



Cumulating Wind Speed Measurement Uncertainties Across Site Calibration and Power Curve Test

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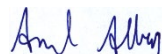
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Contents

1	Introduction	6
2	Inconsistencies and Gaps in the Standards IEC 61400-12-1 and IEC 61400-12-3 Related to Uncertainty Cumulating Across Site Calibration and Power Curve Test	7
2.1	Uncertainty of Anemometer Calibration Before Site Calibration / Power Curve Test, $u_{VS,precal}$, $u_{VT,precal}$	7
2.2	Uncertainty of Anemometer Calibration Residuals Before Site Calibration / Power Curve Test, $u_{VS,precal_res}$, $u_{VT,precal_res}$	8
2.3	Uncertainty Due to Result of Post Calibration of the Anemometer or In-Situ Test, $u_{VS,postcal}$, $u_{VT,postcal}$	8
2.4	Uncertainty Resulting from the Operational Characteristics of the Anemometer, $u_{VS,class}$, $u_{VT,class}$	8
2.5	Uncertainty Due to Anemometer Mounting Effects, $u_{VS,mnt}$, $u_{VT,mnt}$	9
2.6	Uncertainty of Wind Speed Data Acquisition, u_{dVS} , u_{dVT}	10
2.7	Uncertainty Due to Effects of the Lighting Finial, $u_{VS,igt}$, $u_{VT,igt}$	10
3	Uncertainty Model	11
4	Correlation of Uncertainties of Reference Measurement at Site Calibration and Power Curve Test	14
4.1	Correlation of Uncertainty of Anemometer Calibration Before Site Calibration / Power Curve Test, $u_{VS,precal}$	15
4.2	Correlation of Uncertainty of Anemometer Calibration Residuals Before Site Calibration / Power Curve Test, $u_{VS,precal_res}$	16
4.3	Correlation of Uncertainty Due to Result of Post Calibration of the Anemometer or In-Situ Test, $u_{VS,postcal}$	17
4.4	Correlation of Uncertainty Resulting from the Operational Characteristics of the Anemometer, $u_{VS,class}$	18
4.5	Correlation of Uncertainty Due to Anemometer Mounting Effects, $u_{VS,mnt}$	18
4.6	Correlation of Uncertainty of Wind Speed Data Acquisition, u_{dVS}	18
4.7	Correlation of Uncertainty Due to Effects of the Lighting Finial, $u_{VS,igt}$	19
5	Issues Related to Other Site Calibration Uncertainties than Wind Speed Measurement Uncertainties	20
5.1	Statistical Uncertainty, s_{sc}	20
5.2	Systematic Uncertainty of Site Calibration Algorithm, $u_{VT,alg}$	20
5.3	Uncertainty Due to Change in Flow Correction Between Adjacent Wind Direction Bins, $u_{VT,coc}$	20
5.4	Uncertainty Due to Removal of Wind Direction Sensor, $u_{VT,rmv}$	21
5.5	Uncertainty Due to Site Calibration and Power Curve Measurements in Different Seasons, $u_{VT,sv}$	22
6	Guidance on Reporting of Uncertainties	24
6.1	Nomination of Uncertainties and Total Uncertainty of Site Calibration	24
6.2	Guidance on Separate Site Calibration Report	25

7	Uncertainty in Terms of AEP	27
8	Literature	28
9	Appendix A: Uncertainty of Relative Wind Direction Measurement	29
9.1	Correlation of Uncertainty of Calibration of Vanes, $u_{WV,cal,j}$	30
9.2	Correlation of Uncertainty of Vane Calibration Residuals, $u_{WV,cal_res,j}$	30
9.3	Correlation of Uncertainty of Determination of Sensor North Mark, $u_{WV,nm,j}$	31
9.4	Correlation of Uncertainty of Northing of Boom Direction, $u_{WV,bo,j}$	31
9.5	Correlation of Uncertainty due to Mast Effects, $u_{WV,oe,j}$	31
9.6	Correlation of Uncertainty due to Magnetic Declination, $u_{WV,mda,j}$	31
9.7	Correlation of Uncertainty of Wind Direction Data Acquisition, u_{dWV}	32

Disclaimer:

We hereby state, that the results in this report are based upon generally acknowledged and state-of-the-art methods and have been neutrally conducted to the best of our knowledge and belief. No guarantee, however, is given and no responsibility is accepted by Deutsche WindGuard Consulting GmbH for the correctness of the derived results. Any partial duplication of this report is allowed only with written permission of Deutsche WindGuard Consulting GmbH. The results of the following report refer to the investigated object only.

This report covers 32 pages.

1 Introduction

The guidance provided in the standards IEC 61400-12-3 [1] and IEC 61400-12-1 [2] how to cumulate wind speed measurement uncertainties across the process site calibration and power curve test and across the two measurement locations at a site calibration is inconsistent in multiple ways:

- It is inconsistent across the different uncertainty components.
- It is partly inconsistent across the standards IEC 61400-12-3 and IEC 61400-12-1.
- It is partly inconsistent across different sections of the single standards.
- No guidance is given at all for some uncertainty components.

This report presents a consistent method for the uncertainty cumulating based on the rules of error propagation as given in [3].

Furthermore, guidance on the treatment of other site calibration uncertainties is provided.

This report is focusing on site calibrations and power curve tests by the application of hub height met masts, though the presented principles are applicable also for such tests utilising ground-based lidars or combinations of met masts and ground-based lidars.

All uncertainty components treated by the proposed method shall be quantified for each wind speed bin of the measured power curve. IEC 61400-12-1 therefore applies the subscript “i” in the nomination of the uncertainty components, which has been left away here for simplification. An exception from this nomination is made in chapters 5.3 and 5.4 where the subscript “i” is used.

2 Inconsistencies and Gaps in the Standards IEC 61400-12-1 and IEC 61400-12-3 Related to Uncertainty Cumulating Across Site Calibration and Power Curve Test

2.1 Uncertainty of Anemometer Calibration Before Site Calibration / Power Curve Test, $u_{VS,precal}$, $u_{VT,precal}$

The following section of chapter 10.2.2 of IEC 61400-12-3 considers the correlation of uncertainties of the anemometer (pre-)calibration at the reference measurement location and at the turbine location at the site calibration:

The anemometer calibration standard uncertainty shall be taken from the calibrations. Where the anemometer calibrations on the reference meteorological mast and wind turbine location have been performed in the same tunnel, the estimated uncertainties are correlated to some extent; the same is true for calibrations of the anemometer(s) used for the power performance testing. A practical approach is to include the magnitude of one calibration uncertainty if the calibrations are done in the same wind tunnel. Where the calibrations have been done in different wind tunnels or different model anemometers are used, the uncertainties are independent and shall be taken into account as such.

Following that approach means accounting for:

- Uncertainty of anemometer calibration of sensor of the reference measurement at the power curve test $u_{VS,precal}$
- Uncertainty of anemometer calibration of sensor at the turbine location at the site calibration $u_{VT,precal}$
- In addition, if the sensors used at the two measurement locations at the site calibration have been calibrated in different wind tunnels or different anemometer models are used, uncertainty of anemometer calibration of sensor at the reference measurement location at the site calibration $u_{VT,precal}$
- The above two or three uncertainty components are considered as being independent from each other.

In contrast to that, the next section of chapter 10.2.2 of IEC 61400-12-3 considers the correlation of uncertainties of the anemometer (pre-)calibration at the reference measurement location at the site calibration and at the power curve test:

The following specific guidance is given. If the reference anemometer is not exchanged between site calibration and the power curve test, its calibration uncertainty cancels out completely. Only the turbine mast anemometer calibration uncertainty is then relevant. If the reference anemometer is exchanged between the site calibration and the power curve test for an anemometer calibrated in the same wind tunnel as used for the calibration of the first anemometer, a big part of the calibration of the reference anemometers cancels out if the wind tunnel gives highly reproducible results. If the reference anemometer is exchanged between the site calibration and the power curve test for an anemometer calibrated in a different wind tunnel to that used for the calibration of the first anemometer, the uncertainty of both anemometer calibrations is relevant.

Following that approach means accounting for:

- Uncertainty of anemometer calibration of sensor at the turbine location at the site calibration $u_{VT,precal}$
- Depending on the case, no, only part or both of the calibration uncertainties of the anemometer at the reference measurement position at the power curve test and at the site calibration

- Again, the above uncertainty components are considered as being independent from each other.

Often, the uncertainty calculated according to this second approach will be lower than following the first procedure.

2.2 Uncertainty of Anemometer Calibration Residuals Before Site Calibration / Power Curve Test, $u_{VS,precal_res}$, $u_{VT,precal_res}$

The uncertainty due to calibration residuals is not considered in IEC 61400-12-3 and IEC 61400-12-1.

2.3 Uncertainty Due to Result of Post Calibration of the Anemometer or In-Situ Test, $u_{VS,postcal}$, $u_{VT,postcal}$

No guidance is provided in IEC 61400-12-3 and IEC 61400-12-1 how to cumulate the uncertainty resulting from a post calibration or in-situ test across the different wind measurements at the power curve test and site calibration.

2.4 Uncertainty Resulting from the Operational Characteristics of the Anemometer, $u_{VS,class}$, $u_{VT,class}$

Chapter 10.2.4 of IEC 61400-12-3 considers the correlation of uncertainties due to the operational characteristics of the anemometer at the reference measurement location and at the turbine location at the site calibration:

This uncertainty is virtually the same as $u_{VS,class,i}$ with the difference that in this document it is applied to a measurement of wind speeds on two masts. Some of the influence factors for the classification will be experienced in the same way by both sensors, causing a correlation in the operational response and a reduction in the difference between the signals. But major influence factors such as turbulence, shear and upflow may be different between the two measurement locations and as such the magnitude of this uncertainty component shall be set to equal the uncertainty related to the classification of the anemometer on the wind turbine location meteorological mast.

Following that approach means accounting for:

- Uncertainty due to operational characteristics of anemometer at the turbine location at the site calibration $u_{VT,class}$
- Uncertainty due to operational characteristics of anemometer at the reference measurement location at the power curve test $u_{VS,class}$
- The above two uncertainty components are considered as being independent from each other.

The following section of Annex E.9.4 of IEC 61400-12-1 is in line with that approach:

This uncertainty is virtually the same as $u_{VS,class,i}$ with the difference that here it is applied to a measurement of wind speeds on two masts. Some of the influence factors for the classification will be experienced in the same way by both sensors, causing a correlation in the operational response and a reduction in the difference between the signals. Refer to IEC 61400-12-3 for details of how this should be handled.

In contrast to that, Annex E.6.3.4 of IEC 61400-12-1 considers the correlation of uncertainties due to operational characteristics of the anemometer at the reference measurement location at the site calibration and at the power curve test:

The operational uncertainty of the reference anemometer (from a possible site calibration according to IEC 61400-12-3) shall be included in this uncertainty component. This can be none, some, or all of the reference anemometer uncertainty from the site calibration, depending on if the measured range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the site calibration is significantly different from the range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the power curve test.

By default, half of the operational uncertainty of the reference anemometer and all of operational uncertainty of the turbine anemometer during the site calibration and half of the operational uncertainty of the anemometer during the power curve test shall be included. These shall be added using the root-sum-square approach.

Following that approach means accounting for:

- Uncertainty due to operational characteristics of anemometer at the turbine location at the site calibration $u_{VT,class}$
- Depending on the case, no, only part or both of the uncertainties due to operational characteristics of the anemometer at the reference measurement position at the power curve test and at the site calibration, where the default is accounting half of both uncertainties.
- Again, the above uncertainty components are considered as being independent from each other (two to three components).

2.5 Uncertainty Due to Anemometer Mounting Effects, $u_{VS,mnt}$, $u_{VT,mnt}$

Chapter 10.2.5 of IEC 61400-12-3 considers the correlation of uncertainties of the anemometer mounting effects at the reference measurement location and at the turbine location at the site calibration, where it is actually required to fully account both uncertainties:

This uncertainty is virtually the same as $u_{VS,mnt,i}$ with the difference that in this document it is applied to a measurement of wind speeds on two masts. If the sensors are of the same type, the mast layout is the same and the wind direction is the same, one could assume that a high correlation exists between the mounting influences from both masts on both sensors which would be grounds for a reduced uncertainty. However, even with the same sensor type and mast layout often the wind direction that is experienced simultaneously on both masts will not be the same. As the influence from the mast on the sensors is directionally sensitive, the actual correlation of mounting effects between both masts will be limited and the mounting effects need to be taken into account.

The argument given in this section that the uncertainties of both measurements must be accounted for because the wind direction experienced by both masts will not be the same is considered as incorrect. Often, the wind direction averaged over a 10-minute period will deviate only slightly, and hence very similar mast effects will usually occur at the two locations.

Following the above approach means accounting for:

- Uncertainty of anemometer mounting effects of the reference measurement at the power curve test $u_{VS,mnt}$
- Uncertainty of anemometer mounting effects at the turbine location at the site calibration $u_{VT,mnt}$
- Uncertainty of anemometer mounting effects at the reference measurement location at the site calibration $u_{VT,mnt}$
- The above three uncertainty components are considered as being independent from each other.

2.6 Uncertainty of Wind Speed Data Acquisition, u_{dVS} , u_{dVT}

Chapter 10.2.6 of IEC 61400-12-3 considers the correlation of uncertainties of the data acquisition system at the reference measurement location and at the turbine location at the site calibration, where it is actually required to fully account both uncertainties:

This uncertainty is virtually the same as $u_{dVS,i}$ with the difference that here it is applied to a measurement of wind speeds on two masts. As the data acquisition of both signals is assumed independent, this uncertainty needs to be counted twice.

Following the above approach means accounting for:

- Uncertainty of the data acquisition system at the reference measurement location at the power curve test u_{dVS}
- Uncertainty of the data acquisition system at the turbine location at the site calibration u_{dVT}
- Uncertainty of the data acquisition system at the reference measurement location at the site calibration u_{dVT}
- The above three uncertainty components are considered as being independent from each other.

2.7 Uncertainty Due to Effects of the Lightning Finial, $u_{VS,igt}$, $u_{VT,igt}$

Chapter 10.2.7 of IEC 61400-12-3 considers the correlation of uncertainties due to influences of a lightning finial at the reference measurement location and at the turbine location at the site calibration, where it is actually required to fully account both uncertainties:

This uncertainty is virtually the same as $u_{VS,igt,i}$ with the difference that in this document it is applied to a measurement of wind speeds on two masts. If the sensors are of the same type, the mast layout is the same and the wind direction is the same, one could assume that a high correlation exists between the mounting influences from both masts on both sensors which would be grounds for a reduced uncertainty. However, even with the same sensor type and mast layout often the wind direction that is experienced simultaneously on both masts will not be the same. As the influence from the lightning finial on the sensors is directionally sensitive, the actual correlation of mounting effects between both masts will be limited and the lightning finial effects (when the requirements for the finial of IEC 61400-50-1 cannot be met) need to be taken into account.

The argument given in this section is considered being invalid for the same reasons as disused in chapter 2.5 of this report.

Following the above approach means accounting for:

- Uncertainty due to influences of a lightning finial on the reference measurement at the power curve test $u_{VS,igt}$
- Uncertainty due to influences of a lightning finial at the turbine location at the site calibration $u_{VT,igt}$
- Uncertainty due to influences of a lightning finial at the reference measurement location at the site calibration $u_{VT,igt}$
- The above three uncertainty components are considered as being independent from each other.

3 Uncertainty Model

This chapter describes a model for the cumulating of wind speed measurement uncertainties across the process site calibration and power curve test.

The model approximates the wind speed finally applied for the power curve test as ratio of wind speeds measured at hub height at the turbine mast position and reference mast position at the site calibration multiplied by the wind speed measured at hub height at the reference mast position at the power curve test:

$$V_{final} = \frac{V_T}{V_{R_SC}} V_{R_PC} \quad (1)$$

where

- V_{final} : wind speed used for power curve evaluation
- V_T : wind speed measured during site calibration at turbine mast position at hub height
- V_{R_SC} : wind speed measured during site calibration at reference mast position at hub height
- V_{R_PC} : wind speed measured during power curve test at reference mast position at hub height

Applying the rules of error propagation on equation (1) results in:

$$\begin{aligned} u_{V_{final}}^2 = & \frac{V_{R_PC}^2}{V_{R_SC}^2} u_{V_T}^2 + \frac{V_T^2}{V_{R_SC}^2} u_{V_{R_PC}}^2 + \frac{V_{R_PC}^2 V_T^2}{V_{R_SC}^4} u_{V_{R_SC}}^2 + 2 \frac{V_{R_PC} V_T}{V_{R_SC}^2} u_{V_T} u_{V_{R_PC}} \rho_{V_T, V_{R_PC}} \\ & - 2 \frac{V_{R_PC} V_T}{V_{R_SC}^3} u_{V_T} u_{V_{R_SC}} \rho_{V_T, V_{R_SC}} - 2 \frac{V_T^2 V_{R_PC}}{V_{R_SC}^3} u_{V_{R_PC}} u_{V_{R_SC}} \rho_{V_{R_PC}, V_{R_SC}} \end{aligned} \quad (2)$$

where

- $u_{V_{final}}$: uncertainty of V_{final}
- u_{V_T} : uncertainty of V_T
- $u_{V_{R_SC}}$: uncertainty of V_{R_SC}
- $u_{V_{R_PC}}$: uncertainty of V_{R_PC}
- $\rho_{V_T, V_{R_PC}}$: correlation coefficient of uncertainty of V_T and uncertainty of V_{R_PC}
- $\rho_{V_T, V_{R_SC}}$: correlation coefficient of uncertainty of V_T and uncertainty of V_{R_SC}
- $\rho_{V_{R_PC}, V_{R_SC}}$: correlation coefficient of uncertainty of V_{R_PC} and uncertainty of V_{R_SC}

Given the fact that the measurement at the reference mast position during the site calibration and during the power curve test is basically the same measurement, which is just undertaken in different periods, the following approximations apply:

$$\begin{aligned} u_{V_{R_PC}} & \approx u_{V_{R_SC}} \\ \rho_{V_T, V_{R_PC}} & \approx \rho_{V_T, V_{R_SC}} \end{aligned}$$

Furthermore, it is by definition per bin average: $V_{R_PC} = V_{R_SC}$

With these approximations and the introduction of the site calibration factor

$$f_{SC} = \frac{V_T}{V_{R_SC}}$$

equation (2) simplifies to:

$$u_{V_final}^2 = u_{V_T}^2 + f_{SC}^2 (u_{V_{R_PC}}^2 + u_{V_{R_SC}}^2 - 2u_{V_{R_PC}} u_{V_{R_SC}} \rho_{V_{R_PC}, V_{R_SC}}) \quad (3)$$

According to equation (3), the square of the uncertainty of the wind speed applied for the power curve analysis u_{V_final} equals the square sum of the uncertainty of the wind speed measurement at the turbine position u_{V_T} and the uncorrelated and unequal part of the wind speed measurement uncertainty at the reference mast position at the site calibration and power curve test ($u_{V_{R_PC}}^2 + u_{V_{R_SC}}^2 - 2u_{V_{R_PC}} u_{V_{R_SC}} \rho_{V_{R_PC}, V_{R_SC}}$) times the site calibration correction f_{SC} . By that, it is illustrated that a well-designed site calibration and power curve test campaign requires an accurate wind speed measurement at the future turbine position (u_{V_T} small) and a timely consistent measurement at the reference mast position ($\rho_{V_{R_PC}, V_{R_SC}}$ close to 1).

Qualitatively, equation (3) can be understood from the fact that any bias of the wind speed measurement at the reference measurement position due to measurement uncertainties as equally present at the site calibration and at the power curve test will be integrated into the wind speed correction as derived at the site calibration and hence will be corrected for when applying the correction at the power curve test. If for instance the wind speed measurement at the reference measurement location has a bias of -5% throughout the entire measurement period of the site calibration and power curve test this will lift the wind speed correction factor derived from the site calibration data by a factor of about 1.05, and hence the bias does not appear in the wind speed finally applied for the power curve test. Contrary, as the site calibration corrects the wind speed measurement at the reference measurement position to the measurement at the turbine position, the uncertainty of the wind speed measurement at the turbine position will be fully present in the uncertainty of the wind speed finally applied for the power curve analysis.

It is noted that similar uncertainty cumulating over the process site calibration and power curve test as described by equation (3) is recommended for some components of cup anemometer measurements in IEC 61400-12-1 and IEC 61400-12-3, however not in a consistent way for all components and also only by approaching the site calibration factor f_{SC} by 1 (see chapter 2).

Equation (3) needs to be carried out for each uncertainty component of the wind speed and for each wind speed bin. Assumptions on $\rho_{V_{R_PC}, V_{R_SC}}$ are suggested in chapter 4. Furthermore, the following guidance is proposed for the practical implementation of equation (3):

- The left term of the right side of equation (3) u_{V_T} and the right term of the right side of equation (3) $f_{SC}^2 (u_{V_{R_PC}}^2 + u_{V_{R_SC}}^2 - 2u_{V_{R_PC}} u_{V_{R_SC}} \rho_{V_{R_PC}, V_{R_SC}})$ shall be treated as two uncertainty components (for each type of uncertainty), which are cumulated separately to an uncertainty in AEP. This is important to avoid overestimation of the total uncertainty in the AEP as is explained in reference [4]. The uncertainty components represented by u_{V_T} then replace the wind speed measurement uncertainties u_{V_T} given in IEC 61400-12-1, whereas the components represented by $f_{SC}^2 (u_{V_{R_PC}}^2 + u_{V_{R_SC}}^2 - 2u_{V_{R_PC}} u_{V_{R_SC}} \rho_{V_{R_PC}, V_{R_SC}})$ replace the

wind speed measurement uncertainties u_{v_S} of IEC 61400-12-1 (see also chapter 6.1 of this report).

- f_{SC} shall be calculated as ratio of the site-calibrated (but not air density corrected) wind speed and the wind speed measured at the reference mast at the power curve test, both bin-averaged against the wind speed finally applied for the power curve test (air density corrected wind speed).
- $u_{V_{R_{PC}}}$ and $u_{V_{R_{SC}}}$ shall be evaluated for the wind speed measured at the reference mast at the power curve test bin-averaged against the wind speed finally applied for the power curve test. Please note that the specific uncertainties $u_{V_{R_{PC}}}$ and $u_{V_{R_{SC}}}$ can be different (e.g. different calibration uncertainties).
- u_{v_T} shall be evaluated for the site-calibrated (but not air density corrected) wind speed at the power curve test bin-averaged against the wind speed finally applied for the power curve test.

4 Correlation of Uncertainties of Reference Measurement at Site Calibration and Power Curve Test

Table 1 summarises proposed assumptions of $\rho_{V_{R,PC},V_{R,SC}}$ as to be used in equation (3) for the different uncertainty components. The proposed values are discussed in the following sub chapters for each component. The correlation coefficient $\rho_{V_{R,PC},V_{R,SC}}$ can vary from +1 to -1, where the wind speed uncertainty according to equation (3) decreases with increasing $\rho_{V_{R,PC},V_{R,SC}}$.

component	explanation	case	assumed $\rho_{V_{R,PC},V_{R,SC}}$
$u_{VS,precal}$	reference mast anemometer calibration before SC or PC test	anemometer not exchanged between SC and PC	1
		anemometers used for SC and PC calibrated in the same wind tunnel	0.8
		anemometer exchanged during SC or during PC, calibrated in the same wind tunnel	see equation (4)
		anemometers used for SC and PC calibrated in different wind tunnels	0
		anemometer exchanged during SC or during PC, calibrated in different wind tunnels	see equation (5)
$u_{VS,precal,res}$	residuals of reference mast anemometer calibration (see chapter 4.1 of [4])	all	1 if same sign of residuals, -1 if different sign
$u_{VS,postcal}$	uncertainty due to result of post calibration of reference mast anemometer or in-situ test	anemometer not exchanged between SC and PC	see comments in chapter 4.3
		anemometer exchanged between SC and PC	0
		anemometer exchanged during SC or during PC	similar to value c as defined for equation (4)
$u_{VS,class}$	operational characteristics of reference mast anemometer	no S-class available for site calibration or power curve test	0.75
		S-class available for site calibration and power curve test	1
$u_{VS,mnt}$	uncertainty due to flow distortion by mast and mounting effects on anemometer (reference mast)	mounting arrangement of anemometer not changed between SC and PC	1
		mounting arrangement of anemometer changed between SC and PC	0
		mounting arrangement changed during SC or during PC	similar to value c as defined for equation (4)
u_{dvs}	uncertainty of DAS of wind speed measurement at reference mast	DAS and applied channel of DAS identical at SC and PC	1
		DAS or applied channel of DAS different at SC and PC	0
		DAS or applied channel of DAS changed during SC or during PC	similar to value c as defined for equation (4)
$u_{VS,igt}$	uncertainty due to flow distortion by lightning rod on reference mast anemometer	mounting arrangement of lightning finial not changed between SC and PC	1
		mounting arrangement of lightning finial changed between SC and PC	0
		mounting arrangement of lightning finial changed during SC or during PC	similar to value c as defined for equation (4)

Table 1: proposed correlation coefficients of different uncertainty components of the wind speed measurement at the reference met mast at the site calibration (SC) and power curve test (PC)

4.1 Correlation of Uncertainty of Anemometer Calibration Before Site Calibration / Power Curve Test, $\rho_{V_{R,PC},V_{R,SC}}$

If the reference mast anemometer is not exchanged throughout the process site calibration and power curve test its calibration uncertainty cancels out completely ($\rho_{V_{R,PC},V_{R,SC}} = 1$).

If the reference mast anemometer is exchanged between site calibration and power curve test against an anemometer (of the same type) calibrated in the same wind tunnel the uncertainties of the two calibrations are basically correlated except of the statistical uncertainty of the calibrations. As the statistical uncertainty of the calibrations is much smaller than the systematic uncertainty, a high correlation coefficient of $\rho_{V_{R,PC},V_{R,SC}} = 0.8$ is suggested.

If the reference mast anemometer is exchanged during the site calibration or during the power curve test against an anemometer (of the same type) calibrated in the same wind tunnel $\rho_{V_{R,PC},V_{R,SC}}$ is higher than in case of an exchange between site calibration and power curve test (higher than 0.8). It is suggested to assess $\rho_{V_{R,PC},V_{R,SC}}$ according to the following equation, which is consistent with the values 0.8 for a case of an exchange between site calibration and power curve test and 1 in case of no exchange of the anemometer:

$$\rho_{V_{R,PC},V_{R,SC}} = 0.8 + 0.2c \quad (4)$$

where

c minimum of fraction of amount of data of site calibration and fraction of amount of data of power curve test covered by the same anemometer (to be evaluated per wind speed bin)

Example:

Anemometer exchanged during site calibration and 50% of site calibration data of the respective wind speed bin covered by the anemometer also applied for the power curve test: $c = 0.5$ and $\rho_{V_{R,PC},V_{R,SC}} = 0.9$.

If the reference mast anemometer is exchanged between site calibration and power curve test against an anemometer calibrated in another wind tunnel the uncertainties of the two calibrations is basically uncorrelated ($\rho_{V_{R,PC},V_{R,SC}} = 0$).

If the reference mast anemometer is exchanged during the site calibration or during the power curve test against an anemometer calibrated in a different wind tunnel $\rho_{V_{R,PC},V_{R,SC}}$ is higher than 0. A meaningful value for the correlation coefficient is then given by:

$$\rho_{V_{R,PC},V_{R,SC}} = c \quad (5)$$

with c as defined for equation (4).

Example:

Anemometer exchanged during site calibration and 50% of site calibration data of the respective wind speed bin covered by the anemometer also applied for the power curve test: $c = 0.5$ and $\rho_{V_{R,PC},V_{R,SC}} = 0.5$.

It is pointed out that in the above two cases where equation (4) or equation (5) applies, the calibration uncertainty must first be cumulated over the period in which the anemometer is exchanged (site calibration or power curve testing period) before it is cumulated across the site calibration and the power curve test. This cumulating should be done per wind speed bin under consideration of the frequency of the data from the two calibrations and the assumption of $\rho_{V_{R,PC},V_{R,SC}} = 0.8$ if the calibrations took place in the same wind tunnel and full independency ($\rho_{V_{R,PC},V_{R,SC}} = 0$) if the calibrations took place in different wind tunnels.

4.2 Correlation of Uncertainty of Anemometer Calibration Residuals Before Site Calibration / Power Curve Test, $u_{vs,precal_res}$

If the calibration residuals of the reference mast anemometer have the same sign at the site calibration and power curve test in a certain wind speed bin the uncertainty due to the residuals is fully correlated ($\rho_{V_{R,PC},V_{R,SC}} = 1$). This also applies if the anemometer is not exchanged throughout the process site calibration and power curve test or if the anemometer is exchanged during the site calibration or during the power curve test against an anemometer with the calibration residual of the same sign in a certain wind speed bin.

If the calibration residuals of the reference mast anemometer have the opposite sign at the site calibration and power curve test in a certain wind speed bin the respective uncertainty is fully anti-correlated ($\rho_{V_{R,PC},V_{R,SC}} = -1$).

If the reference mast anemometer is exchanged during the site calibration or during the power curve test an effective calibration residual should be calculated per wind speed bin for the period in which the exchange of the anemometer took place (site calibration or power curve test) by weighting the residuals by the frequency of the data before and after the exchange of the anemometer per wind speed bin. The resulting calibration residuals shall then be cumulated across the site calibration and power curve test according to equation (3) under consideration of the sign of the two residuals (same sign: $\rho_{V_{R,PC},V_{R,SC}} = 1$, opposite sign: $\rho_{V_{R,PC},V_{R,SC}} = -1$).

A special treatment is needed for cumulating the uncertainty due to the calibration residuals of the reference mast anemometer across wind speed bins to an uncertainty of power curves in terms of the annual energy production (AEP). As it is outlined in chapter 4.1 of [4] the uncertainty due to residuals of a single anemometer is fully correlated across two wind speed bins if the residuals have the same sign and fully anti-correlated if the residuals have an opposite sign. This can simply be accounted for when calculating the uncertainty in AEP by keeping the sign of the residuals and always assuming full correlation of the uncertainty across two bins (see equation (6) of [4]). Here, the problem arises that the uncertainty cumulated across the process site calibration and power curve test according to the right term on the right side of equation (3) always has a positive sign (for each wind speed bin). For a proper cumulating of this uncertainty across wind speed bins according to equation (6) of [4], it is proposed to introduce an effective sign of the uncertainty equal to the sign of the difference of the two residuals to be cumulated according to equation (3).

4.3 Correlation of Uncertainty Due to Result of Post Calibration of the Anemometer or In-Situ Test, $u_{VS,postcal}$

$u_{VS,postcal}$ is not treated wind speed dependent in IEC 61400-12-1 and IEC 61400-50-1 [5]. Hence, assessing the correlation of this uncertainty for the reference mast anemometer at the site calibration and power curve test cannot meaningfully be treated in dependence of the sign of the residuals of the post calibration or the in-situ test in analogy to the pre-calibration residuals according to chapter 4.2.

If the reference mast anemometer is not exchanged throughout the process site calibration and power curve test there can be only one post calibration of the anemometer for the combined site calibration and power curve testing period. The uncertainty due a shift of the anemometer calibration can influence part of the data of the site calibration measurement period or part of the data of the power curve testing period, depending on the actual date of the shift of the calibration. As the date of the shift of the anemometer calibration is often unknown, it is suggested to consider the full uncertainty as it is evaluated for the combined site calibration and power curve testing period instead of applying equation (3) in that case. The same is also suggested if an in-situ test is applied instead of a post calibration, i.e. only one in-situ test for the combined site calibration and power curve testing period. Actually, the same uncertainty would result by the application of equation (3) if the full uncertainty $u_{VS,postcal}$ is attributed to either the site calibration period or the power curve testing period and $u_{VS,postcal}$ is set to zero in the other period (independently from $\rho_{V_{R,PC},V_{R,SC}}$). If two in-situ tests are applied, one over the site calibration period and one over the power curve testing period, it is quite likely that the uncertainty of one of the tests would be similar to the uncertainty of an in-situ test covering both periods and the uncertainty of the other test would be zero. Also in that case, nearly the same uncertainty as by the above approach would result by the application of equation (3), independently from $\rho_{V_{R,PC},V_{R,SC}}$. If such two in-situ tests both provide results with non-zero uncertainty the choice of $\rho_{V_{R,PC},V_{R,SC}}$ becomes quite arbitrary. It is therefore suggested to carry out just one in-situ test over the entire period if the anemometer is not exchanged between site calibration and power curve test.

If the reference mast anemometer is exchanged between site calibration and power curve test it is suggested to consider the uncertainty $u_{VS,postcal}$ across the periods being independent from each other ($\rho_{V_{R,PC},V_{R,SC}} = 0$).

If the reference mast anemometer is exchanged during the site calibration or power curve test an effective uncertainty $u_{VS,postcal}$ should be calculated per wind speed bin for the period in which the exchange of the anemometer took place (site calibration or power curve test) by considering the uncertainties $u_{VS,postcal}$ as evaluated before and after the exchange of the anemometer as independent from each other and by accounting for the frequency of the data before and after the exchange of the anemometer per wind speed bin (root of sum of square of weighted uncertainty before and after exchange of the anemometer). The resulting uncertainties $u_{VS,postcal}$ shall then be cumulated across the site calibration and power curve test according to equation (3) by setting $\rho_{V_{R,PC},V_{R,SC}}$ equal to the value of c as used in equation (4).

Example:

Anemometer exchanged during site calibration and 50% of site calibration data of the respective wind speed bin covered by the anemometer also applied for the power curve test: $c = 0.5$ and $\rho_{V_{R,PC},V_{R,SC}} = 0.5$.

4.4 Correlation of Uncertainty Resulting from the Operational Characteristics of the Anemometer, $u_{VS,class}$

The uncertainty of the reference mast anemometer due to operational characteristics will usually be highly correlated across the site calibration and power curve test, i.e. the environmental conditions present in the two testing periods will usually be quite similar. As the assessment of the difference of all meteorological conditions influencing the anemometer uncertainty as present at the site calibration and power curve test can be very exhaustive (assessment of all variables per wind speed bin) and as the impact of the difference of the variables on the anemometer output cannot be estimated easily, a rather pragmatic default approach of $\rho_{V_{R_PC},V_{R_SC}} = 0.75$ is suggested.

The value $\rho_{V_{R_PC},V_{R_SC}} = 0.75$ has actually been derived on the basis of the default approach given in Annex E.6.3.4 of IEC 61400-12-1 (see also chapter 2.4 of this report). If the uncertainty $u_{VS,class}$ is of equal size at the site calibration and at the power curve test the default approach given in Annex E.6.3.4 of IEC 61400-12-1 leads to an uncertainty of $1/\sqrt{2}$ times the uncertainty present in a single period (site calibration or power curve testing period). The same uncertainty is reached in that case by equation (3) with $\rho_{V_{R_PC},V_{R_SC}} = 0.75$. This value is believed being reasonable for most cases.

If a full S-classification of the reference mast anemometer is carried out for the site calibration period and for the power curve testing period a more appropriate approach may be to apply equation (3) with $\rho_{V_{R_PC},V_{R_SC}} = 1$.

4.5 Correlation of Uncertainty Due to Anemometer Mounting Effects, $u_{VS,mnt}$

If the mounting arrangement of the reference mast anemometer has not been changed between the site calibration measurement and the power curve test the mounting uncertainty is fully correlated across the site calibration and power curve test ($\rho_{V_{R_PC},V_{R_SC}} = 1$).

If the mounting arrangement of the reference mast anemometer has been changed between the site calibration measurement and the power curve test the mounting uncertainty may be assumed being independent across the site calibration and power curve test ($\rho_{V_{R_PC},V_{R_SC}} = 0$).

If the mounting arrangement of the reference mast anemometer is exchanged during the site calibration or power curve test an effective uncertainty $u_{VS,mnt}$ should be calculated for the period in which the exchange of the anemometer took place (site calibration or power curve test). As a conservative approach, $u_{VS,mnt}$ may be considered being fully correlated across the two sub periods, i.e. $u_{VS,mnt}$ is weighted by the frequency of the data before and after the exchange of the anemometer per wind speed bin. Afterwards equation (3) should be applied, where it is proposed to set $\rho_{V_{R_PC},V_{R_SC}}$ equal to the minimum of the fraction of the amount of data of the site calibration and the fraction of the amount of data of the power curve test covered by the same mounting arrangement (to be evaluated per wind speed bin, similar to value of c as used in equation (4)).

4.6 Correlation of Uncertainty of Wind Speed Data Acquisition, u_{dvs}

Usually, the uncertainty of the data acquisition system (DAS) of the reference mast anemometer will hardly be influenced by the difference of conditions present during the

site calibration and power curve test. Therefore, this uncertainty can be considered being fully correlated across the site calibration and power curve test if the same DAS and the same data channel of the system is applied in both periods ($\rho_{V_{R_PC},V_{R_SC}} = 1$).

Contrary, if a different DAS or different channel of the same DAS is applied for recording the output of the reference mast anemometer it is proposed to consider u_{dVS} being independent across site calibration and power curve test ($\rho_{V_{R_PC},V_{R_SC}} = 0$).

If the DAS or the channel of the DAS of the reference mast anemometer is changed within the site calibration campaign or within the power curve testing campaign it is proposed to set $\rho_{V_{R_PC},V_{R_SC}}$ equal to the minimum of the fraction of the amount of data of the site calibration and the fraction of the amount of data of the power curve test covered by the same DAS or channel of DAS (to be evaluated per wind speed bin, similar to value of c as used in equation (4)). In that case u_{dVS} must first be cumulated over the period in which the anemometer is exchanged (site calibration or power curve testing period) before it is cumulated across the site calibration and the power curve test. This cumulating should be done per wind speed bin under consideration of the frequency of the data covered by the two sub periods and the assumption of full independency of u_{dVS} .

4.7 Correlation of Uncertainty Due to Effects of the Lightning Finial, $u_{VS,lgt}$

The same principle as for the mounting uncertainty $u_{VS,mnt}$ given in chapter 4.5 applies also for the uncertainty due to effects of the lightning finial $u_{VS,lgt}$:

- $\rho_{V_{R_PC},V_{R_SC}} = 1$ if arrangement of lightning finial not changed
- $\rho_{V_{R_PC},V_{R_SC}} = 0$ if arrangement of lightning finial changed between site calibration and power curve test
- $\rho_{V_{R_PC},V_{R_SC}}$ equal to the minimum of the fraction of the amount of data of the site calibration and the fraction of the amount of data of the power curve test covered by the same arrangement of the lightning finial (to be evaluated per wind speed bin, similar to value of c as used in equation (4))

5 Issues Related to Other Site Calibration Uncertainties than Wind Speed Measurement Uncertainties

Other uncertainties of the site calibration than the wind speed measurement uncertainties as treated in chapter 3 and chapter 4 are independent of the wind speed measurement uncertainties and independent from each other and hence must be added in quadrature to each other and to the uncertainties given in chapter 4. Some shortcomings of the treatment of these uncertainty components in IEC 61400-12-1 and IEC 61400-12-3 are described in the following sub chapters with suggestions for improvements.

5.1 Statistical Uncertainty, s_{sc}

There is an error in the last paragraph of chapter 10.1.2 of IEC 61400-12-3 in respect to the number of degrees of freedom f of the site calibration. f must be calculated as the total number of 10-minute periods included in the site calibration minus the number of parameters of the site calibration for the reasons explained in [6].

The k-fold analysis for the assessment of the statistical uncertainty of site calibrations given in chapter 10.1 of IEC 61400-12-3 turned out being unnecessary complicated and leads in the end to similar uncertainty as assessing the standard deviation of residuals and taking into account the number of degrees of freedom (approach from first CDV of IEC 61400-12-1, Ed.2 [7]). Therefore, the method given in [7] should be reintroduced in the upcoming revision of IEC 61400-12-3.

5.2 Systematic Uncertainty of Site Calibration Algorithm, $u_{VT,alg}$

The wind speed correction algorithm established at the site calibration has a limited accuracy to predict the wind speed at the turbine position on the basis of the measurements at the reference measurement position. This systematic uncertainty of the algorithm is not directly addressed in IEC 61400-12-3, though it may be argued that this uncertainty is partly covered by $u_{VT,coc}$ in the standard.

The systematic uncertainty of the algorithm, here called $u_{VT,alg}$, can be derived as the mean residual per wind direction and wind speed bin, with the residual as defined by equation (3) of IEC 61400-12-3. As for the power curve analysis the uncertainty is needed per wind speed bin as given for the analysed power curve, the residual must be bin-averaged against the wind direction measured at the reference measurement position and against the wind speed measured at the turbine position and corrected to the reference air density of the measured power curve.

The residual uncertainty is fully correlated across wind direction and wind speed bins with the same sign of the mean residual and fully anti-correlated across wind direction and wind speed bins with the opposite sign of the mean residual. In order to reflect that when cumulating the uncertainty across wind direction bins according to equation (9) of IEC 61400-12-3 and across wind speed bins to an uncertainty in AEP, the sign of the residuals must be kept as is explained in [4].

5.3 Uncertainty Due to Change in Flow Correction Between Adjacent Wind Direction Bins, $u_{VT,coc}$

Instead of evaluating the absolute deviation of the site calibration consistency parameter from 1 in equation (10) of IEC 61400-12-3, the deviation including sign should be

applied for the following reason: If the site calibration consistency parameter is below 1 in the bin $j-1$ and above 1 in the bin $j+1$ (or vice versa) the error caused by the change of the flow correction partly cancels out when averaged over bin j as then the flow correction is too low in one half of bin j and too high in the other half of bin j . In simple words: The indicated high change of the flow correction is then likely realistic and does constitute no or only a reduced uncertainty. The formulation given in equation (10) of IEC 61400-12-3 does not consider this part cancelation of the error.

Another shortcoming of equation (10) of IEC 61400-12-3 is that it must be multiplied with the wind speed to result in an uncertainty of wind speed.

The corrected version of equation (10) of IEC 61400-12-3 is:

$$u_{VT,coc,i,j} = \frac{1}{2} \left(\frac{1 - sccp_{j,j-1}}{2\sqrt{3}} + \frac{1 - sccp_{j,j+1}}{2\sqrt{3}} \right) V_i \quad (6)$$

for wind direction bins with left and right neighbouring bin and

$$u_{VT,coc,i,j} = \frac{1 - sccp_{j,j\pm 1}}{2\sqrt{3}} V_i$$

for wind direction bins with just one neighbouring bin

where

V_i : wind speed used for power curve evaluation in bin i , including air density correction and possible other corrections

Moreover, the sign of the uncertainty calculated by the so modified equation (10) of IEC 61400-12-3 should be kept when cumulating the uncertainty over the wind direction bins under the assumption of full correlation of the uncertainty across wind direction bins via equation (9) of IEC 61400-12-3. The reason is that the (always positive) uncertainty is anti-correlated over wind directions with opposite sign of the calculation, i.e. again it partly cancels out over such wind direction bins. As is shown in [4], this calculation is mathematically equivalent to applying the rules of error propagation [3] with only positive uncertainties under the assumption of anti-correlation of the uncertainty over bins with opposite signs of the value calculated by the modified equation (9) of IEC 61400-12-3 and the assumption of fully correlated uncertainty over the respective bins with the same sign of the value calculated by this equation.

IEC 61400-12-3 suggests evaluating the uncertainty $u_{VT,coc}$ only if the flow correction changes between adjacent wind direction bins by more than 2 %. As this uncertainty is present also in case of smaller changes of the flow correction, $u_{VT,coc}$ may rather be taken into account always.

It is pointed out that the uncertainty $u_{VT,alg}$ as defined in chapter 5.3 of this report already covers the uncertainty $u_{VT,coc}$. Hence, if $u_{VT,alg}$ is introduced $u_{VT,coc}$ must be disregarded in order to avoid double counting of uncertainties.

5.4 Uncertainty Due to Removal of Wind Direction Sensor, $u_{VT,rmv}$

There is an error in equation (11) of IEC 61400-12-3. The uncertainty must be calculated by multiplying the change of wind speed correction between adjacent wind direction bins with the ratio of the relative wind direction measurement uncertainty and the bin size (as is written in the text of chapter 11.3.2 of IEC 61400-12-3) However, in equation (11) of IEC 61400-12-3 rather the uncertainty due to a change of the flow correction between adjacent wind direction bins is multiplied with the ratio of the relative wind

direction measurement uncertainty and the bin size. The uncertainty is smaller than the change of wind speed correction between adjacent wind direction bins, i.e. the uncertainty due to a change of a wind direction sensor is underestimated by equation (11) of IEC 61400-12-3. Consequently, equation (11) of IEC 61400-12-3 should be corrected as follows:

$$u_{VT,rmv,i,j} = \frac{1}{2} (|1 - sccp_{j,j-1}| + |1 - sccp_{j,j+1}|) \frac{u_{W,j}}{BinSize_j} V_i \quad (7)$$

for wind direction bins with left and right neighbouring bin and

$$u_{VT,rmv,i,j} = |1 - sccp_{j,j\pm 1}| \frac{u_{W,j}}{BinSize_j} V_i$$

for wind direction bins with just one neighbouring bin (with V_i as in equation (6)).

If the exchange of the wind direction sensor takes place within the site calibration measurement period the uncertainty due to the exchange of the sensor should be calculated as in case of an exchange between the site calibration measurement and the power curve test multiplied by the minimum of the fraction of site calibration data collected before and after the exchange of the sensor.

If the exchange of the wind direction sensor takes place within the power curve testing period the uncertainty due to the exchange of the sensor should be calculated as in case of an exchange between the site calibration measurement and the power curve test multiplied by the fraction of power curve testing data collected after the exchange of the sensor.

IEC 61400-12-1 Ed. 3 hardly provides guidance on the calculation of the relative wind direction measurement uncertainty $u_{W,j}$. Detailed instructions for that are given in Appendix A of this report.

5.5 Uncertainty Due to Site Calibration and Power Curve Measurements in Different Seasons, $u_{VT,sv}$

Chapter 11.4 of IEC 61400-12-3 requires considering an uncertainty due to possible seasonal effects on the site calibration on the basis of a comparison of the average shear, turbulence and upflow conditions as present at the site calibration and power curve test. However, it is not defined in the standard over which database the average conditions shall be calculated and whether this uncertainty is to be considered being dependent on the wind direction or wind speed.

Hence, the following procedure is proposed:

- The shear, veer and turbulence conditions are heavily dependent on the wind direction. Hence, mean values of these variables calculated over all wind directions could be strongly influenced by the frequency distribution of wind directions present at the site calibration and power curve test, which is to be avoided for comparing these variables over different seasons. Therefore, $u_{VT,sv}$ is to be assessed per wind direction bin as used for the site calibration.
- To make the meteorological conditions during the site calibration and power curve test comparable and representative, all site calibration data as finally applied to derive the flow correction and all power curve data as finally applied for the power curve analysis and as additionally filtered as for the site calibration (e.g. wind speed filtering from 4 m/s to 16m/s) is taken into account for the

comparison. Based on the so-filtered data, the wind shear, turbulence intensity and vertical upflow angle is bin-averaged against the wind direction measured at the reference measurement position for the site calibration and for the power curve testing data. The difference of the bin averages of each of these three variables is then to be checked on the criteria given in chapter 11.4 of IEC 61400-12-3.

- If one of the three equality criteria is breached for a wind direction bin, the uncertainty is non-zero in that bin.
- To calculate the uncertainty per wind speed bin as applied for the power curve analyses, the site-calibrated wind speed as well as the wind speed measured at the reference measurement position is bin-averaged against the wind direction and the wind speed finally applied for the power curve test on the basis of the complete power curve testing data (data as used for the final power curve analysis, without wind speed filter as applied for site calibration). 1/3 of the difference per combined wind speed and wind direction bin is taken as standard uncertainty if the above condition for non-zero uncertainty is fulfilled. Otherwise, the uncertainty is set to zero. Finally, the uncertainty is weighted by the frequency of wind directions within each wind speed bin. By that, full correlation of the uncertainty across wind direction bins is assumed.

6 Guidance on Reporting of Uncertainties

6.1 Nomination of Uncertainties and Total Uncertainty of Site Calibration

The nomination of uncertainties given in Table 2 is proposed to be applied for the reporting of uncertainties related to site calibrations and reference mast measurements at power curve tests.

As is explained in chapter 3, the uncertainty components u_{VS} (first seven components listed in Table 2) cannot be separated between site calibration and power curve test. As these components are usually much smaller than the components u_{VT} due to the uncertainty part cancellation explained in chapter 3, it is proposed to attribute only the other components to the site calibration when the total uncertainty of the site calibration has to be reported (all components except the first seven listed in Table 2). This applies when the total uncertainty is reported per wind direction bin for 6 m/s 10m/s and 14 m/s (as required in chapter 10, bullet j) of IEC 61400-12-1).

component	explanation	left term of equation (3)	right term of equation (3)
$u_{VS,precal}$	reference mast anemometer calibration before SC or PC test		X
$u_{VS,precal_res}$	residuals of reference mast anemometer calibration		X
$u_{VS,postcal}$	uncertainty due to result of post calibration of reference mast anemometer or in-situ test		X
$u_{VS,class}$	operational characteristics of reference mast anemometer		X
$u_{VS,mnt}$	uncertainty due to flow distortion by mast and mounting effects on anemometer (reference mast)		X
$u_{VS,igt}$	uncertainty due to flow distortion by lightning rod on reference mast anemometer		X
u_{dVS}	DAS of wind speed measurement at reference mast		X
$u_{VT,precal}$	turbine mast anemometer calibration before SC	X	
$u_{VT,precal_res}$	residuals of turbine mast anemometer calibration	X	
$u_{VT,postcal}$	uncertainty due to result of post calibration of turbine mast anemometer or in-situ test	X	
$u_{VT,class}$	operational characteristics of turbine mast anemometer	X	
$u_{VT,mnt}$	uncertainty due to flow distortion by mast and mounting effects on anemometer (turbine mast)	X	
$u_{VT,igt}$	uncertainty due to flow distortion by lightning rod on turbine mast anemometer	X	
u_{dVT}	DAS of wind speed measurement at turbine mast	X	
s_{SC}	statistical uncertainty of site calibration	na	na
$u_{VT,alg}$	systematic uncertainty of site calibration algorithm	na	na
$u_{VT,coc}$	uncertainty due to change in flow correction between adjacent wind direction bins (to be disregarded if $u_{VT,alg}$ applied)	na	na
$u_{VT,rmv}$	uncertainty due to removal of wind direction sensor	na	na
$u_{VT,sv}$	uncertainty due to site calibration and power curve measurements in different seasons	na	na

Table 2: Proposed nomination of uncertainty components related to site calibrations and reference mast measurements at power curve tests. The two columns to the right explain which term on the right side of equation (3) must be used for the assessment of the component.

6.2 Guidance on Separate Site Calibration Report

A consequence of the application of the uncertainty model introduced in chapter 3 is that the site calibration uncertainty cannot be assessed independently from a power curve test. However, this is not possible anyway, as the uncertainty due to seasonal ef-

facts $u_{VT,sv}$ cannot be calculated before the end of the power curve test. Also, the uncertainty component $u_{VT,sv}$ may not be known before the power curve test.

Hence, if a site calibration report is to be conducted before a power curve test the uncertainty of the site calibration is proposed to be reported as explained in chapter 6.1 of this report under exclusion of the components u_{VS} , $u_{VT,sv}$ and $u_{VT,rmv}$

7 Uncertainty in Terms of AEP

In order to avoid an overestimation of the uncertainty in AEP, each of the uncertainty components give in Table 2 should be cumulated across wind speed bins to an uncertainty in AEP separately. The total uncertainty in AEP is then calculated according to equation (8) of [4]. By no means should the different components first be cumulated to a total uncertainty of the site calibration according to equation (8) of IEC 61400-3 before cumulating across wind speed bins.

8 Literature

- [1] IEC 61400-12-3, Edition 1, Wind energy generation systems - Part 12-1: Power performance - Measurement based site calibration, 2022-08
- [2] IEC 61400-12-1, Edition 3.0, Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines, 2022-09
- [3] ISO/IEC Guide 98-3:2008, Uncertainty of measurement – Part 3: Guide to the Expression of Uncertainty in Measurement, 2008
- [4] A. Albers; Practical Aspects of Power Curve Testing Uncertainty Due to Turbulence Effects, Deutsche WindGuard Consulting GmbH, report PP23035.A2, 2023-12-01
- [5] IEC 61400-50-1, Edition 1, Wind energy generation systems - Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments, 2022-11
- [6] A. Albers; Error of Calculation of Statistical Uncertainty of Site Calibration in IEC 61400-12-1, Ed.2, Deliverable to MEASNET Power Curve Expert Group, 2019-11-15, available at Deutsche WindGuard Consulting GmbH on request
- [7] CDV IEC 61400-12-1, Edition 2, Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines 2013-02

9 Appendix A: Uncertainty of Relative Wind Direction Measurement

A difference in wind direction measurements at the site calibration and power curve test can appear from a removal of the wind direction sensor. Relevant for the uncertainty component $u_{VT,rmv,i,j}$ is the difference of wind direction measurements at the site calibration and power curve test resulting from uncertainties of the measurements:

$$\Delta_W = W_{SC} - W_{PC} \quad (8)$$

where

Δ_W : difference of wind direction measurements at site calibration and power curve test at the same wind direction (also called relative wind direction measurement)

W_{SC} : wind direction measured at site calibration

W_{PC} : wind direction measured at power curve test

If the wind direction measurements at the site calibration and power curve test would have no uncertainty, Δ_W would be zero, and in equation (7) (chapter 5.4) $u_{W,j}$ as well as $u_{VT,rmv,i,j}$ would also be zero.

The rules of error propagation applied on equation (8) provide:

$$u_{W,j}^2 = u_{W_{SC},j}^2 + u_{W_{PC},j}^2 - 2u_{W_{SC},j}u_{W_{PC},j}\rho_{W_{SC},W_{PC},j} \quad (9)$$

where

$u_{W,j}$: uncertainty of relative wind direction measurement Δ_W in wind direction bin j

$u_{W_{SC},j}$: uncertainty of W_{SC} in wind direction bin j

$u_{W_{PC},j}$: uncertainty of W_{PC} in wind direction bin j

$\rho_{W_{SC},W_{PC},j}$: correlation coefficient of uncertainty of W_{SC} and uncertainty of W_{PC} in wind direction bin j

As the different uncertainty components of W_{SC} and W_{PC} are independent from each other, equation (9) can be carried out for each component separately, and the total uncertainty $u_{W,j}$ as needed for equation (7) is the root mean square sum of the resulting uncertainty components of $u_{W,j}$. Table 3 summarises proposed assumptions of $\rho_{W_{SC},W_{PC},j}$ as to be used in equation (9) for the different uncertainty components. The proposed values are discussed in the following sub chapters for each component. As in IEC 61400-12-1, the acronym “WV” is used for the single uncertainty components indicating measurements with vanes or ultrasonic anemometers.

component	explanation	case	assumed $\rho_{W_{SC},W_{PC},j}$
$u_{WV,cal,j}$	uncertainty of calibration of vane	vane not exchanged throughout SC and PC	1
		vanes used for SC and PC calibrated in the same wind tunnel	0.8
		vanes used for SC and PC calibrated in different wind tunnels	0
$u_{WV,cal,res,j}$	difference of reference sensor and indicated wind direction at calibration	all	1 if same sign of residuals, -1 if different sign
$u_{WV,nm,j}$	uncertainty of determination of sensor North mark	vane not exchanged throughout SC and PC	1
		vane changed between SC and PC	0
$u_{WV,bo,j}$	uncertainty of determination of boom direction relative to North	mounting boom not exchanged (or not newly oriented)	1
		mounting boom exchanged (or newly oriented)	0
$u_{WV,oe,j}$	mast effects on vane	mounting boom not exchanged (or orientation not changed by more than 10°)	1
		boom exchanged or orientation changed by more than 10°	0
$u_{WV,mda,j}$	uncertainty of magnetic declination	all	1 (see explanation in chapter 9.6)
$u_{dWV,j}$	uncertainty of data acquisition system	same DAS and DAS channel applied at SC and PC	1
		different DAS or DAS channel applied at SC and PC	0

Table 3: proposed correlation coefficients of different uncertainty components of the wind direction measurement at the reference met mast at the site calibration (SC) and power curve test (PC)

9.1 Correlation of Uncertainty of Calibration of Vanes, $u_{WV,cal,j}$

If the reference mast vane is not exchanged throughout the process site calibration and power curve test its calibration uncertainty cancels out completely ($\rho_{W_{SC},W_{PC},j} = 1$).

If the reference mast vane is exchanged between site calibration and power curve test against a vane calibrated in the same wind tunnel the uncertainties of the two calibrations are basically correlated except of the statistical uncertainty of the calibrations. As the statistical uncertainty of the calibrations is much smaller than the systematic uncertainty, a high correlation coefficient of $\rho_{W_{SC},W_{PC},j} = 0.8$ is suggested.

If the reference mast vane is exchanged between site calibration and power curve test against a vane calibrated in another wind tunnel the uncertainties of the two calibrations is basically uncorrelated ($\rho_{V_{R,PC},V_{R,SC}} = 0$).

9.2 Correlation of Uncertainty of Vane Calibration Residuals, $u_{WV,cal,res,j}$

The uncertainty due to residuals of the calibration of vanes is not considered in IEC 61400-12-3 and IEC 61400-12-1. As the residuals are not included in the calibration uncertainty, they should be considered as a separate uncertainty component.

If the calibration residuals of the reference mast vane have the same sign at the site calibration and power curve test in a certain wind direction bin the uncertainty due to the residuals is fully correlated ($\rho_{W_{SC},W_{PC},j} = 1$).

If the calibration residuals of the reference mast vane have the opposite sign at the site calibration and power curve test in a certain wind direction bin the respective uncertainty is fully anti-correlated ($\rho_{W_{SC},W_{PC},j} = -1$).

As the calibration of vanes is reported in smaller wind direction bins as applied for the site calibration, the average residual per wind direction bin as applied for the site calibration must be calculated before equation (9) can be applied. For that, also the northing offset of the vane must be accounted for.

9.3 Correlation of Uncertainty of Determination of Sensor North Mark, $u_{WV,nm,j}$

If the vane is not exchanged between site calibration and power curve test the uncertainty due the determination of the North mark of the vane is fully correlated across site calibration and power curve test and entirely cancels out ($\rho_{W_{SC},W_{PC},j} = 1$).

If the vane is exchanged between site calibration and power curve test the uncertainty due the determination of the North mark of the vane is uncorrelated across site calibration and power curve test ($\rho_{W_{SC},W_{PC},j} = 0$).

9.4 Correlation of Uncertainty of Northing of Boom Direction, $u_{WV,bo,j}$

If the mounting boom for the vane is not dismantled (not newly oriented) between site calibration and power curve test the uncertainty of the northing of the boom direction is fully correlated across site calibration and power curve test and entirely cancels out ($\rho_{W_{SC},W_{PC},j} = 1$).

If the mounting boom is exchanged or newly oriented between site calibration and power curve test the uncertainty of the northing of the boom direction is uncorrelated across site calibration and power curve test ($\rho_{W_{SC},W_{PC},j} = 0$).

9.5 Correlation of Uncertainty due to Mast Effects, $u_{WV,oe,j}$

If the mounting boom for the vane is not exchanged and not newly oriented between site calibration and power curve test the uncertainty due to mast effects on the vane measurements is fully correlated across site calibration and power curve test and entirely cancels out ($\rho_{W_{SC},W_{PC},j} = 1$). The same can be assumed if the orientation of the mounting boom has been changed only slightly, i.e. by up to 10 °.

If the design of the boom has been changed between site calibration and power curve test or the orientation of the boom has been changed by more than 10° the uncertainty due to mast effects on the vane measurements is basically uncorrelated across site calibration and power curve test ($\rho_{W_{SC},W_{PC},j} = 0$).

9.6 Correlation of Uncertainty due to Magnetic Declination, $u_{WV,mda,j}$

The wind direction measurement has three uncertainty components originating from the magnetic declination:

- the declination angle itself (only relevant if it is not applied for correcting the wind direction measurement)
- the shift of the declination angle in time
- the uncertainty of the declination angle

The magnetic declination angle as well as its uncertainty are highly correlated across the site calibration and power curve test ($\rho_{W_{SC},W_{PC},j} = 1$), i.e. these uncertainties cancel out through equation (9). Therefore, $u_{W,j}$ can be approximated by the shift of the declination angle in time between site calibration and power curve test. If the magnetic declination

angle is evaluated and corrected individually for the site calibration and power curve testing period $u_{W,j}$ can well be approximated by zero.

9.7 Correlation of Uncertainty of Wind Direction Data Acquisition, u_{dWV}

Usually, the uncertainty of the data acquisition system (DAS) of the reference mast vane will hardly be influenced by the difference of conditions present during the site calibration and power curve test. Therefore, this uncertainty can be considered being fully correlated across the site calibration and power curve test if the same DAS and the same data channel of the system is applied in both periods ($\rho_{W_{SC},W_{PC},j} = 1$).

Contrary, if a different DAS or different channel of the same DAS is applied for recording the output of the reference mast vane it is proposed to consider u_{dWV} being independent across site calibration and power curve test ($\rho_{W_{SC},W_{PC},j} = 0$).

end of report