Standard, the additional contributions are small. The instructions related to the uncertainty parameters are provided below;

- No lightning finial was installed on the mast.
- Uncertainty for air density related measurements or uncertainty for air density normalization shall not be considered.

- In addition to the Category A uncertainties, only the Category B parameters in the below table should be included in the uncertainty assessment to avoid variation in the results due to issues not related to the wind speed measurements (e.g. power, turbulence).
- All numbers provided in the below table shall be used in the uncertainty calculations. For any fields marked Participant, the value must be derived from the data, calibration certificates, classification reports and/or by using the guidance in Ed. 2 of 12-1.

Table 2 below summarizes the parameters that were considered in the final analysis. Parameters with more than one value and highlighted in red were updated at different iterations throughout the exercise as described above. Table 3 shows a sample of the calibration uncertainty values for the cup anemometer and the lidar.

Table 2. Summary of uncertainty parameters provided to participants.

Measured parameter	Source of uncertainty (references to IEC 61400-12-1 Ed. 2)	WS1 – mast for HHWS and lidar for REWS	WS2 – mast only for HHWS	WS 3 – Lidar for REWS with short mast for verification
Wind speed – measurement				
Wind Speed – cup	Calibration [E.9.2]	Participant	Participant	Participant
	In-situ calibration [E.9.3]	0 m/s	0 m/s	0 m/s
	Operational characteristics [E.9.4]	Class A = 1.32	Class A = 1.32	Class A = 1.32
	Mounting effects [E.9.5]	0.5%	0.5%	0.5%
	Data acquisition [E.9.6]	0.1%	0.1%	0.1%
Wind Speed RSD	Calibration [E.7.2]	Participant	N/A	Participant
	In-situ calibration [E.7.3]	0 m/s	N/A	0 m/s
	Classification [E.7.4]	Table L.8/1.0%	N/A	Table L.8/1.0%
	Mounting [E.7.5]	0.5%/0.1%	N/A	0.5%/0.1%
	Flow variation [E.7.6]	2.0%/0.5%	N/A	2.0%/0.5%
	Monitoring test [E.7.7]	0%	N/A	0%
REWS	Wind shear [E.8.2]	Participant [E.8.2.4]	N/A	Participant [E.8.2.3]
	Wind veer [E.12.3]	Participant	N/A	Participant
Wind speed – terrain effects				
Terrain without site calibration Method	Flow distortion due to terrain [E.9.1]	2%	2%	2%
Wind conditions	Wind shear [E.11.2.2]	Participant [E.11.2.2.3]	Participant [E.11.2.2.2]	Participant [E.11.2.2.3]
	Wind veer [E.11.2.3]	N/A	Participant [E.11.2.3.3]	N/A

Table 3. Sample of uncertainty for cup anemometer and lidar (near hub height) calibration with coverage factor $k = 2$.

Wind speed bin (m/s)	Cup anemometer calibration uncertainty (m/s)	Lidar calibration uncertainty at 100 m (m/s)
4	0.050	0.323
6	0.050	0.297
8	0.050	0.351
10	0.050	0.415
12	0.050	0.448
14	0.051	0.507
16	0.051	0.584

2.4 Instructions to participants

The first round required calculating the following for each wind speed definition:

- Segment weighting and height limits for the REWS
- Binned power curves including number of data points per bin
- Type A, B and combined uncertainty for the binned power curve
- Measured annual energy production (AEP)
- Uncertainty in measured AEP

For the first round, participants were asked to provide results for only the first two wind speed definitions defined below with limited instruction. The intent was to capture discrepancies in the interpretation of the existing documentation to simulate real world variation. It was expected that additional instruction would be required to achieve better agreement in the results. For the subsequent rounds two and three, the third wind speed definition was required.

For the second round, only the third wind speed definition was added to the exercise without any further detailed instruction. The results from the second round were presented and discussed at an IEA Workshop in December of 2016, where most participants were present. The outcome of the discussion was that a third round was needed with some more detailed instructions to limit variations in the binned power curve results, and also some more practical assumptions would be provided for the Type B uncertainty components for RSD classification, mounting and probe volume. The changes to the uncertainty components and exercise instructions included:

- Use coverage factor of $k = 1$ for all analyses (i.e. divide the values by 2 on both the lidar and anemometer calibration sheets)
- Add the lidar window height to the signal channel heights. Therefore the above ground lidar measurement heights are 39.6, 55.6, 69.6m etc. corresponding to the mast heights of 33, 96 and 100m.
- Availability requirement of greater than 95% must be applied to all measurement heights on the lidar for each 10-minute record.
- Wind speed bins are defined as lower limit exclusive and upper limit inclusive, for example $0.25 \leq 0.5\text{m/s bin} < 0.75$.
- Cut out wind speed of 25 m/s: limit AEP calculations to 25 m/s bin.
- After applying the filters, the same data points and overall data count should be used in each wind speed definition.
- Classification changed from Table L.8 to 1% following magnitude provided in Table E.2
- Mounting changed from 0.5% to 0.1% following magnitude provided in Table E.2

Flow variation changed from 2% to 0.5% assuming a very flat site (inflow/outflow of 0.3/-0.3 and 28 degree beam) following formula E.20

3. Results

Table 4 below shows the average and standard deviation for the AEP results for each stage of the exercise. In Round 2 there was a significant outlier and results in the table are shown with and without the outlier included. The low standard deviations values for WS1 and WS2 suggest that a good

consensus was found among participants. The standard deviation for WS3 was consistently higher than the WS1 and WS2, suggesting there was less consensus for how to estimate the uncertainty for this case.

Table 4. Results for uncertainty as percentage of measured AEP for 8 m/s Rayleigh wind speed distribution

WS1 Average (%)	WS1		WS2		WS3		Number of participants
	Average (%)	Standard Deviation (%)	Average (%)	Standard Deviation (%)	Average (%)	Standard Deviation (%)	
Round 1	2.96	0.08	3.25	0.31	NA	NA	8
Round 2	4.58	5.92	4.03	3.65	6.10	5.39	11
Round 2 – outlier removed	2.82	0.98	2.97	1.01	4.56	1.84	10
Round 3	2.95	0.06	3.15	0.13	4.55	0.90	8

Figure 1 shows the data count deviations for each participant from the mean data count from all eight participants in Round 3. In general, the bin counts are within 2 points of the mean for all participants with one outlier in WS2. Figure 2 shows the binned power deviations for each participant from the mean power value from all eight participants in Round 3. For Figure 2, there are multiple cases where participants had the exact values across all wind speeds and the separate results cannot be distinguished in the plots. Figure 3 shows the wind speed bin Type B uncertainty deviations for each participant from the mean Type B uncertainty value from all eight participants in Round 3. From the plots we can see that in some cases participants had identical or nearly identical results, with lines being overlapped.

Figure 4 shows the average uncertainty values for each wind speed definition expressed as a percent of AEP for different Rayleigh wind speed distributions, for all three Rounds of the exercise. The average calculated uncertainty of WS1 and WS2 is comparable, while for WS3 is significantly higher. This is partly due to the uncertainty associated with lidar measurements and partly due to the WS3 method itself that uses the lidar measurements as main reference and the wind speed from the small met mast for verification purposes only.

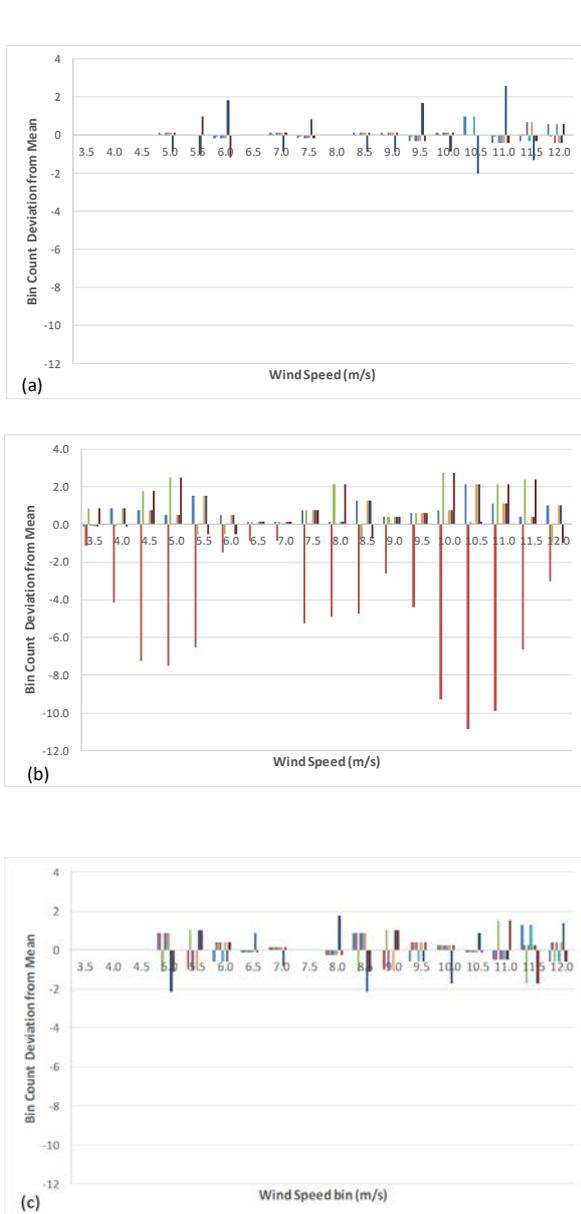


Figure 1. Round 3 results – Data count deviation of for each participant from mean data count per wind speed bin from all eight participants for (a) WS1, (b) WS2 and (c) WS3.

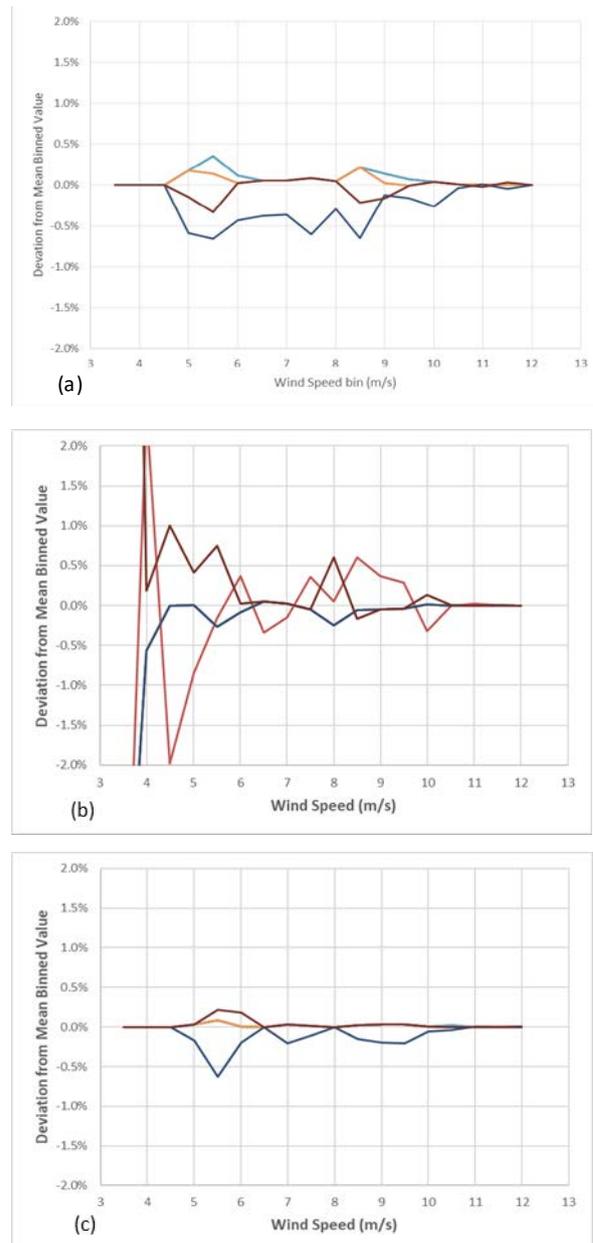


Figure 2. Round 3 results - Deviations of binned power from average for (a) all eight participants for WS1, (b) all eight participants for WS2 and (c) seven of eight participants for WS3. One participant did not complete the WS3 calculation.

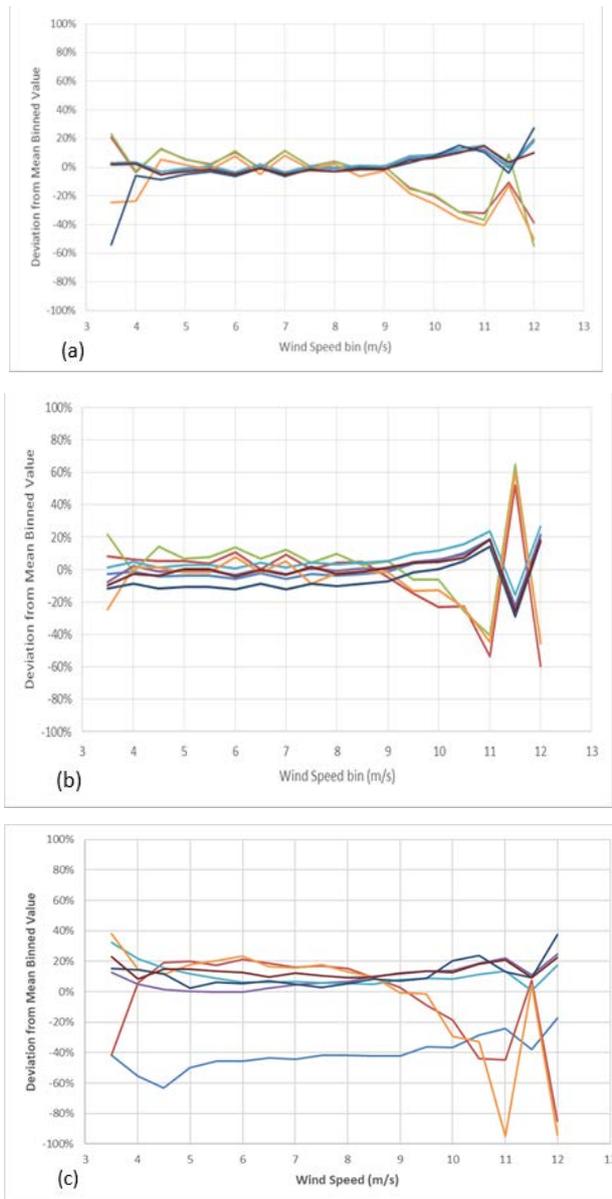


Figure 3. Round 3 results - Type B uncertainty deviation for each participant from mean Type B uncertainty for all eight participants for (a) WS1, (b) WS2 and (c) WS3.

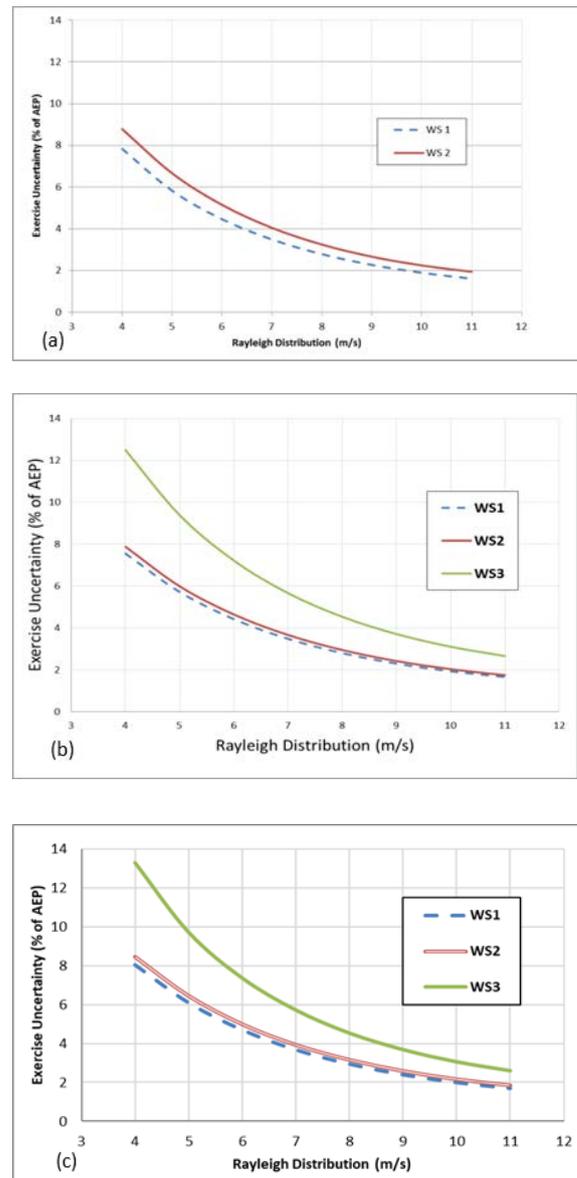


Figure 4. Round 3 results - Each line represents the average uncertainty expressed as a % of AEP from all participants for (a) Round 1 where only WS1 and WS2 were included, (b) Round 2 - outlier removed and (c) Round 3.

4. Conclusions

The goal of IEA Task 32 is to identify and mitigate barriers to the application of lidar in the wind industry. The comparative exercise was able to achieve a general consensus result despite some variability that is to be expected. This variability can be related to the informative nature of Annex E in [2] and also when not providing very detailed instructions for sensitivities, combining uncertainties, etc. Two main conclusions were extracted from the exercise:

- The uncertainty related to the interpretation of [2], and the relative uncertainty of the AEP, is higher for WS3 than for the other two wind speed definitions.
- The addition of a lidar for REWS to a hub height met mast has a relatively small reduction in the overall uncertainty compared to only using a hub height met mast

From the first conclusion, we can see a potential barrier for lidar deployment is the additional uncertainty in using the lidar as the primary wind speed measurement device. It is already known that the classification can be a significant driver in the overall uncertainty of a cup or lidar for a power performance measurement. The classification procedure for lidar is relatively new and as such it should continue to be evaluated and improved which may result in reduced overall uncertainty. Also specific to lidar, the uncertainties from the calibration are limited by the reference measurement device (i.e. cup or sonic anemometer). It is suggested that in order to reduce the calibration uncertainty for lidar the technology must improve its performance relative to the reference measurement and/or a better reference measurement can be applied. Approaches that use the lidar to extrapolate the wind speed from the small met mast could also be considered as an alternative. Such a method could allow for a reduced uncertainty by starting with the cup anemometer wind speed uncertainty from the short mast the basis of the wind speed uncertainty instead of the lidar uncertainty. It should be noted again that the IEC Standard's guidance for uncertainty is only informative and that there is flexibility in how it is interpreted and applied.

It is expected that the exercise will help to guide the industry to focus its efforts in refining the methodology for lidar uncertainty assessment by providing a measure of how much improvement is needed to be as good or better than a cup anemometer. The benefits from any improvements should be applicable for all types of lidar measurements in the wind industry.

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