Measuring-Network of Wind Energy Institutes

Proposal for Revision & Harmonized Implementation of IEC 61400-12-1, Edition 3.0 for Power Performance measurements with a Hub-Height Met Mast

Created by Expert Group on Power Performance

Coordinator: Kostas Papadopoulos

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1 Introduction

Measnet's fundamental goal is to ensure high quality measurements and a uniform interpretation of standards and recommendations, as well as interchangeability of results. This is achieved through technical discussions, organization of internal exercises/ assessments (interlaboratory comparisons) and the participation to Proficiency Tests.

The *Expert Group for Power Performance* (ExG-PP) is the technical forum for realizing Measnet's goals in the specific field, implementing the rules and procedures of the organization and providing its expert support to the Organization on relevant issues.

The member laboratories are accredited according to ISO17025 for the Power Performance Measurements of electricity producing wind turbines according to the IEC standards 61400-12-1, 61400-12-3, 61400-12-5. The wind measurements required for the Power Performance Test (PPT) are covered by the IEC 61400-50 series.

1.1. Background

IEC 61400-12-1, Edition 3.0 (2022) covers 4 wind measurement configurations:

1. *Meteorology mast at hub height and remote sensing at all heights (only flat terrain)*
2. *Meteorology mast below hub height and remote sensing at all heights (only flat terrain)*
3. *Meteorology mast above hub height (all types of terrain)*
4. *Meteorology mast at hub height (all types of terrain)*

Notwithstanding the growing use of remote sensing devices (RSD; predominantly lidars) in PPT, the hub-height meteorology mast still remains the only option in complex terrain applications.

On the other hand, IEC 61400-12-2 (PPT based on nacelle anemometry) provides an alternative methodology which is practically difficult to implement in complex terrain.

Over the years, the ExG-PP activities have focused on *Measurement Configuration 4* for which IEC 61400-50-1 serves as the wind measurement standard.

Still, the ExG-PP closely follows the technological developments on all the aspects of PPTs as many of its experts participate in national and international platforms for harmonization and standardization (e.g. IEC, IECRE etc.). Such aspects relate to ground-based or nacelle-mounted lidars for which IEC 61400-50-2 and IEC 61400-50-3 serve as the respective wind measurement standards.

1.2. Scope

The present document provides *Proposals for the Revision and Harmonization of PPTs performed with a Meteorology mast at Hub Height*. The proposals include clarification and revision of the content of IEC 61400-12-1, IEC 61400-12-3 and IEC 61400-50.1. The Proposals are intended to:

- Identify ambiguities and inconsistencies over the governing IEC documents
- Establish common handling of such issues by all the member laboratories
- Propose and adopt common Lines-of-Choice in uncertainty assumptions and calculations within Measnet (and potentially when conducting PTs)
- Minimize the scatter of PPT results and uncertainties as regards the Power Curve and the AEP.

The work particularly focuses on uncertainty handling.

1.3. Motivation

The IEC standards ruling the PPTs have evolved into extensive procedures involving a multitude of measurements and calculations (corrections, normalizations etc.).

The main results of a PPT (the Power Curve Table and the AEP values) have been demonstrated (e.g. recent IECRE-PTs) to be in excellent agreement between the Test Laboratories provided that prescribed-in-advance Lines-of-Choice are established. The necessity of extra guidance to ensure common interpretation of the IEC standard clearly implies that, until such guidance is incorporated in the standard, it is significant to compile a Technical Document covering this gap.

The measurement uncertainties and the method uncertainties are mostly covered by Informative Sections of the IEC standards, leaving space for varying interpretations on a laboratory level or even on the individual analyst level. Different interpretations have been shown to lead to the calculation of considerably deviating uncertainties. Indeed, the uncertainty comparison tasks of the 20pp01 IECRE-PT [11] were mainly confined to calculations based on given assumptions of a subset of uncertainty components. Consequently, the completion of the PT was followed by several proposed Clarification Sheets to be considered by IEC/ IEC-RE with the aim to remove some of the identified sources of deviations.

The AEP uncertainty has commercial/contractual implications in the context of Power Performance Verification in newly-constructed wind farms because it determines the Pass/Fail threshold which triggers further actions (e.g. turbine interventions, underperformance compensation or proof-of-acceptance/compliance with warranty power curves). It is crucial to establish clear guidelines on the quantification of each uncertainty source and component and on the method of combining these to the final uncertainty value.

Several technical discussions and targeted comparative exercises on assumptions and calculations are regularly organized within the ExG-PP. These have identified important items in the IEC standard(s) which are understood/handled in different ways by the users.

The cumulated experience led the ExG-PP to work on a dual target:

a. Provide harmonized procedures followed by the Measnet laboratories to minimize results' deviation until relevant material is incorporated in the standard(s)
b. Provide inputs to the maintenance / development activities in IEC/TC88 (MT12 and MT50)

In developing and discussing the proposals, it became clear that their value would be reduced if they were limited on clarifying issues and harmonizing interpretations of [1]. Thus, concepts leading to revisions and corrections have been developed next to clarification proposals regarding the IEC standard(s).

1.4. Structure

The issues handled in this document are referenced to the relevant sections of the IEC standards, usually following the order of the Clauses encountered in the IEC 61400-12-1 document.

1.5. Further Use

The principles developed in the document can provide the basis for addressing relevant issues when the power curve and AEP are calculated with other measurement technologies and configurations (remote sensing devices-RSD and combination of RSD with met-masts).

2 Overview

The main issues addressed in the present document are briefly outlined in this section.

1. The theoretical basis for determining the uncertainty of measurement using the method of bins (i.e. the core principle of Annex E of [1]) is generalized and clarified (Section 4.1):
    a. Explicit use of the correlation of uncertainties when cumulating an uncertainty component across wind speed bins, e.g. to derive the uncertainty of AEP.
    b. The correct implementation of Point (a) requires the handling of each and every uncertainty sub-component independently; this leads to the calculation of its individual contribution to the uncertainty of AEP.
    c. Grouping of sub-components is not required and shall not be permitted because it leads to incorrect uncertainty calculations for the derived quantity (u_{AEP}).
2. The AEP-extrapolation is generalized to include the case of de-rated power curves. A consistent framework is provided for calculating the AEP-extrapolation value and its uncertainty (Sections 3.3.1, 4.1.3).
3. The description and application of the power measurement uncertainty are improved (current transformer and power transducer). Section 4.2.
4. The use of calibration certificates in the consideration of measurement uncertainties is harmonized. Sections 4.3.1, 4.4.1 and 4.5.4-4.5.5.
5. The handling of post-calibration procedures for anemometers is clarified. Section 4.3.2.
6. A detailed, consistent framework for calculating the site-calibration contribution to the wind speed measurement using in the power curve is introduced (Section 4.5). The framework leads to clear-cut rules for the handling of all the relevant sub-components.
    a. The framework allows for the establishment of transparent and robust calculation of uncertainties related to a wide range of common conditions encountered during the measurement campaigns when sensors and measurement configuration are substituted/modified. Implicitly, the framework provides an incentive to avoid changing wind sensor models, mounting/measurement configuration and calibration facilities during the measurement campaigns. This is achieved by a fair uncertainty increase related to such events.
    b. The framework proves that $u_{VT,coc}$ is irrelevant, while $u_{VT,rmv}$ is incorrect. New uncertainty component ($u_{VT,model}$) is proposed.
7. Method uncertainties related to turbulence normalization, air density normalization, shear/veer effects are clarified and a specific treatment is provided to harmonize their calculation. Section 4.7.
8. Guidance is provided for the use of Rogowski coils when convention CTs are impossible to install. Annex 4.

3 Calculation Procedures

3.1 Air pressure and temperature corrections

Reference: IEC 61400-12-1, Section 7.4 (Air density)

Key point: Provide specific equations to implement the corrections.

Note: IEC draft document 88/992/Q (2023-10-27)

Air pressure shall always be corrected to hub height using the following equation derived from ISO2533:1975, Equation 13:

$$B_{10min} = B_{10\text{min,meas}} \exp\left[-g_n \left(z_{hub} - z_{\text{baro}}\right)/\text{R}_\text{o}\text{T}_{10\text{min,meas}}\right] \tag{3.1}$$

B_{10min} is the measured air pressure averaged over 10 min, corrected to turbine hub height
$B_{10min,meas}$ is the measured air pressure averaged over 10 min at sensor height
g_n is the gravitational constant 9.80665 [m/s2]
Z_{baro} is the elevation of installed pressure sensor above sea level
Z_{hub} is the elevation of turbine hub height above sea level
R_o is the gas constant of dry air 287.05 [J / kg K]
$T_{10min,meas}$ is the measured air temperature averaged over 10 min

The air temperature shall not be adjusted to hub height because no assumption can be made for the magnitude and the sign of the temperature variation with height.

3.2 Ice filtering of database

Reference: IEC 61400-12-1, Section 8.4 (Data rejection)

Key point: Provide specific condition for screening-out records potentially affected by icing.

A conservative filtering based on the measured air temperature (<2°C) and relative humidity (>80%) is recommended for removing records potentially affected by anemometer & wind direction sensor icing. It is noted that icing may still be present for prolonged periods following the end of a "rejected period" or between short periods of rejected records or even before the ice-filter triggering; the extent of this depends on the rate of change of the ambient conditions. Care must be taken to identify the affected records through comparison with heated cup anemometers and ultrasonic anemometers (when available) or through any other appropriate means.

3.3 (Wind speed-) Derated power curves

3.3.1 AEP-extrapolation

Reference: IEC 61400-12-1, Section 9.3 (Annual Energy Production)

Key point: Generalize extrapolation to de-rated power curves

The IEC standard dictates that "*constant power for wind between the highest wind speed in the measured power curve and the cut-out wind speed*" is applied. "*The constant power used for the extrapolated AEP shall be the power value from the bin at the highest wind speed in the measured power curve*".

This procedure needs to be generalized to de-rated power curves for obvious and practical reasons (e.g. the $AEP_{meas}/AEP_{extrapolated}$ ratio would be negatively biased).

It is proposed to calculate the $AEP_{extrapolate}$ by extrapolating the measured power curve from the last measured wind speed bin (imax) to V_{out} according to:

$$P_{extrap,i} = P_{theor,i}\left(\frac{P_{imax}}{P_{theor,imax}}\right) \qquad for\ i = imax + 1\ to\ iout \qquad (3.2)$$

$P_{theor,i}$	power derived from the manufacturer's reference curve for wind speed bin i
$P_{theor,imax}$	power derived from the manufacturer's reference curve for wind speed bin imax
imax	last completed bin of the power curve
iout	bin corresponding to the cut-out speed

The formula folds back to the IEC definition for conventional power curves where $P_{extrap,i} = P_{imax}$ for all the extrapolated bins (because $P_{theor,i}$=$P_{theor,imax}$).

Referring to Figure 3.1, the application of Equation (3.2) might be ambiguous when imax is located inside the derated range of wind speeds. In this case, the measured power curve is strongly influenced by the specific variation of wind speed within the recorded 10min records; the recorded bin-averages could exhibit an "erratic" pattern. In the latter case the extrapolation according to Equation (3.2) will be strongly influenced by the last measured bin. To avoid this, a plausible approach would be to set $P_{extrap,i}$ = $P_{theor,I}$ $\ for\ i = imax +$

$1\ to\ iout$ in Equation (3.2). This would possibly create a "discontinuity" of the extrapolated power curve between the *imax* and *imax+1* bins.

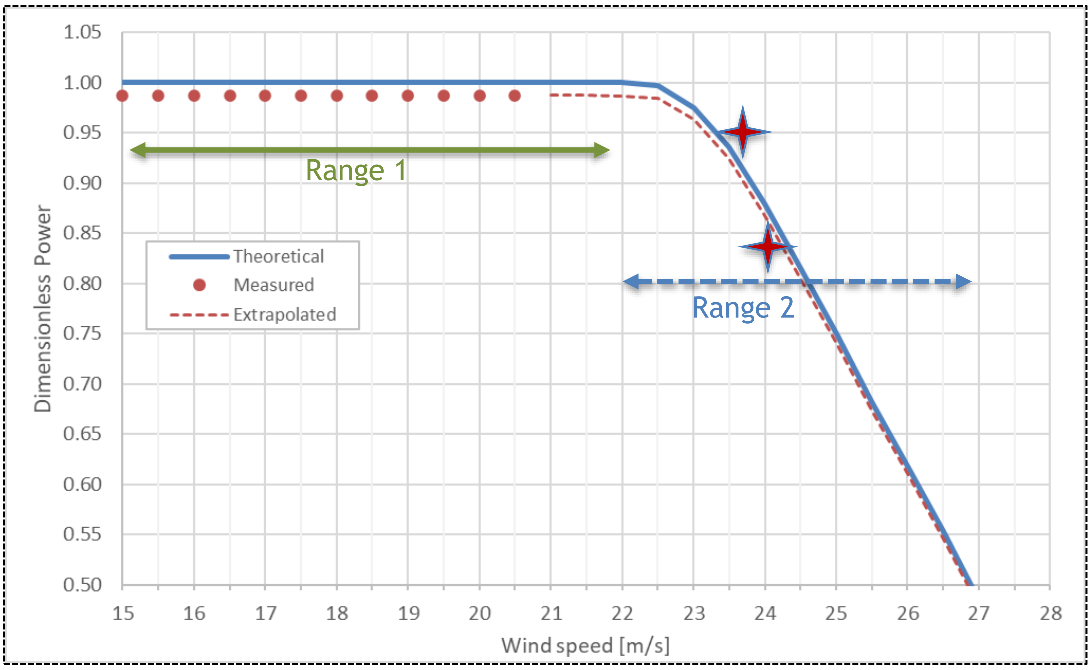


Figure 3.1 Power Curve extrapolation of derated power curves. The extrapolated line is adjusted to resemble the theoretical derate gradient. The two points depict a possible situation when the last measured points of the power curve fall inside the derated region (Range 2).

3.3.2 TI normalization

Reference: IEC 61400-12-1, Annex M

Key point: Generalize procedure to de-rated power curves

Annex M of [1] describes the procedure of establishing the *Initial zero-turbulence* power curve and the *adjusted theoretical zero-turbulence* power curve $P_{o,th}$. Both curves include a "horizontal segment" at ordinate value P_{rated} ($P_{rated,th}$); the segment extends from V_{rated} (or $V_{rated,th}$) to V_{out}.

In the case of a de-rated power curve, with de-rate becoming effective from wind speed bin V_{derate} to V_{out}, the calculations of Annex M shall be adapted as follows:

- Implement the algorithms of Annex M of [1] for all bins up to bin V_{derate}-0.5 m/s.
- The turbulence-normalized value $P_{ti,norm,i}$ is set to the non-turbulence normalized value of power P_i from V_{derate} to V_{out} multiplied by the ratio $P_{ti,norm,Vderate-0.5}$ / $P_{i,Vderate-0.5}$.

The adaptation is consistent with the one applied in Section 3.3.1.

3.4 In situ comparison

Reference: IEC 61400-50-1, Section 9.4

Key point: Equation (26) of the standard is mathematically incorrect.

The standard writes: "*Calculate the standard uncertainty of wind speed differences (statistical deviation) of the estimated primary anemometer and the measured primary anemometer wind speeds for each wind speed bin. The standard uncertainty of the wind speed differences is the standard deviation of wind speed differences divided by the square root of the number of measured data points. The standard uncertainty is*:

$$\sigma = \frac{stdev(\gamma)}{\sqrt{n}} = \frac{\sqrt{\frac{\sum(V_{primary,est} - V_{primary})^2}{n}}}{\sqrt{n}}$$

The numerator is not the standard deviation of the deviations between the estimated and the measured values of the primary anemometer; instead, it is the RMSE and includes the systematic deviation between the estimated and measured values of the primary anemometer which is included already in quantity γ in Equation (25) of [3].

The equation is incorrect, as it contradicts what is described in the text and is mathematically wrong. The correct equation is:

$$\sigma = \frac{\sqrt{\frac{\sum(V_{primary,est} - V_{primary} - \gamma)^2}{n-1}}}{\sqrt{n}} \tag{3.3}$$

where γ is as defined by Equation (25) of [3]:

$$\gamma = \frac{\sum(V_{primary,est} - V_{primary})}{n}$$

3.5 Reference Conditions for Power Curve Verification

Key point: The uncertainty of the Power Curve Test is affected by the deviation between the *measured/assumed* conditions and the *reference* conditions for which e.g. a warranty power curve is provided.

It is strongly recommended that a clear, non-ambiguous set of reference conditions shall be determined prior to the power curve test. This is directly analogous to the definition of data filtering based on a set of measured flow conditions. Given the current state of the art, the reference conditions required are for turbulence, wind shear and wind veer because they affect the uncertainty of the PP. Additional explanation is provided in Section 4.7.1, 4.7.2. and 4.7.5.

4 Uncertainties

4.1 Combination of uncertainties

Reference: IEC 61400-12-1, Section E.2.1 (Combining uncertainties-General)

Key points: Application of rules of error propagation (GUM) – Cumulating each uncertainty component individually across wind speed bins to derive its contribution to the AEP uncertainty. Same approach as in IEC 61400-12-2.

4.1.1 Power Curve

A large list of M uncertainty components is defined in each wind speed bin i of the power curve table. The general form of the combined standard uncertainty of the power in wind speed bin i is

$$u_{c,i}^2 = \sum_{k=1}^{M} \sum_{l=1}^{M} c_{k,i} u_{k,i} c_{l,i} u_{l,i} \rho_{k,l,i} \tag{4.1}$$

$c_{k,i}$ sensitivity factor of component k in bin i
$u_{k,i}$ standard uncertainty of component k in bin i
$\rho_{k,l,i}$ correlation coefficient between uncertainty components k and l in bin i
M number of uncertainty components

The mutual independence of these components ($\rho_{k,l,i}$ =0 when k≠l, $\rho_{k,l,i}$ =1 when k=l) leads to:

$$u_{c,i}^2 = \sum_{k=1}^{M} c_{k,i}^2 u_{k,i}^2$$

or the equivalent expression (E.3 in the standard)

$$u_{c,i}^2 = \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + \sum_{k=1}^{M_B} c_{k,i}^2 u_{k,i}^2 \tag{4.2}$$

which includes the partial aggregation of the M_A category A components and of the M_B category B components.

4.1.2 AEP-measured

The aggregation of the power curve measurement components $u_{c,i}$ over the wind speed bins determines the combined uncertainty u_{AEP}. Under the assumption that each uncertainty component of the power curve test is independent from each other, Equation E.2 of [1] simplifies to

$$u_{AEP}^2 = 8760^2 \sum_{k=1}^{M} \sum_{i=1}^{N} \sum_{j=1}^{N} f_i c_{k,i} u_{k,i} f_j c_{k,j} u_{k,j} \rho_{k,ij} = \sum_{k=1}^{M} u_{AEP,k}^2 \tag{4.3}$$

f_i relative occurrence of wind speed in a wind speed interval bin i

As a consequence, Equation (4.3) suggests that the contribution of each uncertainty component k is calculated individually (across the wind speed bins) and then quadratically summed with all the other components to calculate u_{AEP}.

Category A uncertainty components

Category A uncertainties (M_A components) are uncorrelated across wind speed bins ($\rho_{k,ij} = 0$), therefore

$$u_{AEP,m,A}^2 = 8760^2 \sum_{i=1}^{N} (f_i c_{m,i} s_{m,i})^2 \text{ where m=1 to } M_A \tag{4.4a}$$

Category B uncertainty components (general case)

Category B uncertainties (M_{B1} components) are fully correlated across wind speed bins ($\rho_{k,ij} = 1$), therefore

$$u_{AEP,m,B1}^2 = 8760^2 (\sum_{i=1}^{N} f_i c_{m,i} u_{m,i})^2 \text{ where m=1 to } M_{B1} \tag{4.4b}$$

Category B uncertainty components (special cases)

The modelling of some "method" uncertainties (u_{TInorm}, $u_{AD,method}$, $u_{M,shear}$, $u_{M,veer}$) is based on the difference between corrected/uncorrected values of the respective parameter (power or wind speed). Each of these simplified models results in a signed correction on wind speed or power. Irrespective of whether the correction is applied on the results, an assumed part of the correction is used to calculate the associated uncertainty. The sign of this quantity is not the same in each wind speed bin: thus, the component's uncertainty contribution to u_{AEP} is fully anti-correlated ($\rho_{k,ij} = -1$) across wind speed bins with a different sign of the correction and fully-correlated ($\rho_{k,ij} = +1$) across wind speed bins with the same sign of the correction. This means that when the sign of the correction reverses across the wind speed bin, then the uncertainty contribution to the AEP is smaller than the case when the correction sign is constant (i.e. always positive or always negative). Therefore, to avoid an artificial increase of the AEP uncertainty, such components need to be treated by properly handling the sign of the correction according to:

$$u_{AEP,m,B2}^2 = 8760^2 \sum_{i=1}^{N} \sum_{j=1}^{N} f_i c_{m,i} u_{m,i} f_j c_{m,j} u_{m,j} \rho_{k,ij} \xLeftrightarrow{see\ proof\ in\ reference\ [5]}$$

$$u_{AEP,m,B2}^2 = 8760^2 (\sum_{i=1}^{N} f_i c_{m,i} d_{m,i})^2 \text{ where m=1 to } M_{B2} \tag{4.4c}$$

$d_{m,i}$ signed value of the uncertainty of component m in bin i

As an example, the application of Equation (4.4c) for the air density correction component would be based on $d_{AD,method,i}$= ($V_{n,i}$-$V_{10min,i}$)/2, where

$V_{n,i}$ normalized, measured (or site-calibrated) wind speed in bin i

$V_{10min,I}$ measured (or site-calibrated) wind speed in bin i

The same principle of full correlation/anti-correlation also applies to other uncertainty components as a consequence of their definition (Table 4.1).

Table 4.1 Categorization of the uncertainty components according to A, B1 and B2. Note: Although s_{SC} is Type A, it has to be cumulated according to Equation (4.4b) because of its calculation as a single value irrespective of wind speed bin (see Equation 4.19).

Type A to be handled with Equation (4.4a)	s_P	
Type B to be handled with Equation (4.4b) Components B1	$u_{VS,precal,i}$ $u_{VS,postcal,i}$ $u_{VS,class,i}$ $u_{VS,mnt,i}$ $u_{VS,lgt,i}$ $u_{dVS,i}$	$u_{VT,precal,i}$ $u_{VT,postcal,i}$ $u_{VT,class,i}$ $u_{VT,mnt,i}$ $u_{VT,lgt,i}$ $u_{dVT,i}$ $u_{V_{T,sv,i}}$ s_{SC}
	$u_{M,upflow,i}$ $u_{M,sfx,i}$ $u_{M,cc,i}$ All u_T subcomponents All u_B subcomponents All u_{RH} subcomponents $u_{P,CT,i}$ $u_{P,VT,i}$ $u_{P,PT,i}$ u_{dP}	
Type B to be handled with Equation (4.4c) Components B2	$u_{VS,precal\ res,i}$ $u_{VT,model,i}$ $u_{V_{T,rmv,i}}$ $u_{M,shear,i}$ $u_{M,shear,model,i}$ $u_{M,veer,i}$ $u_{M,veer,model,i}$ $u_{M,TInorm,i}$ $u_{AD,method,i}$	$u_{VT,precal\ res,i}$

Combined AEP uncertainty

Following the notation of the previous paragraphs, Equation (4.3) is re-arranged as:

$$u_{AEP}^2 = \sum_{m=1}^{M_A} u_{AEP,m,A}^2 + \sum_{m=1}^{M_{B1}} u_{AEP,m,B1}^2 + \sum_{m=1}^{M_{B2}} u_{AEP,m,B2}^2 \quad (4.5)$$

The application of Equation (4.5) shall follow the scheme provided in the next paragraph for each uncertainty component.

Note on summation across wind speed bins

Given the definition of AEP according to Equation 17 of [1], in order to align the bin-wise calculation of the AEP value and the AEP uncertainty, the implementation of Equations 4.4a, 4.4b and 4.4c is done according to:

$$u_{AEP,m.A}^2 = 8760^2 \left\{ \sum_{i=1}^{N} \{ [F(V_i) - F(V_{i-1})] \left(\frac{c_{m,i-1} s_{m,i-1} + c_{m,i} s_{m,i}}{2} \right) \right\}^2 \text{ where m=1 to } M_A \quad (4.6a)$$

$$u^2_{AEP,m.B1} = 8760^2\{ \sum_{i=1}^{N}[F(V_i) - F(V_{i-1})] \left(\frac{c_{m,i-1}u_{m,i-1}+c_{m,i}u_{m,i}}{2}\right) \}^2 \text{ where m=1 to } M_{B1} \quad (4.6b)$$

$$u^2_{AEP,m.B2} = 8760^2\{ \sum_{i=1}^{N}[F(V_i) - F(V_{i-1})] \left(\frac{c_{m,i-1}d_{m,i-1}+c_{m,i}d_{m,i}}{2}\right) \}^2 \text{ where m=1 to } M_{B2} \quad (4.6c)$$

The sensitivity coefficients used in these equations are as defined in Table E.2 of [1] for the power curve uncertainty. This avoids the calculation of separate sensitivities for the power curve and the AEP; effectively, the product quantities $c_{m,i}u_{m,i}$ in power units are already computed for each wind speed bin of the power curve and can be conveniently “carried” into Equations (4.6a) to (4.6c). Specifically, the following formula is applied:

$$c_{v,i} \approx \frac{1}{2}\left\{\frac{P_{i+1}-P_i}{V_{i+1}-V_i} + \frac{P_i-P_{i-1}}{V_i-V_{i-1}}\right\} \quad (4.7)$$

The summation in Equations (4.6a) to (4.6c) start at i=1. This introduces the need to handle the undefined values for i=0 as below:

$V_o=V_1-0.5$ m/s

$P_o=0$

$c_{v,o} \approx \frac{P_1-P_o}{V_1-V_o}$

$s_{m,0} = s_{m,1}$

$d_{m,0} = d_{m,1}$

For $m = P$: $u_{P,0} = u_{P,1}$, $c_{P,0} = c_{P,1} = 1$ (power uncertainty components)

For $m = V$: $u_{V,0}$ as evaluated for V_0 (wind speed uncertainty components)

For $m \neq P$ and $m \neq V$: $u_{m,0} = u_{m,1}$, $c_{m,0} = c_{m,1}$ (other uncertainty components)

Note 1: This calculation scheme replaces Equation E.4 of [1] in the sense that allows the proper handling of fully-anticorrelated uncertainties of several components across the wind speed bins. The scheme permits the partial cancelling of bin-wise uncertainties of specific components when cumulating them into the AEP uncertainty.

Note 2: Equation E.5 ignores the correlation of several uncertainty components across the wind speed bins by first cumulating all M_B components inside each wind speed bin before summing them across the wind speed bins. This leads to an estimate of u_{AEP} which is always equal or larger than derived from Equation E.4. Equation E.5 is not to be used.

4.1.3 AEP-extrapolated

The calculation is used in [1] as one of the methods to characterize the completion of the PC test. AEP-extrapolated is normally used in the context of power curve verification tests; however, only its value is considered without assigning an uncertainty value. Instead, it is assumed that the relative uncertainty (% units) of $AEP_{extrapolated}$ equals that of $AEP_{measured}$ i.e. $u_{AEP,measured}/AEP_{measured}$. The assumption leads to an inconsistent approximation of the $u_{AEP,extrapolated}$; the uncertainty of the extrapolated part of the measured power curve needs to be addressed explicitly.

There are two ways to circumvent the inconsistency:

Option 1: In order to compare the $AEP_{measured}$ with the $AEP_{theoretical}$, the latter is calculated only up to the last complete bin of the measured power curve. In this case, the applicable uncertainty value is $u_{AEP,measured}$.

This can be justified in case of fulfilling the 95%-AEP criterion or the 1.5-times 85% of rated power criterion, as these two criteria ensure the AEP-measured being representative for the site conditions.

Option 2: $AEP_{extrapolated}$ is calculated from the measured power curve according to Section 3.3.1.

The theoretical power curve, when provided, is given without an associated uncertainty. The contractually binding verification tests rely on the comparison between the warranty AEP and the AEP derived from the measured power curve (as extrapolated to V_{out}); the warranty AEP is discounted by an amount proportional to the AEP measurement uncertainty. For the purpose of the verification, it is thus assumed that the theoretical power curve has zero uncertainty.

Therefore, the uncertainty of $P_{extrap,i}$ is determined by the uncertainty of P_{imax}. The combined power uncertainty in the extrapolated range is given by:

$$u_{c,i} = \frac{P_{theor,i}}{P_{theor,imax}} u_{c,imax} \qquad for\ i = imax + 1\ to\ iout \tag{4.8}$$

Consequently, the uncertainty of the AEP-extrapolated value is:

$$u_{AEP,extrap} = u_{AEP} + \sum_{i=imax+1}^{iout} [F(V_i) - F(V_{i-1})] \frac{P_{theor,i-1} + P_{theor,i}}{2P_{theor,imax}} u_{c,imax} \tag{4.9}$$

4.2 Power measurement

4.2.1 Current Transformers

Reference: IEC 61400-12-1, Section E.5.2 (Current transformers)

Key point: Application of load-dependent values for the uncertainty

The following points are underlined:

a) The CT class compliance shall be checked at the rated current of the test turbine.
b) An over-dimensioned CT with respect to the rated current may fail to comply with the Class requirement.
c) The application of a constant value of 1.5 times the CT Class accuracy as the uncertainty over the whole load range (respectively over all the wind speed bins of the power curve) may not be adequate for high wind speed distributions and/or for over-dimensioned CTs. Note: the 1.5x reflects the fact that the accuracy of the CT at 20% load is 1.5x the accuracy at 100% load (i.e. 1.5x the class accuracy).
d) The equivalent of rule (c) for special class transducers is that the class accuracy value applies over the whole range (without the need to apply the 1.5x factor, because the class accuracy is preserved down to the 20%xRated for these CTs).

Shortcomings (b) to (d) are removed by applying the following principles.

Assume that Class X CTs (IEC 61869-2) are used (X≤0.5). The % current (ratio) error is given at 5%, 20%, 100% and 120% of the rated current $I_{prim,rated}$ (Table 4.2).

Table 4.2 Load-dependent accuracy of current transformers for typical Classes

Class	1% Rated	5% Rated	20% Rated	100% Rated	120% Rated
X	$A_{1\%}$	$A_{5\%}$ X	$A_{20\%}$ X	X	X
0.5		1.5	0.75	0.5	0.5
0.2		0.75	0.35	0.2	0.2
0.1		0.4	0.2	0.1	0.1
0.2s	0.75	0.35	0.2	0.2	0.2
0.5s	1.5	0.75	0.5	0.5	0.5

For each wind speed bin, the average loading of the CTs is calculated as:

$$load_i = \frac{I_i}{I_{prim,rated}} \tag{4.10}$$

I_i is the average current (measured or calculated) from the 3 phases in wind speed bin i

The applicable error value e_i between two given loads of the table will be linearly interpolated from the given Table.

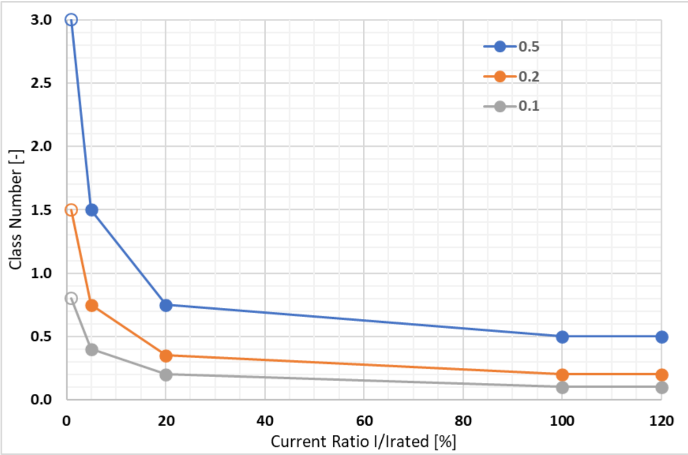
The accuracy of s-class CTs is defined at 120%, 100%, 20%, 5% and 1% of rated load. The value at 1% is applied for loads below 1% of rated.

The accuracy of "conventional" CTs is defined at 120%, 100%, 20% and 5% of rated load. For loads smaller than 5%, the error could be any value. A rough assumption is applied: observing that the accuracy of s-class CTs at 1% is twice the value at 5%, the same proportionality is applied to calculate the accuracy of "conventional" CTs at 1%: e.g. the class accuracy of a

0.5 CT is 3% at 1% of rated load. A linear interpolation is applied between 1% and 5% of rated load. The value at 1% of rated load is assumed to apply for loads below 1% of rated.

The implementation is shown in Figure 4.1.

Note: The term “rated” load refers to the CT rating (not of the test turbine).



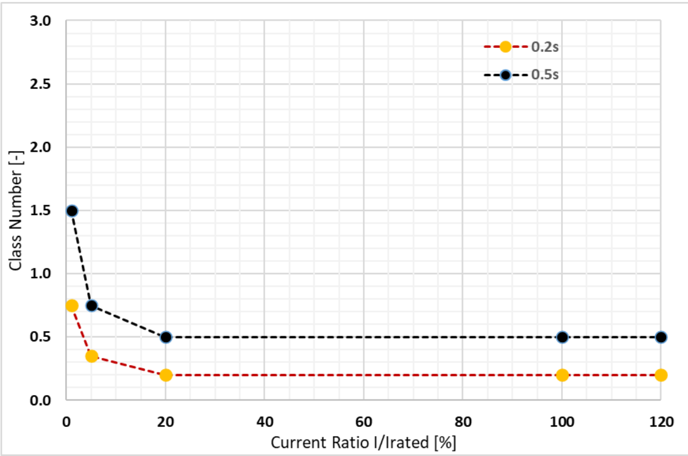


Figure 4.1 The interpolation of CT accuracy between the class characteristic values at 5%, 20%, 100% and 120% of rated load. The accuracy for s-class CTs is provided also at 1% of rated load. The open symbols at the upper plot denote the calculated value at 1% of rated low based on the assumption that it is double the value at 5% (same proportion as for s-class CTs).

The uncertainty of the power measurement due to the current transformers is:

$$u_{P,CT,i} = \frac{e_i P_i}{\sqrt{3}} \frac{1}{3} 3 \ kW \tag{4.11}$$

4.2.2 Power transducer

Reference: IEC 61400-12-1, Section E.5.4 (Power transducer or other power measurement device)

Assuming that the power transducer of Class X (X≤0.5) measures power up to P_{max}, the uncertainty of the power transducer is:

$$u_{P,PT,i} = \frac{X\% P_{max}}{\sqrt{3}}\ kW \tag{4.12}$$

Examples:

A Digital power transducer is used. It is configured so that the maximum power value which can be output is 3000 kW. Then Pmax=3000 kW.

An analogue power transducer is used with a 0…20mA output. The 20mA corresponds to 3500 kW, while 0 mA corresponds to -700kW. Then, Pmax=4200 kW.

4.2.3 Data acquisition

Reference: IEC 61400-12-1, Section E.5.5 (Data acquisition)

In case a serial output of the power transducer is read by the data-logger, then $u_{dP,i}$=0 kW because the resolution accuracy of the output is included in the power transducer accuracy Class, provided the data is stored at least with the resolution of the serial output.

4.3 Uncertainty of wind speed measurement (no site calibration)

The current section addresses the treatment of the wind speed measurement uncertainties when a site-calibration is not required, i.e. the wind speed measured at the reference mast is directly used to calculate the power curve and the AEP. It is not to be followed when flow corrections established from a site-calibration are applied to correct the wind speed measurements of the reference mast. The uncertainty components relevant to this section are $u_{VS,precal}$, $u_{VS,class}$, $u_{VS,mnt}$, $u_{VS,lgt}$, $u_{dVS,precal}$ etc. of [1] plus the uncertainty related to the assumption that the wind speed at the test turbine is equal to the wind speed measured at the reference mast. This component is described as u_{VT} in [1].

When a site-calibration is performed, the treatment of the wind speed measurement uncertainties of the SC and PC campaigns shall be done according to Section 4.5 which addresses the measurement uncertainties of the flow-corrected wind speed measurement of the reference mast. Sections 4.3.1 to 4.3.6 shall be ignored in that case.

4.3.1 Pre-calibration (including treatment of residuals)

Reference: IEC 61400-12-1, Section E.6.3.2 and IEC 61400-50-1, Section 11.3.2

Key point: Appropriate use of anemometer calibration certificates

The calibration certificates provide uncertainty values at the distinct calibration points (nominally 4 to 16 m/s) which are used to determine $u_{VS,precal}$. They also provide the values and uncertainties of the calculated linear regression parameters (OLS). The residuals from the application of the OLS (difference between calculated and measured speed at each calibration point) are either provided in the calibration certificates or can be readily calculated from the results included in the calibration certificates.

An additional uncertainty component $u_{VS,precal,res,i}$ for each wind speed bin of the power curve is introduced to cover the contributions from the application of the OLS to calculate the wind speed.

In each wind speed bin of the power curve, the average measured wind speed (no normalization) $V_{meas,i}$ shall be calculated. Two independent components are calculated, i.e. $u_{Vprecal,i}$ and $u_{Vprecal,res,i}$. The two components should not be quadratically summed in each wind speed bin in order to allow proper cumulating of $u_{Vprecal,res,i}$ across the process site calibration and power curve test according to Section 0 and across wind speed bins as explained below (see next paragraph).

Interpolation/Extrapolation of $u_{Vprecal,i}$. The calibration uncertainty shall be interpolated from the values given in the calibration certificate in the range 4-16 m/s. The value at the lowest calibration speed (~4 m/s) shall be used for lower wind speeds, while the value at the highest calibration speed (~16 m/s) shall be used for higher wind speeds.

Interpolation/Extrapolation of $u_{Vprecal,res,i}$. In the wind speed range covered by the calibration, the residuals shall be interpolated linearly to the bin-averaged measured wind speed (not density normalised). In the wind speed range below the lowest covered wind speed, linear interpolation from the calibration offset at a wind speed of 0 m/s to the residual of the lowest covered wind speed bin shall be done. In the wind speed above the highest covered wind speed bin, the residual of the highest covered bin shall be scaled by the ratio of bin-averaged measured wind speed and the highest wind speed covered by the calibration.

The uncertainty due to the residuals has to be cumulated to an uncertainty in AEP according to Equation (4.4c) by setting $d_{m,i}$ equal to the signed residual. By that it is taken into account that the uncertainty due to residuals is fully correlated across two wind speed bins with the same sign of the residuals and fully anti-correlated across two wind speed bins with the opposite sign of the residuals [5].

4.3.2 Post-calibration

Reference: IEC 61400-12-1, Section 7.2.2 and IEC 61400-50-1, Sections 9 & 11.3.3

Key point: Clarify ambiguous options

The post-calibration in the wind tunnel prevails over the *In-situ comparison* test.

a. When the difference (absolute value) between the regression lines of calibration and post- calibration is ≤0.1 m/s for all 1-m/s steps over the range 4-12 m/s, then $u_{VS,postcal,i}$=0 for all wind speed bins of the power curve. This applies irrespective of the in-situ comparison outcome.

b. When the difference (absolute value) between the regression lines of calibration and post- calibration exceeds 0.1 m/s in any 1-m/s step in the range 4-12 m/s, then $u_{VS,postcal,i}$ is set equal to the maximum difference (its absolute value) for all wind speed bins of the power curve. This applies irrespective of the in-situ comparison outcome. If the maximum difference exceeds 0.2 m/s, then two options apply:

   i. The in-situ comparison is able to identify the point in time when the deviation occurred and it is possible (due to data completion requirements) to eliminate the “deviating” period. Then, the maximum δ-value from the in-situ comparison of the “clipped” dataset will be used as $u_{VS,postcal,i}$ for all wind speed bins of the power curve. However, if δ≤0.1 m/s over the range 4-12 m/s of the clipped dataset, then $u_{VS,postcal,i}$=0 for all wind speed bins of the power curve.

   ii. The in-situ comparison is unable to identify the point in time when the deviation occurred or the in-situ comparison cannot be implemented. Then, the anemometer readings should be discarded as unreliable for the purpose of the PPT.

c. When only the in-situ comparison test has been performed, then the above rules still apply (with the understanding that all instances of “post-calibration” are replaced by “in-situ comparison” and “the difference between the regression lines” are replaced by the δ-value).

The $u_{VS,precal,i}$ values shall not be adjusted, whatever the outcome of post-calibration and/or in-situ comparison.

4.3.3 Classification

Reference: IEC 61400-12-1, Section 7.2.2

Key point: Clarification

Clause 7.2.2 of [1] foresees that anemometers classified according to Class B, D or S are used in terrain that requires a site calibration.

Clause 10.2.4 of IEC 61400-12-3 dictates the reporting of the measured range of the influence parameters used for the classification as determined from the data set of the SC. Presumably this applies on (a) the primary anemometers of the reference and turbine mast during the SC and (b) the primary anemometer of the reference mast during the PC.

Note: The **measured** wind speed value $V_{meas,i}$ is used in formula (0.05+0.005 $V_{meas,i}$) k /√3, i.e. the uncertainty is calculated prior to correcting for site calibration and air density.

<u>Complex terrain case</u>

The conditions describing Complex Terrain in Class B, D aim to encompass an all-inclusive range expected in complex terrain.

In some cases, the range of the <u>measured</u> conditions of turbulence intensity, σu/σv/σw turbulence structure, air temperature, air density and average upflow angle terrain (reference mast in the used SC, PC datasets; turbine mast in the used SC dataset) are demonstrated to fall inside the conditions of Class A or Class C, either because of mild terrain complexity or due to the required filtering of SC and PC records within specified ranges of turbulence and upflow-angle (e.g. case of power curve verification for warranty purposes). In such cases, the classification index for each measurement location and measurement campaign (e.g. $u_{V_{T,class}}$, $u_{V_{R_{SC,class}}}$ and $u_{V_{R_{PC,class}}}$) shall be taken from the relevant classification reports as applicable to Class A or C.

In case the range of the measured conditions cannot be accommodated inside the A or C conditions, but lies inside-but-away from the extreme limits of the prescribed envelopes of B, D, it is recommended to calculate the appropriate S-class index for each of $u_{V_{T,class}}$, $u_{V_{R_{SC,class}}}$ and $u_{V_{R_{PC,class}}}$. The use of an S-class index shall be supported through reference to a valid classification report compliant to IEC 61400-50-1.

The above-described provisions aim to avoid an overestimation of the *class* uncertainty when the measured conditions are much gentler than those supposed for a general-purpose complex terrain site.

4.3.4 Mounting

Reference: IEC 61400-12-1, Section E6.3.5 and IEC 61400-50-1, Section 11.3.5

Key point: Clarification

The mounting uncertainty of the primary anemometer is $u_{VS,mnt,i}$ = 0.5% $V_{meas,i}$ for single top-mounted anemometer and $u_{VS,mnt,i}$ = 1% $V_{meas,i}$ for side-by-side top-mounted anemometers compliant to Section 10.2 and 10.3 of IEC 61400-50-1.

The 1% value of the latter case can be reduced by applying a documented flow distortion correction procedure according to Section 10.4.4 and Annex B of IEC 61400-50-1.

4.3.5 Lightning finial

Reference: IEC 61400-12-1, Section E6.3.6 and IEC 61400-50-1, Section 11.3.6

Key point: Clarification

The uncertainty is $u_{VS,lgt,i}$ = 0 when the top-mounted lightning finial complies with the requirements of Section 10.5 of IEC 61400-50-1.

Note: The finial itself is not bound by the limitations in Section 10.2 of [3], most notably the 11:1 half-cone. The horizontal separation between finial and primary anemometer cup is specified in Section 10.5 of [3] to be at least 30 times the finial diameter. This document proposes that the vertical separation of the finial's mounting bracket from the primary anemometer shall be 1.5m following Section 10.2 of [3].

4.3.6 Data Acquisition

Reference: IEC 61400-12-1, Section E6.3.7 and IEC 61400-50-1, Section 11.3.7

Key point: Clarification

The uncertainty $u_{VS,DAQ,i}$ is derived from the DAQ specifications. The resolution of values in the datafile and the resolution of output values from a digital sensor shall be considered, as applicable, when calculating the value of this component.

4.3.7 Additional uncertainty due to lack of site calibration

Reference: IEC 61400-12-1, Sections 6.3.4 & E9.1

Key point: Clarification

The assumption that the wind speed at the test turbine is equal to the wind speed measured at the reference mast introduces a flow model uncertainty. The simplified flow model in non-complex terrain is that of horizontal homogeneity of the hub-height wind speed between the reference mast and test turbine locations.

This uncertainty is denoted by u_{VT} in [1]. Table 4.3 shows that different sections of [1] provide ambiguous guidance for the applicable values. In anticipation of flow model results, it is proposed to apply the default values according to the last column of the Table.

It is noted that these values cannot be used when a site calibration has not been performed although it is mandatory due to the terrain violating the Test Site requirements of Table 5 of IEC 61400-12-5.

Table 4.3 Values proposed in [1] for the uncertainty due to lack of site calibration

	Section 6.3.4 of [1]	Section E9.1 of [1]
Onshore	Minimum 2% of measured speed if wind measurement equipment is positioned at a distance between 2 and 3 times the rotor diameter of the wind turbine	2% of measured speed when 2D≤distance≤3D
Onshore	Minimum 3% of measured speed if wind measurement equipment is positioned at a distance between 3 and 4 times the rotor diameter of the wind turbine	3% of measured speed when 3D<distance≤4D
Offshore	Not mentioned	1% of measured speed when 2D≤distance≤3D
Offshore	Not mentioned	2% of measured speed when 3D<distance≤4D

4.3.8 Weighting of uncertainties when modifications occur

Precal, Precal-res (same model, same wind tunnel)

One or more replacements of the reference anemometer during the PC campaign (e.g. cup1, cup2,…; same model) do not affect $u_{Vprecal,i}$ when the anemometers are calibrated in the same wind tunnel (the calibration uncertainty is assumed fully correlated; in practice $u_{Vprecal\ cup1,i} = u_{Vprecal,cup2,i}$ etc.).

The $u_{Vprecal,res\ cup1,i}$, $u_{Vprecal,res\ cup2,i}$ etc. are weighted according to the fraction $h_{p,i}$ of the records of the PC table collected with each of cup1, cup2 per wind speed bin etc.:

$$u_{Vprecal,res,i} = \sum_{p=1}^{N_{config}} h_{p,i} u_{Vprecal,res,cup_p,i} \tag{4.13}$$

Where N_{config} is the number of different anemometers in the PC campaign.

No square-summing is applied in order to preserve the sign of the residuals.

Postcal, class, mounting, lightning finial, DAQ

Each of the $u_{VS_{postcal}}$, $u_{VS_{class}}$ etc. are weighted values of the respective uncertainties of each measurement configuration. The weighting is based on the fraction h_p of the PC records collected with each different configuration, e.g.

$$u_{VS,i} = \sqrt{\sum_{p=1}^{N_{config}} h_p^2 u_{VS_{i,p}}^2} \tag{4.14}$$

where:

N_{config} is the number of different configurations in the PC campaign

$u_{VS_{i,p}}$ is the uncertainty value (*postcal*, *class*, etc.) attributed to configuration p for wind speed bin i

Note: When the anemometers exchanged are of the <u>same model</u>, the <u>linear weighting</u> is applied for the *class* uncertainty component (i.e. as in Equation (4.13) or (4.24a)).

4.4 Uncertainty of temperature, pressure & relative humidity

Reference: IEC 61400-12-1, Sections E.10.3 to E10.14

Key point: Harmonization of approach and assumptions

The sub-components included in [1] for each of these parameters are those related to calibration, mounting and data acquisition; the radiation shielding is added for the temperature. The principles underlying each category are the same.

Note: The contribution of the RH to the PC & AEP uncertainty is very low. It is estimated that an absolute 1% change of RH affects the power value by 0.03%.

4.4.1 Calibration / Operational

The accuracy specification from the sensors' technical sheets describes the maximum error of the sensor, including effects coming from a possible calibration or from lacking calibrations. The accuracy value from the specification sheets shall be selected to be compatible with the range of ambient conditions measured during the PC dataset.

The thermometers, barometers and hygrometers shall be tested in calibration facilities to verify that they operate within the specifications. The results and uncertainty values reported in the calibration certificates are strictly valid only for the conditions at the calibration facility (OLS calibration regression parameters shall not be applied).

The scheme to determine if the sensor operates within specifications or deviates from the latter is described in Annex 1 including the calculation of the uncertainty in each case.

4.4.2 Data Acquisition

The $u_{dT,i}$, $u_{dB,i}$ and $u_{dRH,i}$ components related to the temperature, pressure and relative humidity, respectively are estimated from the data-logger specifications. The standard uncertainty is calculated according Annex 1.

For each parameter, the standard uncertainty of the DAQ measurement (e.g. voltage, current etc.) shall be scaled to the respective units (e.g. hPa, etc.) by considering the nominal transfer function of the sensor output.

4.4.3 Mounting

Section 7.4 of [1] states that temperature, barometric pressure and relative humidity sensors shall be located within 10m of the hub height on the meteorological mast at a minimum of 1.5 m below the primary anemometer whilst meeting the mounting requirements for other instruments defined in [3].

<u>Clarification</u>: To be consistent, the differences between measurement height and hub height shall be evaluated with respect to a common reference ground elevation (e.g. mean sea level or test turbine base). But when accounting for the terrain elevation differences between the reference mast and the test turbine it could be impossible to comply with the requirement of the 10m difference between the absolute measurement height (of T, B and RH) at the reference mast and the absolute height of the test turbine hub.

It is proposed to install the temperature, barometric pressure and relative humidity sensors as close as possible to the top of the reference mast accounting for the mounting requirements of [3]. The actual elevation difference between the measurements and the hub of the test turbine shall be used when assessing the measurement uncertainty of T, B and RH due to mounting.

Temperature

Paragraph E.10.5 of [1] proposes a default magnitude for the mounting uncertainty 0.25 to 0.4°C, while IEC 61400-12:1998 assumed a value of 0.33°C per 10m from z_{hub}. The latter value lies in the middle of the 0.25-0.4 range quoted in [1]. The uncertainty shall be assumed to be $u_{T,mnt,i}$= 0.033°C/m x $(z_{hub} - z_{thermo})$. The absolute value is used.

Pressure

The uncertainty is assumed equal to 10% of the pressure correction (calculated in Equation (3.1)), i.e. $u_{B,mnt,i} = 0.1B_{10min,meas}\{1 - exp\left(-g_n \frac{z_{hub}-z_{baro}}{R_0 T_{10min,meas}}\right)\}$.

Relative Humidity

A conservative value based on the estimation of the RH change due to a temperature change of 0.033°C/m would be 0.15 RH%/m or 1.5RH% over a 10m elevation difference (hygrometer/hub height), i.e. $u_{RH,mnt,i} = 0.15RH\%_{10min,meas}(z_{hub} - z_{hygro})$; see also Figure 57 of [6].

Section E.10.13 of [1] suggests an uncertainty between 0.1% to 0.2% of the measured value (this would be 0.2% at 100%RH).

Applicable formulas:

		Proposal
$u_{T,mnt,i} = 0.033°C/m(z_{hub} - z_{thermo})$	(4.15)	Apply this value in all wind speed bins of the PC.
$u_{B,mnt,i} = 0.1B_{10min,ave,PC}\{1 - exp\left(-g_n \frac{z_{hub}-z_{baro}}{R_0 T_{10min,ave,PC}}\right)\}$	(4.16)	Apply this value in all wind speed bins of the PC. The values $B_{10min,ave,PC}$ and $T_{10min,ave,PC}$ are the average temperature and pressure calculated over all the records of the PC table.
$u_{RH,mnt,i} = 0.15RH\%_{10min,ave,PC}(z_{hub} - z_{hygro})$	(4.17)	Apply this value in all wind speed bins of the PC. The value $RH\%_{10min,ave,PC}$ is the average relative humidity calculated over all the records of the PC table.

4.4.4 Radiation shield - Temperature / Relative Humidity

The IEC proposed range is 1.5 to 2.5°C and the most popular value applied in practice is the mid-value of 2°C (estimated effect on power value is 0.8%). WMO [7] states that "*the temperature of the air in a screen can be expected to be higher than the true air temperature on a day of strong sunshine and calm wind, and slightly lower on a clear, calm night, with errors perhaps reaching 2.5 and –0.5 K, respectively, in extreme cases. Additional errors may be introduced by cooling due to evaporation from a wet screen after rain.*"

A one-year field intercomparison of thermometer/hygrometer screens was organized by WMO in hot desert conditions; the comparison included 18 different types of screens/shields (7 ventilated, 11 non-ventilated) and 2 Thies wind sensors for evaluating ultrasonic temperature measurement [6].

It was found that "*the air temperature calculated*[1] *from the Thies ultrasonic anemometers was much colder than all other screens, the absolute difference increasing with solar radiation and decreasing with the wind speed. … this instrument could be less influenced by radiation than the screens, and thus could be a good candidate for use as a reference*."

All the passive ventilated screens (commonly used in the wind industry) had radiation errors <0.5ºC (4 different models ranging between 0.3 and 0.5ºC; more than 1 unit per model).

The respective analysis for relative humidity indicated a range of 3% in RH% units (estimated effect on power value is 0.1%).

The applicable uncertainty value is $u_{T,shield}$ = 0.5ºC

The applicable uncertainty value is $u_{RH,shield}$ = 3%RH (additional component introduced).

[1] The virtual air temperature is reported by ultrasonic anemometers and can be "corrected" to air temperature using its meteorological definition and the air temperature, pressure and relative humidity values from the meteo sensors available at the mast.

4.5 Uncertainty of wind speed measurement (site calibration)

Reference: IEC 61400-12-1, Section E.6.3.4 & Sections E.9.2-E.9.10 and IEC 61400-12-3, Section 10.2

Key point: Inconsistent approach and lack of guidance

When no site calibration is performed, the wind speed measurement uncertainty includes 6 u_{VS} components (pre-calibration and residuals, post-calibration, classification, mounting, lightning finial and DAQ) plus a contribution u_{VT} due to the assumption that the wind speed at the test-turbine is equal to the wind speed measured at the reference mast.

When a site calibration is undertaken, the flow correction factors are determined per wind direction bin either as a 1st order linear function or as a wind speed ratio depending on wind shear. Given that the power curve refers to the flow-corrected wind speed, the uncertainty of the wind speed in the power curve includes the wind speed measurement uncertainty at the reference mast during the PC and the uncertainty of the flow correction values established in the SC. These uncertainties are not independent because the wind speed measurement at the reference mast is performed for both the SC (where it is used to determine the flow-correction factors) and the PC campaigns (where it is used to estimate the wind speed at the test turbine through the established flow correction factors).

The IEC standard recognises the existence of a correlation between the SC and PC but fails to provide a clear and consistent guidance on how this affects the measurement uncertainty of the flow-corrected wind speed. Discussions and comparison exercises performed internally within the *Measnet ExG-PP* have revealed different interpretations of the rules given in [1] and [2].

The ambiguities are caused due to the avoidance of introducing a site-calibration model from which the uncertainty of the flow-corrected wind speed can be derived through appropriate mathematic formulas.

Section 4.5.1 addresses the Type-A uncertainty of the site-calibration.

Section 4.5.2 provides the basic principles of the framework for calculating the Type-B uncertainty of the site-calibration, as developed in [4]. This fills the gap in [1] and [2] by introducing the generic *Site Calibration Model.*

Section 4.5.3 establishes the common rules applicable to the *precal* and *residuals*, *postcal*, *classification*, *mounting*, *lightning finial* and *DAQ* uncertainties in relation to the flow-corrected wind speed.

Sections 4.5.4 to 4.5.10 provide examples for calculating each of these uncertainties.

Section 4.5.11 applies a variant of the generic *Site Calibration Model* to assess the effect of wind direction measurement uncertainty on the flow-corrected wind speed. The uncertainties of the wind direction measurement are explained in Section 4.6.

Section 4.5.12 introduces a new uncertainty component to cover the bias of the flow-correction factors.

Section 4.5.13 clarifies the uncertainty of the flow-corrected wind speed due to different ambient conditions between the SC and PC.

Section 4.5.14 provide the cumulation of the flow-corrected wind speed uncertainties across the wind direction bins.

Section 4.5.15 comments on the convergence check of the flow-correction in each wind direction bin.

Section 4.5.16 presents the “verification” checks of the flow-correction factors.

KEY STATEMENTS

The IEC standards [1] and [2] introduce u_{VS} and u_{VT} as independent uncertainties to describe (a) the wind speed measurement uncertainty at the reference mast and (b) the wind speed measurement uncertainty during the site calibration (reference and turbine mast). The two components are treated as independent from each other.

The formulation developed in this document is based on introducing the uncertainty of the flow-corrected wind speed u_{Vfinal}. It is shown that this can be split in two independent quantities:

- ✓ u_{VTM} is the wind speed measurement uncertainty at the temporary mast (TM) during the SC. It replaces u_{VT}.
- ✓ $u_{VS,eff}$ is the “effective” wind speed measurement uncertainty at the reference mast for the SC and PC campaigns. It is a discounted value compared to u_{VS} of [1], because the measurement uncertainties in the SC and PC campaign are partially or totally cancelled out due to the use of similar or identical equipment/configuration and similar ambient conditions.

4.5.1 Category A uncertainty of site calibration

Reference: IEC 61400-12-3, Section 10.1

Key point: k-fold analysis unjustifiably complicated.

The k-fold analysis for the assessment of the statistical uncertainty of the site calibration, while complicated, leads to similar uncertainty as when considering the complete data set of the SC. Effectively, the k-folds are replaced by a single fold encompassing all data of the SC dataset (only the final site-calibrated sectors used for the power curve shall be used).

The deviation d_k between the predicted and the measured wind speed at the turbine mast is calculated for each 10 min period, and the standard deviation of the d_k values is given by:

$$d_{std} = \sqrt{\frac{\sum_{k=1}^{N_{SC}}(d_k-\bar{d})^2}{N_{SC}-1}} \tag{4.18}$$

where

$d_k = V_{turb\_predicted,k} - V_{turb\_measured,k}$

$\bar{d} = \frac{1}{N}\sum_{k=1}^{N} d_k$

N_{SC} number of records in the final site-calibrated sectors used for the power curve

The statistical (Category A) uncertainty of the site calibration is calculated as a single value over all speed and directions by:

$$s_{SC} = d_{std} \frac{\sqrt{N_{SC}-1}}{\sqrt{f N_{SC}}} \tag{4.19}$$

where

f number of degrees of freedom of the site calibration.

If J denotes the number of the final site-calibrated sectors, then:

$f=N_{SC}-S$ where S is the number of all wind shear bins in all J wind direction sub-sectors
$f=N_{SC}-2J$ when Method 2 is applied (two-parameter linear regression in each direction bin)

4.5.2 Site Calibration model

The measurement-based site calibration is performed according to [2]. It is introduced as a measurement and analysis procedure for deriving the wind speed correction due to terrain effects. The wind speed correction is based on two options which are described in [2] as:

- *Method 1-Bins of wind direction and wind shear*. A wind speed ratio is calculated for each bin using the wind speed measured at the reference and the temporary (turbine) mast.
- *Method 2- Linear regression method where wind shear is not a significant influence.* The wind speed measured at the temporary (turbine) mast is regressed against the wind speed measured at the reference mast. The analysis is done for each wind direction bin.

Note: The criterion for the method selection is the significance of the wind shear as a factor influencing the wind speed correction. Yet, the tests and decision rules for assessing the significance according to [2] do not provide a firm decision tree. The closing of this gap is outside the scope of the present document.

The general case of the wind speed correction due to terrain effects is defined by:

$$V_{final} = \frac{V_{TM}}{V_{R\_SC}} V_{R\_PC} = f_{SC}\, V_{R\_PC} \tag{4.20}$$

V_{final}	wind speed used in the power curve (flow-corrected; before normalization)
V_{TM}	wind speed measured during SC at turbine mast
V_{R_SC}	wind speed measured during SC at reference mast
V_{R_PC}	wind speed measured during PC at reference mast
f_{SC}	site calibration factor (flow correction)

For simplicity, the flow correction is applied as the ratio of (hub-height) wind speeds at the turbine and reference masts during the SC. Still, Equation (4.20) can be applied to calculate the uncertainty of V_{final} for both Method-1 and Method-2.

The rules of error propagation are applied under the simplifying assumptions that:

i. The measurement uncertainty at the reference mast is similar during the SC and PC

ii. The correlation of uncertainties between the turbine mast and the reference mast remains similar between the SC and PC campaigns.

The uncertainty of V_{final} is then expressed by (see [4] for details):

$$u^2_{V_{final}} = u^2_{V_{TM}} + f^2_{SC}(u^2_{V_{R_{PC}}} + u^2_{V_{R,SC}} - 2u_{V_{R_{PC}}} u_{V_{R_{SC}}} \rho_{V_{R_{PC}} V_{R_{SC}}}) \tag{4.21}$$

$$or\ u^2_{V_{final}} = u^2_{V_{TM}} + f^2_{SC}\ u^2_{VS,eff}$$

$u_{V_{TM}}$	uncertainty of wind speed V_{TM}
$u_{V_{R,SC}}$	uncertainty of wind speed $V_{R,SC}$
$u_{V_{R,PC}}$	uncertainty of wind speed $V_{R,PC}$
$\rho_{V_{R_{PC}} V_{R_{SC}}}$	correlation coefficient of the uncertainties of wind speed measurement at the reference mast during the SC and PC campaigns ($u_{V_{R_{SC}}}$ and $u_{V_{R_{PC}}}$, respectively)
$u_{VS,eff}$	uncorrelated uncertainty of wind speed measured at the reference mast during the SC and PC campaigns

Equation (4.21) shows that the uncertainty of the flow-corrected wind speed is determined by the measurement uncertainties of three wind speeds (measured at the reference and temporary masts during SC, and at the reference mast during PC) and the correlation of the uncertainties of the wind speed measured at the reference mast across the SC and PC campaigns.

Each of the $u_{V_{TM}}$, $u_{V_{R,SC}}$ and $u_{V_{R,SC}}$ involves the *precal* and *residuals*, *postcal*, *classification*, *mounting*, *lightning finial* and *DAQ* uncertainties, as discussed in Section 4.3. These uncertainties are mutually independent. The $\rho_{V_{R_{PC}} V_{R_{SC}}}$ values for the reference mast (correlation of uncertainties across the SC and PC campaigns) are specific and different for each uncertainty component (*precal* etc.).

4.5.3 Common rules for the uncertainties of the flow-corrected wind speed

The rules refer to the *precal* and *residuals*, *postcal*, *classification*, *mounting*, *lightning finial* and *DAQ* uncertainties when using the flow-corrected wind speed. The rules apply to Equation (4.21).

a. Each uncertainty component is treated separately, i.e. Equation (8) of IEC 61400-12-3 is not used. The detailed treatment per component is addressed in Sections 4.5.4 to 4.5.10.
b. The $u_{V_{TM}}$ term replaces the relevant u_{V_T} components in Sections E9.2-E9.7 of [1] (also Sections 10.2.2-10.2.7 of [2]).
c. The $f_{SC} u_{VS,eff}$ term replaces the relevant u_{V_S} components in Sections E6.3.2-E6.3.7 of [1] (also Sections 11.3.2-11.3.7 of [2]).
d. The two terms above shall be treated as two distinct components, never to be combined until their contribution to u_{AEP} has been calculated according to Equations 4.4b or 4.4c.

e. f_{SC} is the bin-averaged value of the ratio between the flow-corrected and the measured wind speed during the PC (binned by the air-density normalized wind speed of the power curve).
f. $u_{V_{R_{PC}}}$ and $u_{V_{R_{SC}}}$ are calculated for the bin-averaged value of the measured wind speed at the reference mast during the PC (binned by the air-density normalized wind speed of the power curve).
g. $u_{V_{TM}}$ is calculated for the bin-averaged value of the flow-corrected wind speed of the reference mast during the PC (binned by the air-density normalized wind speed of the power curve).

Note: The flow-corrected and measured wind speeds in (e), (f) and (g) refer to the respective values before air density normalization.

Table 4.4 further distinguishes the implementation of common rules for the two possible cases encountered during a SC/PC power performance test.

Table 4.4 Implementation of common rules for the two possible cases encountered during a SC/PC power performance test

Case 1: No change of wind speed sensor, mounting and measurement configuration has taken place between the SC and PC campaign.	**Case 2**: A change of wind speed sensor, and/or change of mounting and measurement configuration has taken place between the SC and PC campaign.
The correlation of uncertainties $\rho_{V_{R_{PC}}V_{R_{SC}}} = 1$ by default except for the case of the *class* uncertainty.	Assumptions required per uncertainty for the values of $\rho_{V_{R_{PC}}V_{R_{SC}}}$
$u_{V_{R_{PC}}} = u_{V_{R_{SC}}}$	$u_{V_{R_{PC}}} \neq u_{V_{R_{SC}}}$ The value of $u_{V_{R_{SC}}}$ shall be calculated as a weighted average from the changes applied during the SC campaign. The value of $u_{V_{R_{PC}}}$ shall be calculated as a weighted average from the changes applied during the SC campaign.
Due to the above two conditions, the term $f_{SC}\, u_{VS,eff} = 0$ in Equation (4.21)	$f_{SC}\, u_{VS,eff} \neq 0$ in Equation (4.21)
Equation (3.15) yields $u_{V_{final}} = u_{V_{TM}}$ for each uncertainty component	Equation (4.21) yields $u_{V_{final}} > u_{V_{TM}}$ for each uncertainty component affected by a change between SC and PC
Each uncertainty component is calculated according to Sections 4.3.1 to 4.3.6	Each uncertainty component is calculated according to Sections 4.5.4 to 4.5.10.
Note: The removal of the primary anemometer from the reference mast at the end of the SC and its re-mounting prior to the start of the PC is not considered a change of sensor or of mounting.	

Table 4.4 indicates that any change relevant to the primary wind speed measurement on the reference mast between the SC and PC results to an increase of $u_{V_{final}}$. The increase is significantly affected by the assumed values of $\rho_{V_{R_{PC}}V_{R_{SC}}}$.

The sensitivity of $u_{V_{final}}$ on the ρ-effect can be approximated by assuming that the uncertainty values $u_{V_{TM}}$, $u_{V_{R_{PC}}}$ and $u_{V_{R_{SC}}}$ in Equation (4.21) are similar and the flow-correction factor $f_{SC} \sim 1$. Table 4.5 shows that the uncertainty increase for any change reaches ~73% when the uncertainties are caused to be independent between the SC and PC due to a sensor/configuration change.

Table 4.5 Indicative increase of uncertainty under different assumptions for the correlation of uncertainties across the SC and PC

Correlation	Uncertainty $u_{V_{final}}$	Applicable to:
$\rho_{V_{R_{PC}}V_{R_{SC}}}$=1	u_{V_T}	Case 1, no change
$\rho_{V_{R_{PC}}V_{R_{SC}}}$=0.9	1.095 $u_{V_{TM}}$	Case 2, any change
$\rho_{V_{R_{PC}}V_{R_{SC}}}$=0.8	1.183 $u_{V_{TM}}$	Case 2, any change
$\rho_{V_{R_{PC}}V_{R_{SC}}}$=0.5	1.414 $u_{V_{TM}}$ $(\sqrt{2}u_{V_{TM}})$	Case 2, any change
$\rho_{V_{R_{PC}}V_{R_{SC}}}$=0	1.732 $u_{V_{TM}}$ $(\sqrt{3}u_{V_{TM}})$	Case 2, any change

4.5.3.1 Rules for correlation of SC/PC uncertainties at reference mast

The applicable value for the correlation of uncertainties is determined by the nature of the modification between the SC and PC campaigns. This is treated in Sections 4.5.4 to 4.5.10.

Yet, it is not sufficient to simply select a correlation value and apply it in Equation (4.21) for any case when a change has occurred between the SC and PC campaigns. It is required to calculate an effective correlation value to better represent the effect of the change on the uncertainty; e.g. the change might affect few or many records of the power curve, so this has to be accounted for by applying a weighting between the records affected by the change and those which have not.

The procedure to practically calculate the effective (weighted) value of the correlation for any case/number of changes is explained in Figure 4.2.

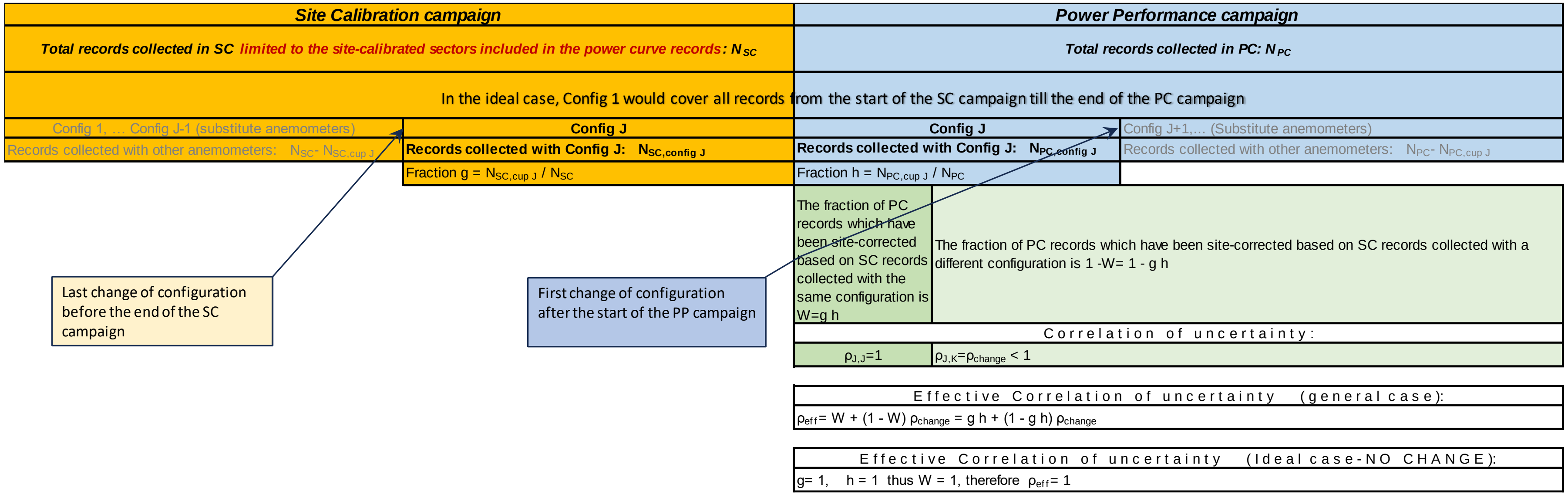


Figure 4.2 Graphical explanation of procedure to calculate the effective (weighted) value of the correlation ρ_{eff} for any case/number of changes between the SC and PC campaign. The changes refer to the primary wind speed measurement at the reference mast. Depending on the uncertainty component the terms Config J will be replaced by:

- Cup J (when dealing with precal uncertainty)
- Tunnel J (when dealing with change of wind tunnel for calibrations)
- Model J (when dealing with classification uncertainty)
- Mounting J (when dealing with mounting uncertainty)
- Lightning J (when dealing with lightning configuration uncertainty)
- DAQ J (when dealing with DAQ uncertainty)

➢ A modified approach is required for precal-res and postcal uncertainties (refer to Sections 4.5.5 and 4.5.6, respectively).

The formula for calculating the effective correlation value is:

$$\rho_{eff,V_{R_{PC}}V_{R_{SC}}} = \rho_{no\ change,V_{R_{PC}}V_{R_{SC}}} W + (1-W)\,\rho_{change,V_{R_{PC}}V_{R_{SC}}} \quad (4.22)$$

Where:

$\rho_{no\ change,V_{R_{PC}}V_{R_{SC}}} = 1$ by default (except for a conservative assumed value ρ_{class} for *class*)

$W = g\,h$ The fraction of PC records which have been flow-corrected based on SC records collected with the same configuration

g The fraction of SC records which have been collected with a configuration common with the PC records (or a fraction *h* of these)

h The fraction of PC records which have been flow-corrected with a configuration common with the SC records (or a fraction *g* of these)

Equation (4.22) can be applied to all Cases 1 and 2 of Table 4.4, as shown in Table 4.6.

Table 4.6 Calculation of effective correlation of uncertainties between SC and PC for the wind speed measured at the reference mast

Configuration change	g	h	W	$\rho_{eff,V_{R_{PC}}V_{R_{SC}}}$
No change between SC, PC	1	1	1	1 (all components except class) Apply ρ_{class} for *class* (see Section 4.5.7)
Change for the start of PC	0	0	0	$\rho_{change,V_{R_{PC}}V_{R_{SC}}}$
Change(s) during SC, no change during PC	g	1	g	g + (1-g) $\rho_{change,V_{R_{PC}}V_{R_{SC}}}$
No change during SC, change(s) during PC	1	h	h	h + (1-h) $\rho_{change,V_{R_{PC}}V_{R_{SC}}}$
Change(s) during SC, change(s) during PC	g	h	g h	g h + (1-g h) $\rho_{change,V_{R_{PC}}V_{R_{SC}}}$

Example:

Suppose that the primary anemometer of the reference mast was replaced twice during the SC campaign. The anemometers that operated during the SC campaign were cup1, cup2, and cup3.

Suppose that the primary anemometer of the reference mast was replaced close to the end of the PC campaign. The anemometers that operated during the PC campaign were cup3 and cup4.

Assume that 90% of the PC records were collected with cup 3, while 30% of the SC records were collected with cup 3.

$$\rho_{eff,V_{R_{PC}}V_{R_{SC}}} = (0.3\ x\ 0.9) + (1 - 0.3\ x\ 0.9)\rho_{change,V_{R_{PC}}V_{R_{SC}}}$$

Note: For simplicity, it is proposed to calculate a single value irrespective of wind direction and wind speed bin. Otherwise, it is straightforward to generalize the approach by considering fractions per wind direction bin j, sector-wise $\rho_{eff,j,V_{R_{PC}}V_{R_{SC}}}$ values and weighting for each wind speed bin (e.g. $\rho_{eff,V_{R_{PC}}V_{R_{SC}}} = \sum_{j=1}^{sectors} w_j \rho_{eff,j,V_{R_{PC}}V_{R_{SC}}}$).

4.5.3.2 Rules for calculating weighted values of uncertainties

The applicable values for each of $u_{V_{R_{SC}}}, u_{V_{R_{PC}}}$ are calculated by applying an appropriate weighting in each of the SC and PC campaigns according to Section 4.3.7.

$$u_{V_{R_{SC}}} = \sqrt{\sum_{q=1}^{N_{config,SC}} {g'_q}^2 u^2_{V_{R,SC_q}}} \tag{4.23}$$

$$u_{V_{R_{PC}}} = \sqrt{\sum_{p=1}^{N_{config,PC}} {h'_p}^2 u^2_{V_{R,PC_p}}} \tag{4.24}$$

$$u_{V_{TM}} = \sqrt{\sum_{r=1}^{N_{config,SC}} {e'_r}^2 u^2_{V_{TM,r}}} \tag{4.25}$$

g'_p	the fraction of SC records collected with configuration q for reference mast
h'_p	the fraction of PC records collected with configuration p for reference mast
e'_r	the fraction of SC records collected with configuration r for temporary mast
$u_{V_{R,SC_q}}$	the uncertainty related to configuration q at reference mast during PC
$u_{V_{R,PC_p}}$	the uncertainty related to configuration p at reference mast during PC
$u_{V_{TM_r}}$	the uncertainty related to configuration r at temporary mast during SC

Equations (4.23) to (4.25) are modified when the “configuration change” refers to the calibration uncertainty of cups and direction sensors (same tunnel; precal and residuals) and operational uncertainty (same model) according to:

$$u_{V_{R_{SC}}} = \sum_{q=1}^{N_{config,SC}} g'_q \, u_{V_{R,SC_q}} \tag{4.23a}$$

$$u_{V_{R_{PC}}} = \sum_{p=1}^{N_{config,PC}} h'_p \, u_{V_{R,PC_p}} \tag{4.24a}$$

$$u_{V_{TM}} = \sum_{r=1}^{N_{config,SC}} e'_r \, u_{V_{TM,r}} \tag{4.25a}$$

4.5.4 Pre-Calibration

Equation (4.21) is applied by introducing the *precal* components:

$$u^2_{V_{final,precal}} = u^2_{V_{TM,precal}} + f^2_{SC}\left(u^2_{V_{R_{PC}},precal} + u^2_{V_{R,SC,precal}} - 2\, u_{V_{R_{PC,precal}}} u_{V_{R_{SC,precal}}} \rho_{precal,V_{R_{PC}}V_{R_{SC}}}\right) \tag{4.26}$$

$$or\ u^2_{V_{final,precal}} = u^2_{V_{TM,precal}} + f^2_{SC}\, u^2_{V_{S,eff,precal}}$$

The value obtained depends on possible changes of the primary anemometers on the turbine and reference mast through the SC and PC campaigns according to Table 4.7.

A plausible value for the correlation of calibration uncertainties in Equation (4.26) is required. Based on the analysis presented in Annex 2, it is concluded that $\rho_{precal,V_{R_{PC}}V_{R_{SC}}} = 0.9$ leads to conservative values for the wind speed range 4-16 m/s for the case when the calibrations are performed in the same wind tunnel.

Table 4.7 Handling of *precal* uncertainty for different scenarios of anemometer exchange

Case # and description		Assumptions	$\rho_{precal,V_{R_{PC}}V_{R_{SC}}}$	$u_{VT,precal}$ of [1] replaced by:	$u_{VS,precal}$ of [1] replaced by $f_{SC}u_{VS,eff,precal}$:
i	None of the involved anemometers of reference/turbine masts has been changed in the SC and the PC campaign (this covers also the case of removing the anemometers after the SC campaign completion and re-installing them for the initiation of the PC campaign)	$\rho_{no\ change,precal,V_{R_{PC}}V_{R_{SC}}} = 1$	1	$u_{VTM,precal}$ from Equation (4.25)	0
ii	Change of anemometer of reference and/or temporary mast using <u>same calibration tunnel</u>	$\rho_{change,precal,V_{R_{PC}}V_{R_{SC}}} = 0.9$	g h + 0.9 (1-g h) from Section 4.5.3.1		$f_{SC}(u^2_{V_{R_{PC,precal}}} + u^2_{V_{R,SC,precal}} - 2\,u_{V_{R_{PC,precal}}}u_{V_{R_{SC,precal}}}\rho_{precal,V_{R_{PC}}V_{R_{SC}}})^{0.5}$ See Equations (4.23),(4.24) for weighting uncertainties
iii	Change of anemometer of reference and/or temporary mast using <u>different calibration tunnel</u>	$\rho_{change,precal,V_{R_{PC}}V_{R_{SC}}} = 0$	g h from Section 4.5.3.1		$f_{SC}(u^2_{V_{R_{PC,precal}}} + u^2_{V_{R,SC,precal}} - 2\,u_{V_{R_{PC,precal}}}u_{V_{R_{SC,precal}}}\rho_{precal,V_{R_{PC}}V_{R_{SC}}})^{0.5}$ See Equations (4.23),(4.24) for weighting uncertainties

4.5.5 Pre-Calibration residuals

Equation (4.21) is applied by introducing the *pre-calibration residual uncertainty* components:

$$u^2_{V_{final,precal,res}} = u^2_{V_{TM,precal,res}} + f^2_{SC}(u^2_{V_{R_{PC}},precal,res} + u^2_{V_{R,SC,precal,res}} - 2\, u_{V_{R_{PC,precal,res}}} u_{V_{R_{SC,precal,res}}} \rho_{precal,res,V_{R_{PC}}V_{R_{SC}}}) \quad (4.27)$$

$$or \qquad u^2_{V_{final,precal,res}} = u^2_{V_{TM,precal,res}} + f^2_{SC} u^2_{V_{S,eff,precal,res}}$$

The approach differs from the approach in Section 4.5.4 because the magnitude of $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}}$ always equals 1:

- When the anemometer of the reference mast is not exchanged through the SC/PC campaigns, then $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}} = 1$ for all wind speed bins.
- When the anemometer of the reference mast is exchanged during the SC and/or PC campaigns, then $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}} = 1$ for all wind speed bins where the respective residuals have the same sign (between the SC and PC campaigns), while $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}} = -1$ for all the remaining wind speed bins.

If the reference mast anemometer is exchanged during the SC or during the PC then an effective calibration residual should be calculated per wind speed bin for each of the SC and PC datasets.

The effective calibration residual value shall be calculated by weighting the residuals by the fraction of records collected before and after the exchange of the anemometer per wind speed bin:

- If the effective residual for wind speed bin i has the same sign in SC and PC, then Equation (4.27) shall be calculated by using the absolute values of the residuals (as uncertainty) and $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}} = 1$.
- If the effective residual for wind speed bin i has an opposite sign between SC and PC, then Equation (4.27) shall be calculated by using the absolute values of the residuals (as uncertainty) and $\rho_{precal\_res,V_{R_{PC}}V_{R_{SC}}} = -1$.

If the temporary mast anemometer is exchanged during the SC then an effective calibration residual should be calculated per wind speed bin of the SC dataset.

The uncertainty due to the residuals has to be cumulated to an uncertainty in AEP according to Equation (4.4c) by setting $d_{m,i}$ equal to the signed residual. By that it is taken into account that the uncertainty due to residuals is fully correlated across two wind speed bins with the same sign of the residuals and fully anti-correlated across two wind speed bins with the opposite sign of the residuals [5].

4.5.6 Post-Calibration

Equation (4.21) is applied by introducing the *postcal* components:

$$\begin{aligned} u^2_{V_{final,postcal}} &= u^2_{V_{TM,postcal}} + f^2_{SC}(u^2_{V_{R_{PC}},postcal} + u^2_{V_{R,SC,postcal}} \\ &\quad - 2\, u_{V_{R_{PC,postcal}}} u_{V_{R_{SC,postcal}}} \rho_{postcal,V_{R_{PC}}V_{R_{SC}}}) \end{aligned} \tag{4.28}$$

or $$u^2_{V_{final,postcal}} = u^2_{V_{TM,postcal}} + f^2_{SC} u^2_{VS,eff,postcal}$$

The post-calibration prevails over the in-situ comparison (see Section 4.3.2). The value for each of the *postcal* uncertainties is calculated according to the rules provided in Section 4.3.2; this suggests that a unique value is applied at all wind speed bins.

The first term $u_{V_{TM,postcal}}$ of the right-hand-side of Equation (4.28) refers to the primary anemometer of the temporary mast, while the 2nd term refers to the anemometer at the reference mast.

Case 1. Reference mast anemometer is not exchanged over the SC and PC campaigns

The same reference anemometer can be used for the SC and PC campaigns under the following requirements:

- At the end of the SC campaign, the reference mast anemometer shall be verified through either an in-situ comparison (anemometer not removed from the mast) or through a wind tunnel re-calibration (anemometer removed from the mast). If it is verified that $u_{V_{R_{SC,postcal}}} = 0$ (through the rules of Section 4.3.2), then the anemometer can be used also for the PC campaign; if not and especially if $u_{V_{R_{SC,postcal}}} > 0.2$ m/s, then a new anemometer shall be installed for the PC (see Case 2 of this section).
- If the anemometer remains on the mast, the in-situ comparison shall be repeated for the period between its initial installation and the period immediately before the start of the PC. If it is verified that $u_{V_{R_{SC,postcal}}} = 0$ (through the rules of Section 4.3.2), then the anemometer can be used also for the PC campaign; if not and especially if $u_{V_{R_{SC,postcal}}} > 0.2$ m/s, then a new anemometer shall be installed for the PC (see Case 2 below).

At the end of the PC campaign, the reference anemometer shall be checked for maintaining its calibration through its complete operational period on the field. The check is applied once through either wind tunnel re-calibration or in-situ comparison and the result determines the $u_{VS,postcal}$ uncertainty:

- *Wind tunnel re-calibration*: The comparison is performed based on the linear regression parameters before the initiation of the SC and after the end of the PC.
- *In situ-comparison*: The calculations are done for the first period after the installation of the anemometer (usually prior to the onset of the SC) and the 2nd period (the last

weeks of the PC). The in-situ comparison is <u>only permitted</u> if the control anemometer has not been exchanged throughout the complete operational period (SC and PC).

- The outcome of the check replaces the term $f_{SC}^2 u_{VS,eff,postcal}^2$ in Equation (4.28).

<u>Case 2. Reference mast anemometer is used throughout the SC; exchanged anemometer from start to end of the PC campaign</u>

Equation (4.28) is applied by setting $\rho_{postcal,V_{R_{PC}}V_{R_{SC}}} = 0$. The $u_{V_{R_{SC,postcal}}}$ and $u_{V_{R_{PC,postcal}}}$ components are calculated through either wind tunnel re-calibration or in-situ comparison separately for the SC and PC campaigns.

<u>Case 3. Reference mast anemometer is changed either during the SC or during the PC</u>

If the control anemometer is the same throughout the campaigns, then a single in-situ comparison from the installation of the initial primary anemometer before the SC till the completion of the PC campaign can be applied to verify that the *postcal* uncertainty of the reference anemometer (even though represented by different physical units of the same model, calibrated in the same wind tunnel) across the SC and PC is zero.

If the test of the previous paragraph cannot be performed (due to change of the control anemometer or due to insufficient data for the in-situ comparison) or fails, then apply the following:

- Assume that L_1 and L_2 periods are identified over the SC and PC campaigns covered by different anemometers on the reference mast. The relevant values $u_{V_{R_{SC,postcal,k1}}}$ (k_1=*1 to* L_1) and $u_{V_{R_{PC,postcal,k2}}}$ (k_2=*1 to* L_2) are calculated.
- The $u_{V_{R_{SC,postcal,k1}}}$ and $u_{V_{R_{PC,postcal,k2}}}$ values are reasonably assumed to be independent from each other.
- The term $f_{SC}^2 u_{VS,eff,postcal}^2$ in Equation (4.28) is substituted by the term $(\sum_{k1=1}^{L1} g_{k1,SC}{}^2 u_{V_{R_{SC}},postcal,k1}^2 + \sum_{k2=1}^{L2} h_{k2,PC}{}^2 u_{V_{R_{PC}},postcal,k2}^2)^{0.5}$ where a weighting is applied based on the % data records g_k of the SC dataset and h_k of the PC dataset covered by each anemometer.

<u>Case 4. Turbine mast anemometer is changed during the SC</u>

If the control anemometer is the same throughout the SC campaign, then a single in-situ comparison from the installation of the initial primary anemometer before the SC till the completion of the SC campaign can be applied to verify that the *postcal* uncertainty of the turbine anemometer (even though represented by different physical units of the same model, calibrated in the same wind tunnel) across the SC is zero.

If the test of the previous paragraph cannot be performed (due to change of the control anemometer or due to insufficient data for the in-situ comparison) or fails, then apply the following:

- Assume that L periods are identified over the SC campaign covered by different anemometers on the turbine mast. The relevant $u_{V_{T_{postcal,k}}}$ (*k*=*1 to L*) values are calculated.
- The $u_{V_{TM_{postcal,k}}}$ values are reasonably assumed to be independent from each other.

- The term $u^2_{V_{TM},postcal}$ in Equation (4.28) is substituted by the term $\sum_{k=1}^{L} {g_k}^2 u^2_{V_{TM},postcal,k}$ where a weighting is applied based on the % data records g_k of the SC dataset covered by each anemometer.

4.5.7 Classification

Equation (4.21) is applied by introducing the *class* components:

$$u^2_{V_{final,class}} = u^2_{V_{TM,class}} + f^2_{SC}(u^2_{V_{R_{PC}},class} + u^2_{V_{R,SC,class}} - 2\, u_{V_{R_{PC,class}}} u_{V_{R_{SC,class}}} \rho_{class,V_{R_{PC}}V_{R_{SC}}}) \quad (4.29)$$

$$\text{or} \quad u^2_{V_{final,class}} = u^2_{V_{TM,class}} + f^2_{SC} u^2_{VS,eff,class}$$

The value obtained depends on the correlation of the operational uncertainty of the reference mast anemometer across the SC and PC campaigns. When the environmental conditions in the two periods are similar, then the respective operational uncertainties will be highly correlated.

Annex 3 provides an alternative calculation which avoids the arbitrary choice for the value of $\rho_{class,V_{R_{PC}}V_{R_{SC}}}$ and applies principles which are already in effect in IEC 61400-50-2 and IEC 61400-12-2.

The remaining part of Section 4.5.7 provides guidance on the handling of the correlation of operational uncertainties between the SC and PC (primary anemometer of the reference mast).

The inconsistencies across the IEC documents include the following:

- Section E6.3.4 of [1] for $u_{VS,class}$ recommends a combination of operational uncertainties by considering $0.5\, u_{V_{R_{SC,class}}}$, $u_{V_{T,class}}$ and $0.5\, u_{V_{R_{PC,class}}}$ and adding them using the root-sum-square approach (i.e. as independent values). If each component is assumed equal to $u_{V,class}$, the result is 1.225 $u_{V,class}$.
- Section E9.4 of [1] for $u_{VT,class}$ states that "*as long as the SC and PC tests stay within the ranges defined for Class B … no additional uncertainty needs to be taken into account*".
- Section 10.2.4 of [2] for $u_{VT,class}$ states that "*turbulence, shear and up-flow 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*".

Table R1 of [1] proposes a correlation value of 0.9. The value of 0.9 would result to $u_{Vfinal,class}$=1.095 $u_{V,class}$. Equation (4.29) yields $u_{Vfinal,class}$=1.225 $u_{V,class}$ when ρ=0.75.

The values for $u_{V_{R_{SC,class}}}$, $u_{V_{TM,class}}$ and $u_{V_{R_{PC,class}}}$ are calculated as weighted quantities according to Equations (4.23) to (4.25).

Applicable formulas:

i. The magnitude of $u_{Vfinal,class}$ is calculated from Equation (4.29) assuming $\rho_{class,V_{R_{PC}}V_{R_{SC}}} = 0.9$ when the B-class uncertainty values are applied for $u_{V_{R_{SC,class}}}$, $u_{V_{TM,class}}$ and $u_{V_{R_{PC,class}}}$.

ii. The magnitude of $u_{Vfinal,class}$ is calculated from Equation (4.29) assuming $\rho_{class,V_{R_{PC}}V_{R_{SC}}} = 1$ when $u_{V_{R_{SC,class}}}$ and $u_{V_{R_{PC,class}}}$ are derived from a full (separate) S-classification of the reference mast anemometer for the SC and the PC.

Note 1: All the anemometers shall be of the same model/configuration. The special condition that the anemometer of the reference mast is of different model between the SC and PC test leads to an increased uncertainty due to the reduction of the correlation between the corresponding operational uncertainties. It would be highly arbitrary to propose a correlation value since it would depend on the design of each anemometer model. In the absence of any evidence, a value ρ=0 shall be applied on this special case. This leads to a significant increase of $u_{Vfinal,class}$ which could be partially compensated by seeking an S-classification for each of the SC and PC tests.

Table 4.8 Handling of *class* uncertainty for different scenarios of anemometer exchange

Case # and description		Assumptions	$\rho_{class,V_{R_{PC}}V_{R_{SC}}}$	$u_{VT,class}$ of [1] replaced by:	$u_{VS,class}$ of [1] replaced by $f_{SC}u_{VS,eff,class}$:
i	None of the involved anemometers of reference/turbine masts has been changed in the SC and the PC campaign in terms of anemometer model.	$\rho_{no\ change,class,V_{R_{PC}}V_{R_{SC}}} = 0.9$	0.9	$u_{VTM,class}$ from Equation (4.25)	$f_{SC}(u^2_{V_{R_{PC}},class} + u^2_{V_{R,SC,class}} - 1.5\, u_{V_{R_{PC,class}}} u_{V_{R_{SC,class}}})^{0.5}$
ii	Change of anemometer model of reference and/or temporary mast during any campaign.	$\rho_{change,class,V_{R_{PC}}V_{R_{SC}}} = 0$	g h from Section 4.5.3.1		$f_{SC}(u^2_{V_{R_{PC}},class} + u^2_{V_{R,SC,class}} - 2\, u_{V_{R_{PC,class}}} u_{V_{R_{SC,class}}} \rho_{class,V_{R_{PC}}V_{R_{SC}}})^{0.5}$ See Equations (4.23),(4.24) for weighting uncertainties

4.5.8 Mounting

Equation (4.21) is applied by introducing the *mnt* components:

$$u^2_{V_{final,mnt}} = u^2_{V_{TM,mnt}} + f^2_{SC}(u^2_{V_{R_{PC}},mnt} + u^2_{V_{R,SC,mnt}} - 2\, u_{V_{R_{PC,mnt}}} u_{V_{R_{SC,mnt}}} \rho_{mnt,V_{R_{PC}}V_{R_{SC}}}) \quad (4.30)$$

$$\text{or} \quad u^2_{V_{final,mnt}} = u^2_{V_{TM,mnt}} + f^2_{SC} u^2_{VS,eff,mnt}$$

The value obtained depends on the correlation of the mounting uncertainty of the reference mast anemometer across the SC and PC campaigns. When the mounting configuration has not been changed in the two periods, then the respective mounting uncertainties will be fully correlated.

The ambiguities across the IEC documents include the following:

- Section E6.3.5 of [1] for $u_{VS,mnt}$ refers to the applicable value (e.g. 0.5% or 1% depending on the selected configuration) for the anemometer of the reference mast during the PC test.
- Section 10.2.5 of [2] for $u_{VT,mnt}$ states that it is "*virtually the same as $u_{VS,mnt}$ with the difference that ... it is applied to a measurement of wind speeds on two masts… 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.*"

Table 4.9 Handling of *mnt* uncertainty for different scenarios of anemometer exchange

Case # and description		Assumptions	$\rho_{mnt,V_{R_{PC}}V_{R_{SC}}}$	$u_{VT,mnt}$ of [1] replaced by:	$u_{VS,mnt}$ of [1] replaced by f_{SC} $u_{VS,eff,mnt}$
i	None of the involved anemometers of reference/turbine masts has undergone a change of mounting configuration in the SC and the PC campaign.	$\rho_{no\ change,mnt,V_{R_{PC}}V_{R_{SC}}} = 1$	1	$u_{VTM,mnt}$ from Equation (4.25)	0
ii	Change of anemometer mounting of reference and/or temporary mast during any campaign.	$\rho_{change,mnt,V_{R_{PC}}V_{R_{SC}}} = 0$	g h from Section 4.5.3.1		$f_{SC}(u^2_{V_{R_{PC}},mnt} + u^2_{V_{R,SC,mnt}} - 2\, u_{V_{R_{PC,mnt}}} u_{V_{R_{SC,mnt}}} \rho_{mnt,V_{R_{PC}}V_{R_{SC}}})^{0.5}$ See Equations (4.23),(4.24) for weighting uncertainties

The cases of Table 4.9 are considered. A change of mounting related to the primary anemometers (single top-mounted or side-by-side mounted) is considered to trigger case (ii) of Table 4.9 when one or more of the following conditions is met:

i. The height of the anemometer has changed by more than 0.5%, or
ii. The orientation of a side-by-side mounted top boom is changed by more than 10°, or
iii. Fundamental change of the design of the mast top or of the mounting boom (without further specification in order to keep flexibility), or

The entire mast has been exchanged.

4.5.9 Lightning Finial

When the lightning protection systems (or their modifications during the SC, PC tests) comply to the requirements of Section 10.5 of IEC 61400-50-1, then $u_{Vfinal,lgt} = 0$ and no further analysis is required. If not, the same assumptions with Table 4.9 shall be applied.

4.5.10 Data Acquisition

Equation (4.21) is applied by introducing the *DAQ* components:

$$u^2_{V_{dfinal}} = u^2_{dV_{TM}} + f^2_{SC}(u^2_{dV_{R_{PC}}} + u^2_{dV_{R,SC}} - 2\, u_{dV_{R_{PC}}} u_{dV_{R_{SC}}} \rho_{dV_{R_{PC}} dV_{R_{SC}}}) \tag{4.30}$$

or

$$u^2_{V_{dfinal}} = u^2_{dV_{TM}} + f^2_{SC} u^2_{dVS,eff}$$

The value obtained depends on the correlation of the wind speed DAQ uncertainty of the reference mast anemometer across the SC and PC campaigns. When the same DAQ and same channel and configuration is applied in the two periods, then the respective uncertainties will be fully correlated.

The ambiguities across the IEC documents include the following:

- Section 10.2.6 of IEC 61400-12-3 for u_{dVT} states that it is "*virtually the same as u_{dVS} with the difference that ... 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.*"
- IEC 61400-12-1, in treating separately u_{dVSi} fails to account for the correlation of the reference mast's DAQ system between the SC and PC test.

The relevant cases for DAQ uncertainties are discussed in Table 4.10.

Note 1: The magnitude of the relevant components shall be taken from the manufacturer specifications.

Table 4.10 Handling of *DAQ* uncertainty for different scenarios of DAQ changes

Case # and description		Assumptions	$\rho_{dV_{R_{PC}}dV_{R_{SC}}}$	u_{dVT} of [1] replaced by:	u_{dVS} of [1] replaced by $f_{SC}u_{dVS,eff}$
I	None of the involved anemometers of reference/turbine masts has been affected by any DAQ configuration change in the SC and the PC campaign	$\rho_{no\ change,dV_{R_{PC}}dV_{R_{SC}}} = 1$	1	u_{dVTM} from Equation (4.23)	0
ii	Change of DAQ configuration of reference and/or temporary mast during any campaign in a way that affects the wind speed measurement.	$\rho_{change,dV_{R_{PC}}dV_{R_{SC}}} = 0$	gh from Section 3.5.3.1		$f_{SC}(u^2_{dV_{R_{PC}}} + u^2_{dV_{R,SC}} - 2\, u_{dV_{R_{PC,}}} u_{dV_{R_{SC}}} \rho_{dV_{R_{PC}}dV_{R_{SC}}})^{0.5}$ See Equations (4.23), (4.24) for weighting uncertainties

4.5.11 Effect of directional dependence of flow correction factors on the PC/AEP uncertainty

Reference: IEC 61400-12-3, Sections 11.3.1, 11.3.2
Key point: Harmonization of approach and assumptions. Erroneous formulation. Modification proposal.

Sections 4.5.2 to 4.5.10 established a consistent, robust methodology to calculate the uncertainty of the site-calibrated wind speed used in the power curve considering the wind speed measurement uncertainties of the reference mast (SC and PC) and their correlations and the wind speed measurement uncertainty of the temporary (turbine) mast. This was based on Equation (4.20), i.e. the definition of the site-calibrated wind speed.

The uncertainty framework applied the error propagation law considering only the wind speeds, i.e. the wind direction dependency of the flow correction factors was ignored.

The same procedure is now applied (Equation (4.20) and error-propagation law) to account for the wind direction dependency of the flow correction factors. The separate treatment is permitted because the wind direction measurement uncertainty is independent from the wind speed measurement uncertainty.

The analytical derivation of the final formula is given in [4]:

$$u_{V_{final}} = \frac{\vartheta f_{SC}}{\vartheta \Theta_{R\_SC}} V_{R\_PC} u_{\Delta WV} \tag{4.31}$$

Where $u_{\Delta WV} = u_{\Theta_{R\_SC} - \Theta_{R\_PC}}$ is the uncertainty of the wind direction measurement difference between the SC and the PC. It shall be calculated according to the guidance given in Section 4.6.

The important outcome of Equation (4.31) is that <u>when the configuration of the wind direction measurement (sensor, mounting, alignment, DAQ) is not modified between the SC and PC</u>, then $u_{\Delta WV} = 0$ which means that there are no additional uncertainty components ($u_{VT,coc,i} = 0$ and $u_{VT,rmv,i} = 0$) related to the site-calibrated wind speed in the power curve.

The $\frac{\vartheta f_{SC}}{\vartheta \Theta_{R\_SC}}$ term is the slope of the site calibration factor (vs. the wind direction measurement during the SC). It can be directly expressed as a central difference through the *sccp* parameters:

$$\frac{\vartheta f_{SC}}{\vartheta \Theta_{R\_SC}} = \frac{sccp_{i,j+1} - sccp_{i,j-1}}{2\ BinWidth} \frac{V_T}{V_{R\_SC}} \tag{4.32}$$

Combining (4.31) and (4.32):

$$u_{V_{T,rmv,i,j}} = \frac{sccp_{i,j+1} - sccp_{i,j-1}}{2\ BinWidth} u_{\Delta WV} V_i \tag{4.33}$$

The respective one-sided formulas are:

$$u_{V_{T,rmv,i,j}} = \frac{sccp_{j+1} - 1}{BinWidth} u_{\Delta WV} V_i \quad \text{and} \quad u_{V_{T,rmv,i,j}} = \frac{1 - sccp_{j-1}}{BinWidth} u_{\Delta WV} V_i \tag{4.34a,b}$$

Note 1: In the left-hand side of Equations (4.33) and (4.34), the parameter $u_{V_{final}}$ has been "renamed" $u_{V_{T,rmv,i,j}}$ to reflect the fact that it attains a non-zero value when the configuration of the wind direction measurement (sensor, mounting, alignment, DAQ) is modified between the SC and PC.

Note 2: Equation (11) from IEC 61400-12-3 for the $u_{VT,rmv,i}$ component yields an underestimate of the correct value which is provided by Equation (4.33) above. Further discussion is given in the following paragraphs.

Note 3: The analytical approach introduced in this Section shows that the $\boldsymbol{u_{VT,coc,i}}$ **component is irrelevant in any case**; indeed, a strong directional variation of the flow correction parameters does not per se impose an uncertainty in the site-calibrated wind speed. Nevertheless, when the configuration of the wind direction measurement (sensor, mounting, alignment, DAQ) is modified between the SC and PC, Equation (3.27) indicates that a strong directional dependence will induce a large uncertainty value.

Note 4: A strong directional variation of the flow correction parameters will most likely be accompanied by large scatter. Only a small part of this effect is captured by the Category A uncertainty of the site calibration (Section 4.5.1). The largest part can be captured by including the *residuals* of the site calibration model as defined by Equation (3) of IEC 61400-12-3 ($V_{Turb\_predicted}$-$V_{Turb\_measured}$). This new component is introduced in Section 4.5.12 and captures likely bias of the flow correction parameters at low/high speeds.

4.5.12 Model uncertainty of Site Calibration

Key points: The Category-A uncertainty of the site calibration turns out to have a small contribution even in highly -complex terrain. A new component is required to describe the uncertainty contribution of wind speed-dependent residual errors of the flow correction factors.

The systematic uncertainty of the site calibration model $u_{VT,model,i,j}$ is derived from the SC dataset for each wind speed & direction bin according to:

$$u_{VT,model,i,j} = V_{TM\_predicted,i,j} - V_{TM,i,j} \tag{4.35}$$

The wind speed bins refer to the wind speed measured at the temporary mast ($V_{TM,i,j}$) and the wind direction bins refer to the wind direction measured at the reference mast.

Note 1: Since the SC data cover the range 4-16 m/s, an extrapolation of the $u_{VT,model,i,j}$ will be required in the PC evaluation for winds below 4 and above 16 m/s. Additionally, interpolation or extrapolation might be also required due to lack of SC data in some wind speed/direction bins. A linear interpolation across wind speed bins of the same direction bin shall be applied when required:

1. The down-speed extrapolation across wind speed bins of the same direction bin shall be done by assuming values equal to the value of the lowest wind speed bin for which data exists (≥3 records). By that, the percentage uncertainty in wind speed increases with decreasing wind speed, which is usually in line with the observed wind speed dependency of the residual error in the wind speed range covered by the site calibration.

2. The up-speed extrapolation across wind speed bins of the same direction bin shall be done by scaling the value of the highest wind speed bin for which data exists (≥3 records) with the ratio of the mean wind speeds of the considered wind speed bin and the highest bin covered by the site calibration. By that, increased absolute uncertainty with increasing difference of the considered wind speed and the wind speed covered by the site calibration is reached, which reflects the fact that the site calibration is applied in a wind speed range outside the range covered by the site calibration.

Note 2: As the power curve refers to the air density corrected wind speed, while the values of $u_{VT,model,i,j}$ are binned against $V_{TM,k,j}$, it is required to follow these steps:

i. Calculate the bin average value V_i of the site-calibrated speed in each (normalized) wind speed bin of the power curve table
ii. Interpolate the $u_{VT,model,k,j}$ to align to the V_i values. Let the interpolated values be denoted by $u_{VT,model,i,j}$
iii. Use V_i and the number of records $N_{i,j}$ from each direction bin j to select the appropriate $u_{VT,model,i,j}$ value for each record within the bin
iv. Calculate $u_{VT,model,i} = \frac{\sum_j u_{VT,model,i,j}}{\sum_j N_{i,j}}$

Note 3: The signed value of Equation (4.35) shall be used to represent correlation/ anticorrelation across the wind speed bins (replaces the value $d_{m,i}$ in Equation (4.4c)).

4.5.13 Uncertainty due to SC and PC recorded in different seasons

Reference: IEC 61400-12-3, Section 11.4
Key points: Clarifications

The component $u_{VT,sv,i}$ represents the uncertainty due to possible seasonal effects on the flow correction factors based on a comparison of the average shear, turbulence and upflow conditions between the SC and PC. The SC data are restricted in the 4-16 m/s range while the PC data extend beyond this range. It is important to align the calculation of the average conditions in the same range for both datasets, otherwise the comparison would be biased. The implementation procedure is as follows:

i. Filter the records of the PC data in the 4-16 m/s range (in terms of flow-corrected, no air-density normalized wind speed) to align with the 4-16 m/s of the SC data.

ii. For each direction bin j of the PC, calculate the average shear, turbulence and upflow for the data derived in step i ($\alpha_{PC,j}$, $TI_{PC,j}$, $incl_{PC,j}$).

iii. For the same direction bins j of the SC, calculate the average shear, turbulence and upflow ($\alpha_{SC,j}$, $TI_{SC,j}$, $incl_{SC,j}$).

iv. For each direction bin j of the PC, calculate the absolute values of the differences $\Delta\alpha = |a_{PC,j} - a_{SC,j}|$, $\Delta TI = |TI_{PC,j} - TI_{SC,j}|$ and $\Delta incl = |incl_{PC,j} - incl_{SC,j}|$

v. For each wind direction bin j of the PC, compare the results of step (iv) to the maximum permitted values given in [1]. If any of the calculated differences exceeds the corresponding limit (0.05 for wind shear, 3% for turbulence intensity and ±2deg for upflow), then $u_{VT,sv,i,j} = \frac{|V_{i,j} - V_{meas,i,j}|}{3}$. The wind speed and direction bin-averaged values of the flow-corrected and the measured wind speed are calculated

4.5.14 Cumulation of u_{VT} components across the direction bins

Reference: IEC 61400-12-3, Section 10.3

Key point: Clarification for implementing Equation 9.

The framework introduced in Section 4.1.2 is based on the treatment of each uncertainty component independent from each other which allows the appropriate calculation of its individual cumulated effect on u_{AEP}.

In this respect, Equation (9) of IEC 61400-12-3 is applied separately for each wind direction-dependent VT component:

$$u_{VT,rmv,i} = \frac{\sum_j u_{VT,rmv,i,j}}{\sum_j N_{i,j}}\ ,\ u_{VT,model,i} = \frac{\sum_j u_{VT,model,i,j}}{\sum_j N_{i,j}}\ ,\ u_{VT,sv,i} = \frac{\sum_j u_{VT,sv,i,j}}{\sum_j N_{i,j}} \tag{4.36}$$

on the assumption that each uncertainty component is fully correlated (or anti-correlated) across the wind direction bins.

Note: The components $u_{VT,rmv,i}$ and $u_{VT,model,i}$ are calculated as signed values to be properly cumulated across wind direction bins (refer to Equation (4.4c)).

4.5.15 Convergence check

Reference: IEC 61400-12-3, Section 11.1

Key point: Clarification.

The convergence check does not lead to any uncertainty penalty. Convergence for a direction bin is demonstrated when the cumulative average of $scp=V_{turb\_predicted}/V_{turb\_measured}$ is stabilized within 0.5% of the final average (of the direction bin) for a period equal to 16h of data (in the direction bin) or 25% of the total number of data points in the direction bin.

4.5.16 Verification of results

Reference: IEC 61400-12-3, Annex A

Key point: Clarification of tolerance depending on distance between reference mast and test turbine.

The verification procedure of Annex A of [2] is applied on the PC data to identify site-calibrated wind direction bins which deviate from the assumption that the flow-corrected wind speed is representative for the hub-height wind speed at the test turbine. The procedure is based on the calculation of the Reverse Power Curve. The procedure may lead to the rejection of non-convergent wind direction bins or of wind direction bins exhibiting large variation of the wind speed correction factor compared to their adjacent wind direction bins.

The average wind speed ratio (wind speed derived from the power curve divided by the site-calibrated speed) in each direction sector shall be in the range of [0.98, 1.02] when the reference mast lies within L< 3 D from the test turbine and [0.97, 1.03] when the reference mast lies between 3 D and 4 D from the test turbine.

Note: The verification is also applied for cases with no site calibration.

4.5.17 Reporting of site-calibration uncertainties

A consequence of the application of the uncertainty model introduced in Section 4.5.2 is that the SC uncertainty cannot be assessed independently from a power curve test. Specifically:

- $u_{VT,sv}$ depends on the difference of conditions between the SC and PC campaigns which are not known before the power curve test completion;
- $u_{VT,rmv}$ applies only when the wind direction sensor/measurement configuration at the reference mast will be modified in the PC campaign or has been modified during the SC campaign.

Nevertheless, if a separate Site Calibration report is issued prior to the power curve test, [1] requires the reporting of the total uncertainty per wind direction bin for 6 m/s, 10 m/s and 14 m/s. The way to report this is provided in Table 4.11. It is noted that when treating the wind speed measurement uncertainties at the temporary mast, the guidance in Section 4.3 of this document can be applied for the respective components, i.e. the rules for $u_{VS,precal}$ are also valid for $u_{VTM,precal}$ etc.

The total uncertainty at each wind speed for each wind direction bin shall be calculated under the assumption that the uncertainties in Table 4.11 are mutually independent. The reported total uncertainty values shall be supplemented by the following statement (or equivalent):

"The reported uncertainties do not represent the uncertainty of the flow-corrected wind speed, which is required in the power curve test. The latter will be larger than the reported uncertainties due to the addition of uncertainties related to the correlation of uncertainties between the SC and PC campaigns at the reference mast".

Table 4.11 Reporting of uncertainties in the Site Calibration Report. To be done for each site-calibrated wind direction bin at 6, 10 and 14 m/s.

Parameter	Comment
$u_{VTM,precal}$	If weighting is required, calculate from Equation (4.13)-same tunnel or Equation (4.25)-different tunnel
$u_{VTM,precal,res}$	Calculate according to guidance in Section 4.3.1; if weighting is required, apply Equation (4.13)
$u_{VTM,postcal}$	Calculate according to guidance in Section 4.3.2; if weighting is required, apply Equation (4.14)
$u_{VTM,class}$	If weighting is required apply Equation (4.14)
$u_{VTM,mnt}$	If weighting is required apply Equation (4.14)
$u_{VTM,lgt}$	If weighting is required apply Equation (4.14)
u_{dVTM}	If weighting is required apply Equation (4.14)
$u_{VT,rmv}$	To be reported as zero when no modifications are applied during the SC. Otherwise calculate according to Sections 4.5.11 and 4.6.2 by assuming that h=1 (i.e. no further change will be implemented until the end of the PC campaign)
$u_{VT,model}$	Calculate according to Equation (4.35)
$u_{VT,sv}$	To be reported as zero under the assumption that the deviation of turbulence, wind shear and upflow average conditions at the reference mast between SC and PC will be within the tolerance of Section 11.4 of [1]
s_{SC}	Calculate according to Equation (4.19); same value for all speeds and all direction bins

4.6 Uncertainty of wind direction measurement

Reference: IEC 61400-12-1, Section E.12.2 & IEC 61400-12-3, Section 11.3.2

Key point: Determination of the relevant wind direction measurement uncertainties to be applied in the context of $u_{VT,rmv}$

IEC 61400-12-3 states that "*If the wind direction sensor is removed between site calibration and the power performance test, an error may be introduced due to the uncertainty of the wind direction sensor alignment between the two installations. An additional uncertainty component for each wind direction bin shall be applied*". Section E12.2 of [1] provides the list of the uncertainty components relevant to the wind direction measurement.

The change of the configuration of the wind direction measurement (sensor, mounting, alignment, DAQ) between the SC and PC results to a potential difference Δ_{WV} in the wind direction measurement between the two campaigns. The uncertainty $u_{\Delta WV}$ results to an uncertainty in wind speed ($u_{VT,rmv}$) under the condition of a wind direction-dependent flow correction. The $u_{VT,rmv}$ uncertainty has been addressed in Section 4.5.11. The present section provides the procedure to calculate the $u_{\Delta WV}$.

4.6.1 Uncertainty of wind direction measurement difference between SC and PC

The difference Δ_{WV} in the wind direction measurement between the SC and PC campaigns due to the change of any relevant parameter (sensor, mounting, orientation, DAQ) is defined as

$$\Delta_{WV} = WV_{SC} - WV_{PC} \tag{4.37}$$

The rules of error propagation lead to:

$$u^2_{\Delta WV,j} = u^2_{WV_{SC,j}} + u^2_{WV_{PC,j}} - 2u_{WV_{SC,j}} u_{WV_{PC,j}} \rho_{WV_{SC}WV_{PC,j}} \tag{4.38}$$

where the wind direction measurement uncertainties in the SC and PC datasets are included for each wind direction bin j.

Each of the wind direction measurement uncertainty components (calibration, alignment etc.) are independent from each other; thus Equation (4.38) is applied for each component separately. The results per component are combined according to:

$$u^2_{\Delta WV,j} = u^2_{WV_{cal,j}} + u^2_{WV_{cal,res,j}} + u^2_{WV_{nm,j}} + u^2_{WV_{bo,j}} + u^2_{WV_{oe,j}} + u^2_{WV_{mda,j}} + u^2_{WV_{dWV,j}} \tag{4.39}$$

4.6.2 Uncertainty model - application

Table 4.12 provides the correlation values to be applied in each case.

Table 4.12 and Equation (4.39) include component $u_{WV,cal,res}$ related to the calibration residuals, i.e. the difference between the reference direction and the indicated (or corrected/calibrated) direction from the sensor. These follow a systematic azimuthal pattern (they are not random) and have a lower magnitude when the calibration parameters are applied on the sensor output. The handling of this component is explained with the aid of the following example.

Assume sensor 1 has been used in the SC and sensor 2 has been used in the PC, both calibrated in the same wind tunnel.

Assume that the final site-calibrated sector as used in the PC is mapped on the direction sensor azimuthal range (relative to its 0 reference/north mark) Φ1 to Φ2 which include calibration bins j,j+1,…,j+l.

The calibration certificates of sensors 1 and 2 are used to calculate the average deviations $res_1 = \frac{1}{l+1}\sum_{n=0}^{l} res_{1,j+n}$ and $res_2 = \frac{1}{l+1}\sum_{n=0}^{l} res_{2,j+n}$.

Assuming that the same value applied for all wind direction bins:

$$u_{WV,cal,res}^2 = res_1^2 + res_2^2 - 2res_1 res_2 \rho$$

where ρ=1 if the res_1 *and* res_2 *have the same sign and ρ=-1 when their sign is opposite. If res1 and res2 are equal (magnitude and sign), then the above formula yields* $u_{WV,cal,res} = 0$.

In case the sensors were calibrated in different wind tunnels or are not of the same model, then ρ=0.

Table 4.12 Handling of wind direction measurement uncertainty for different scenarios of sensor/ mounting/ configuration changes

Component	Case	Correlation to apply in Equation (4.38)
$u_{WV,cal}$	Sensor not changed between SC and PC Sensor changed but calibrated in the same wind tunnel Sensor changed but calibrated in different wind tunnel	1 0.9 0
$u_{WV,cal,res}$	Sensor not changed between SC and PC Sensor changed but calibrated in the same wind tunnel Sensor changed but calibrated in different wind tunnel	1 ±1 0
$u_{WV,nm}$	Sensor not changed between SC and PC Sensor changed	1 0
$u_{WV,bo}$	Mounting boom not changed and not re-oriented Mounting boom changed or re-oriented	1 0
$u_{WV,oe}$	Mounting boom not exchanged (or orientation changed by ≤ 10 deg) between SC and PC Mounting boom exchanged (or orientation changed by > 10 deg) between SC and PC	1 0
$u_{WV,mda}$	This component is practically “activated” when a boom re-alignment is performed based on a magnetic compass measurement. The applicable value in Equation (4.39) is defined as follows: i. If the magnetic declination value used for the sensor signal correction is not updated between the SC and PC (i.e. the old correction is applied for both SC and PC), then the “modelled” time-shift of the declination angle shall be introduced as an uncertainty contribution. ii. If the magnetic declination value used for the sensor correction is updated between the SC and PC, $u_{WV,mda}$ shall be neglected.	
u_{dWV}	DAQ and measurement channel not changed between SC and PC DAQ or measurement channel has changed between SC and PC	1 0

The cases of Table 4.12 can be combined for each component to cover the case of a change in the wind direction measurement <u>during the PC or during the SC, according to the principles introduced in Sections 4.5.3.1 and 4.5.3.2</u>:

- Let the same configuration cover the last g fraction of the SC records and the first h fraction of the PC records.

- Let the value of the uncertainty correlation due to the change be ρ_{change}. Example: $\rho_{change,cal}$=0.9 when the sensor is exchanged.
- The effective correlation to be applied in this case is g h $\rho_{no\ change}$ + (1-g h) ρ_{change} (where $\rho_{no\ change}$ =1). Example: the sensor is exchanged during the SC at a time point when 50% of the SC records were collected before and 50% after the change. Then, the sensor is exchanged during the PC at a time point when 50% of the PC data were collected before and 50% after the change. The effective value $\rho_{effective,cal}$=0.25 + (1-0.25) x 0.9=0.925. The values for $u_{WV_{SC,cal,j}}, u_{WV_{PC,cal,j}}$ can be substituted by weighted values of the respective uncertainties for sensor 1 and sensor 2, in a way similar to Equations (4.23) and (4.25).
- The same exemplary reasoning is applied for any component.

4.7 Method Uncertainties

Reference: IEC 61400-12-1, Section E.11

The wind shear, wind veer, turbulence and upflow have a direct influence on the power performance of a wind turbine (Section E.11.2.1 of [1]). Therefore, the result of a PC measurement campaign is a Climate-Specific Power Curve measured and reported under given conditions of shear/veer/turbulence/upflow with the purpose of comparison/verification against a power curve (mostly theoretical; but could also be measured in other period or location) valid for specified reference conditions of such parameters.

- The PC is intended to be valid for such reference conditions.
- It may or may not be possible to normalize the PC to such reference conditions. In either case, an uncertainty needs to be calculated to cover the effect of the deviation between the measured and the reference conditions of shear, veer, turbulence and upflow.

4.7.1 Shear

Reference: IEC 61400-12-1, Section E.11.2.2.2 and Annex P.

Key point: Clarification for the case of hub-height met mast (no RSD).

Background:

- The concepts of REWS and shear normalization do not apply, because the REWS cannot be calculated.
- The measured power curve is assessed with regard to a reference, hub-height-wind-speed power curve (i.e. not a REWS power curve).

The uncertainty is related to the deviation between the site-calibrated hub-height wind speed $V_{h,i}$ and its shear-normalized value $V_{h,normalised\ shear,i}$ for the desired reference shear conditions. Equation P.6 of [1] which is based on the definition of the wind shear correction factor f_r gives:

$$V_{h,normalized\ shear,i} = \frac{f_{r,measured\ shear,i}}{f_{r,reference\ shear,i}} V_{h,i} \tag{4.40}$$

where:

$f_{r,reference\ shear,i}$ the shear correction factor calculated through application of E.11.2.2.2 of [1] and assuming that the reference wind shear value α_{ref} applies for the entire height range of the rotor.

$f_{r,measured\ shear,i}$ the shear correction factor calculated through application of E.11.2.2.2 of [1].

It is expected that the wind speed is measured at hub height and at one or two additional levels (e.g. mid blade and low-blade tip).

The following rules shall be followed in the implementation of the procedure for $f_{r,measured\ shear,i}$:

- Calculate the bin-average value of wind shear α_i for each wind speed bin of the power curve.
- Assume that α_i applies in the lower rotor half
- Assume that α_i /2 applies in the upper rotor half (signed quantity)
- Calculate the shear correction factor $f_{r,measured\ shear,i}$ for each wind speed bin

Special case:

When the wind speed is measured at H, H-R/2 and H-R (or any other heights), then the bin-average wind shear to be used in the lower rotor half will be calculated from the best-fit shear exponent values of each 10min record in the bin according to the best-fit slope passing through the points {0,0}, $\{\log(\frac{H}{H-0.5R}), \log(\frac{V_h}{V_{H-0.5R}})\}$ and $\{\log(\frac{H}{H-R}), \log(\frac{V_h}{V_{H-R}})\}$. Half of this value shall be assumed for the upper rotor half.

The possible effect of wind shear on the measured power curve (hub-height wind speed definition, without shear normalization) when assessing this power curve against the reference power curve is approximated through the difference between $V_{h,normalized,i}$ and $V_{h,i}$; it follows from Equation (3.34) that this quantity is:

$$V_{h,normalized\ shear,i} - V_{h,i} = (\frac{f_{r,measured\ shear,i}}{f_{r,reference\ shear,i}} - 1)\ V_{h,i} \tag{4.41}$$

It is noted that the calculation of $f_{r,measured\ shear,i}$ involves the assumption that the shear of the upper-half of the rotor (which is not measured) is half its (measured) value in the lower half, which is extremely conservative.

Even if the measured wind shear α_l in the lower rotor half equals α_{ref}, the imposed assumption for the wind shear at the upper-rotor half leads to $f_{r,measured\ shear,i} \neq f_{r,reference\ shear,i}$, thus overestimating the magnitude of the difference in Equation (4.41). Therefore, in accordance with E.23 of [1], the value calculated from Equation (4.41) is assumed to represent the maximum “error”, while the standard uncertainty related to shear is determined by dividing by √3:

$$u_{M,shear,i} = \frac{1}{\sqrt{3}}(\frac{f_{r,measured\ shear,i}}{f_{r,reference\ shear,i}} - 1)\ V_{h,i} \tag{4.42}$$

The value $\frac{1}{\sqrt{3}}(\frac{f_{r,measured\ shear,i}}{f_{r,reference\ shear,i}} - 1)$ can be interpreted as the virtual wind speed correction from the measured to the reference shear conditions.

Note 1: Annex P of [1] interprets $u_{M,shear,i}$ to be caused by the lack of the integration of wind shear in the PC evaluation for the desired reference wind shear conditions.

Note 2: Equation E.23 of [1] for $u_{M,shear,i}$ shall be replaced by Equation (4.42) because the former is correct only when $f_{r,reference\ shear,i} = 1$, i.e the reference power curve refers to zero wind shear.

Note 3: The values of $f_{r,reference\ shear,i}$ and $f_{r,measured\ shear,i}$ are calculated from the ratios $V_{eq,reference}/V_h$ and $V_{eq,measured}/V_h$, respectively. In both cases, V_{eq} is calculated according to Section E.11.2.2.2 of [1] using 20 virtual wind speed measurements where the wind speed varies with height according to the reference or the measured/assumed wind shear values, respectively.

Additional uncertainty component related to shear-method

Annex P of [1] implies that a 2nd shear method uncertainty shall be applied to reflect the incompleteness of the REWS model used in assessing $u_{M,shear,i}$. This is defined to be 1/3 of the virtual wind speed correction from the measured to the reference shear conditions. Combining this with the definition in Equation (4.42), the additional uncertainty component is given by:

$$u_{M,shear,model,i} = \frac{1}{3\sqrt{3}}\left(\frac{f_{r,measured\ shear,i}}{f_{r,reference\ shear,i}} - 1\right) V_{h,i} \tag{4.43}$$

The extra component is justified through the following considerations:

- “*The rotor equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical wind shear*” (Section 9.1.3.2 of [1]).
- “…the wind shear correction is based on the assumption that a wind turbine is able to convert all of the available kinetic energy” (Section 9.1.3.1 of [1]).
- The wind turbines in reality cannot convert all the kinetic energy calculated from the integration of the wind profile over the rotor.

Reference shear conditions

The calculations rely on establishing a reference shear condition $\alpha_{ref,i}$ (presumably over the full rotor diameter) for the warranted power curve:

- If a reference shear condition $\alpha_{ref,i}$ is <u>not specified</u>, the following values will be assumed to represent the wind speed profile over the entire height range of the turbine rotor: 0.2 for onshore and 0.1 for offshore sites.
- If the reference shear conditions are determined as a <u>shear range</u>, then the mean of this range per wind speed bin shall represent $\alpha_{ref,i}$.

Rules for $u_{M,shear,i}$ and $u_{M,shear,model,i}$ components:

i. The two components shall be handled as independent from each other.
ii. The value for each wind speed bin shall be calculated once per each component using the relevant bin-average wind shear value; this is a justified simplification compared to calculating the $f_{r,measured\ shear}$ values for each 10min record and deriving the bin-average value $f_{r,measured\ shear,i}$.
iii. The sign of the values calculated from Equations (4.42) and (4.43) shall be maintained to properly handle the correlation/anticorrelation of each sub-component across the wind speed bins. The cumulation scheme of Equation (4.4c) shall be applied.

4.7.2 Veer

Reference: IEC 61400-12-1, Sections E.11.2.3.2, E.11.2.3.3, Annex P.

Key point: Clarification for the case of hub-height met mast (no RSD).

Background:
- The concepts of REWS and veer normalization do not apply, because the REWS cannot be calculated.
- The measured power curve is assessed with regard to a reference, hub-height-wind-speed power curve (i.e. not a REWS power curve).

The content of Section 4.7.1 is repeated here adjusted for the case of veer.

The uncertainty is related to the deviation between the measured hub-height wind speed $V_{h,i}$ and its normalized value $V_{h,normalised\ veer,i}$ for the desired reference veer conditions. Equation P.6 of [1] which is based on the definition of the wind veer correction factor f_r gives:

$$V_{h,normalized,veer,i} = \frac{f_{r,measured\ veer,i}}{f_{r,reference\ veer,i}} V_{h,i} \tag{4.43}$$

where:

$f_{r,reference\ veer,i}$	the veer correction factor calculated through application of E.11.2.3.2/ E.11.2.3.3 of [1] and assuming that the reference wind veer value θ_{ref} applies for the entire height range of the rotor.
$f_{r,measured\ veer,i}$	the veer correction factor calculated through application of E.11.2.3.2/ E.11.2.3.3 of [1].

It is expected that the wind direction is measured only at (near) hub height and at one or two additional heights (e.g. mid blade and low-blade tip).

The following rules shall be followed in the implementation of the procedure for $f_{r,measured\ veer,i}$:

- Calculate the bin-average value of wind veer θ_i for each wind speed bin of the power curve.
- Assume that θ_i applies in the lower rotor half.
- Assume that 1.5 θ_i applies in the upper rotor half.
- Calculate the veer correction factor $f_{r,measured\ veer,i}$ for each wind speed bin assuming wind speed to be equal to 1 at all virtual measurement heights.

Special cases:

i. When no veer measurements are available, Section E.11.2.3.2 of [1] dictates the use of a wind veer of 40°/100m over the entire rotor height. It is recommended to apply values appropriate for the specific power curve test considering the terrain type and atmospheric stability conditions.

ii. When the wind direction is measured at H, H-R/2 and H-R (or any other heights) then:
   - the bin-average wind veer (deg/m) calculated from the wind directions measured at H and H-R shall be applied for the lower rotor half.
   - a value of 1.5 times the veer of the previous step shall be applied for the upper rotor half.

The possible effect of wind veer on the measured power curve (hub-height wind speed definition, without veer normalization) when assessing this power curve against the reference power curve is approximated as the difference between $V_{h,normalized\ veer,i}$ and $V_{h,i}$; it follows from Equation (4.43) that this quantity is:

$$V_{h,normalized\ veer,i} - V_{h,i} = \left(\frac{f_{r,measured\ veer,i}}{f_{r,reference\ veer,i}} - 1\right) V_{h,i} \tag{4.44}$$

It is noted that the calculation of $f_{r,measured\ veer,i}$ involves the assumption that the veer over the upper rotor half is 1.5 times the lower-half veer which is extremely conservative.

Even if the measured wind veer θ_l in the lower rotor half equals $\theta_{ref,}$ the imposed assumption for the wind veer at the upper-rotor half leads to $f_{r,measured\ veer,i} \neq f_{r,reference\ veer,i}$, thus overestimating the magnitude of the difference in Equation (4.44). Therefore, in accordance with E.24 of [1], the value calculated from Equation (4.44) is assumed to represent the maximum “error”, while the standard uncertainty related to veer is determined by dividing by √3:

$$u_{M,veer,i} = \frac{1}{\sqrt{3}}\left(\frac{f_{r,measured\ veer,i}}{f_{r,reference\ veer,i}} - 1\right) V_{h,i} \tag{4.45}$$

The value $\frac{1}{\sqrt{3}}\left(\frac{f_{r,measured,veer,i}}{f_{r,reference\ veer,i}} - 1\right)$ can be interpreted as the <u>virtual wind speed correction</u> from the measured to the reference veer conditions.

Note 1: Annex P of [1] interprets $u_{M,veer,i}$ to be caused by the lack of the integration of wind veer in the PC evaluation for the desired reference wind veer conditions.

Note 2: Equation E.24 of [1] for $u_{M,veer,i}$ shall be replaced by Equation (4.45) because the former is correct only when $f_{r,reference\ veer,i} = 1$, i.e the reference power curve refers to zero wind veer.

Note 3: The values of $f_{r,reference\ veer,i}$ and $f_{r,measured\ veer,i}$ are calculated from the ratios $V_{eq,reference}/V_h$ and $V_{eq,measured}/V_h$, respectively. In both cases, V_{eq} is calculated according to Section E.11.2.3.2 of [1] using 20 virtual wind direction measurements where the wind direction varies with height according to the reference or the measured/assumed wind veer values, respectively.

Additional uncertainty component related to veer-method

Annex P of [1] implies that a 2nd shear method uncertainty shall be applied to reflect the incompleteness of the REWS model used in assessing $u_{M,veer,i}$. This is defined to be 1/3 of the virtual wind speed correction from the measured to the reference veer conditions. Combining this with the definition in Equation (4.45), the additional uncertainty component is given by:

$$u_{M,veer,model,i} = \frac{1}{3\sqrt{3}}\left(\frac{f_{r,measured\ veer,i}}{f_{r,reference\ veer,i}} - 1\right) V_{h,i} \tag{4.46}$$

Reference veer conditions

The calculations rely on establishing a reference veer condition $\theta_{ref,i}$ (presumably over the full rotor diameter) for the warranted power curve:

i. If reference veer is <u>not specified</u>, then a reference value of 10°/100m shall be assumed to represent the wind veer conditions over the entire height range of the turbine rotor.
ii. If the reference veer conditions are determined as a <u>veer range</u>, then the mean of this range per wind speed bin shall be assumed to represent $\theta_{ref,i}$.

Rules for $u_{M,veer,i} and\ u_{M,veer,model,i}$ components:

i. The two components shall be handled as independent from each other.
ii. The value for each wind speed bin shall be calculated once per each component using the relevant bin-average wind veer value; this is a justified simplification compared to the calculation of $f_{r,measured\ veer}$ values for each 10min record followed by the calculation of their bin-average value $f_{r,measured\ veer,i}$.
iii. The sign of the values calculated from Equations (4.45) and (4.46) shall be maintained to properly handle the correlation/anticorrelation of each sub-component across the wind speed bins. The cumulation scheme of Equation (4.4c) shall be applied.

4.7.3 Upflow

Reference: IEC 61400-12-1, Sections E.11.2.4

Key point: Clarification

No model is provided in the IEC for the effect of upflow angle on the turbine performance contrasting the case of shear, veer and turbulence[2]. Nevertheless, an uncertainty component due to partial or complete lack of upflow measurements is introduced in Table E.5 of [1] for terrain not compliant with IEC 61400-12-5 requirements. The uncertainty is proposed as a range of values.

In the absence of any better judgement, it is proposed to apply the central value of the given range for each case of Table E.5 of [1].

Table 4.13 Values for $u_{M,upflow}$ depending on the number of upflow measurement heights

Number of measurement heights	Percentage of flow-corrected wind speed
0 (no upflow measurement):	0.4%
1 (at hub height only):	0.2%
2 (lower rotor area):	0.1%
3 :	0.05%
5 :	0.02%
7 :	0.01%

4.7.4 Seasonal effects

Reference: IEC 61400-12-1, Sections E.11.3

Key point: Clarification

It is expected that the main effect to be covered by the $u_{M,sfx}$ component is the blades' condition as affecting their aerodynamic performance. A default magnitude of 0.7% of the flow-corrected wind speed shall be applied when special ambient conditions have been encountered affecting the blades' condition. Otherwise, the uncertainty $u_{M,sfx}$=0.

[2] The shear, veer and turbulence effects are assessed through proposed models which can be used to normalize the power curve to prescribed reference conditions for shear, veer and turbulence. Consequently, an uncertainty is calculated for either normalized or non-normalized power curves by applying the respective models.

4.7.5 Turbulence normalization

Reference: IEC 61400-12-1, Sections E.11.4 and Annex M

Key point: Clarification. Consideration of correlation across the wind speed bins when cumulating into the u_{AEP}.

The uncertainty $u_{M,tinorm}$ related to the 10-min averaging effects on the evaluated power curve shall be applied for the non-turbulence normalized power curve. It shall also be applied to the turbulence-normalized power curve if provided as a result of the PC test. That is to say that $u_{M,tinorm}$ is non-zero independent of whether turbulence normalization has been applied on the reported power curve or not.

Table 4.14 Applicable formulas for PC uncertainty related to turbulence normalization effects

Case	Value assumed for $u_{M,tinorm,i}$	Comments
1. Turbulence normalized power curve	$\frac{P_{norm,i} - P_{measured,i}}{\sqrt{3}}$	The normalized power curve refers to given reference turbulence conditions.
2. Non-turbulence normalized power curve	$2\frac{P_{norm,high\ TI,i} - P_{normalized,low\ TI,i}}{\sqrt{3}}$	There is no benchmark power curve against which to compare the measured power curve. A maximum range of turbulence intensity has to be assumed. The default values for the extreme low and extreme high turbulence are 0.05 and 0.15, respectively (wind speed independent, offshore: 0.03 and 0.09). The normalized power curves are calculated at the two assumed extreme TI conditions.
3. Non-turbulence normalized power curve	$2\frac{P_{norm,reference\ TI,i} - P_{norm,bin-average\ TI,i}}{\sqrt{3}}$	There is a benchmark power curve against which to compare the measured power curve. The P-normalized value is calculated at the reference TI and at the bin average-value of the measured TI.

Note 1: The TI-normalized power value at any reference or assumed TI value is calculated for each 10min record of the PC dataset. These values are then averaged inside each bin of the power curve.

Note 2: The 3rd case of Table 4.14 is also applicable for the case of reporting a non-turbulence normalized power curve which has been derived from a dataset filtered according to a range of turbulence conditions usually set by the OEMs in the context of power curve warranty (verification) tests. Despite using the specific TI filter, the actual distribution of the TI conditions measured during the PC test may be different in different periods or locations. In this case, even if the reference TI is not defined, its value will be assumed for each wind speed bin to be the mean of the values of the upper and lower TI filter (*e.g. if the TI filter ranges between 8% and 9% at 5 m/s, then the reference TI is 8.5% at 5 m/s. If the bin-averaged TI is 8.3%, then the difference of the normalized power values at 8.5% and 8.3% must be calculated from the average of all 10min records in the 4.75 to 5.25 m/s bin*).

Accumulation of $u_{M,tinorm,i}$ into AEP uncertainty

The $u_{M,tinorm,i}$ values in Table 4.14 shall be cumulated with their signs across the wind speed bins to calculate $u_{AEP,M,tinorm}$ for each wind speed distribution (Rayleigh or site-specific) according to Equation (4.4c) of this document, as re-written here for the particular component:

$$u_{\mathrm{AEP,M,tinorm}} = 8760 \sum_{i=1}^{N}[F(V_i) - F(V_{i-1})]\frac{(u_{M,tinorm,i-1}+u_{M,tinorm,i})}{2} \tag{4.47}$$

For each of the cases given in Table 4.14, the summation represented by Equation (4.47) can be proven (see [5]) to equal the difference between the AEP values derived e.g. from the measured and the TI-normalized power curve (Table 4.15).

Table 4.15 Calculation of $u_{AEP,M,tinorm}$ for the cases of Table 4.14.

Case	$u_{AEP,M,tinorm}$
1. Turbulence normalized power curve	$\frac{\lvert AEP_{norm} - AEP_{measured}\rvert}{\sqrt{3}}$
2. Non-turbulence normalized power curve	$2\,\frac{\lvert AEP_{norm,high\,TI} - AEP_{norm,low\,TI}\rvert}{\sqrt{3}}$
3. Non-turbulence normalized power curve	$2\,\frac{\lvert AEP_{norm,reference\,TI} - AEP_{norm,bin-average\,TI}\rvert}{\sqrt{3}}$

4.7.6 Cold climate

Reference: IEC 61400-12-1, Section E.11.5 & Annex O

Key point: Clarification. Removal of ambiguity

Ice accretion on supports and mounting structures can have a significant effect on the flow conditions around the anemometer.

It is proposed to apply the highest value of the default range (1% of wind speed) given in [1]. This value is then scaled by estimating the weighted effect of “cold conditions” on the PC records. The “cold conditions” are assumed to refer to periods when the ambient air temperature T<0ºC. Thus:

$$u_{M,cc,i} = 0.01\frac{n_{i,T<0}}{n_i}V_i \tag{4.48}$$

where

$n_{i,T<0}$ number of records with T<0ºC in wind speed bin i
n_i number of records in wind speed bin i

4.7.7 Air density correction

Reference: IEC 61400-12-1, Sections E.10.15

Key point: Include sign and perform appropriate accumulation across wind speed bins to establish $u_{AEP,AD,method}$.

Applicable formulas:

For PC: $u_{AD,method,i} = \frac{V_{n,i} - V_i}{2}$ or $u_{AD,method,i} = \frac{P_{n,i} - P_i}{2}$ for stall (4.49)

For AEP: $u_{\mathrm{AEP,AD,method}} = 8760 \sum_{i=1}^{N} [F(V_i) - F(V_{i-1})] \frac{(u_{AD,method,i-1} + u_{AD,method,i})}{2}$ or (4.50)

$$u_{\mathrm{AEP,AD,method}} = \frac{|AEP_{measured,norm} - AEP_{measured,no\ density\ corrected}|}{2} \quad (4.51)$$

Equation (4.51) is derived by direct analogy with the case for the TI normalization, as proved in [5].

4.8 Sensitivity factors

Reference: IEC 61400-12-1, Table E.2

The sensitivity factors are applied to translate wind speed, air temperature, pressure and relative humidity uncertainty components into power uncertainty as required to calculate the combined power uncertainty per wind speed bin of the power curve (and its subsequent cumulation into the AEP uncertainty).

The set of sensitivity coefficients for the power curve uncertainty is applied for both the PC and the AEP.

The sensitivity coefficient for wind speed (Table E.2 of [1]) is:

$$c_{V,i} = \frac{1}{2}\left(\frac{P_{i+1}-P_i}{V_{i+1}-V_i} + \frac{P_i-P_{i-1}}{V_i-V_{i-1}}\right) \tag{3.47}$$

The bin-averaged values used in Equation (3.47) refer to density-corrected values of power or wind speed. The consistent application of (3.47) dictates that the values of the uncertainty components of wind speed and power are scaled/adjusted to represent their density-corrected values.

The sensitivity coefficients for air temperature, pressure and relative humidity are defined by equations E.17, E.19 and E.21 of [1] for turbines with active power control. The corresponding equations for stall-regulated turbines are E.18, E.20 and E.22 of [1]. In analogy to the previous paragraph, the consistent application of the sensitivity coefficients shall consider the uncertainty of the height-corrected air temperature and pressure.

The relevant guidance is provided below for all the uncertainty components.

Table 4.16 Required adjustment of uncertainty values to ensure consistent translation to power units through the application of sensitivity coefficients.

Component	Unit	Without SC	With SC	Comments
$u_{VS,precal,i}$	[m/s]	$u_{V_{R,PC,precal,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},precal,i} + u^2_{V_{R,SC,precal,i}} - 2\,u_{V_{R_{PC,precal,i}}} u_{V_{R_{SC,precal,i}}} \rho_{precal,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	For both cases (with/without SC) the uncertainty value for each component is stated in terms of the measured, bin-averaged wind speed. For the case without SC, the uncertainty of the measured wind speed at the reference mast is valid for the uncertainty of the wind speed at the test turbine. For the case with SC, thanks to the site-calibration factor $f_{SC,i}$, the uncertainty of the site calibration is scaled to represent the uncertainty of the wind speed at the test turbine. **For turbines with active power control, these values shall be scaled by $(\frac{\rho_i}{\rho_o})^{\frac{1}{3}}$ before transforming them into power units through the sensitivity coefficient c_V.**
$u_{VS,precal\,res,i}$	[m/s]	$u_{V_{R,PC,precal\,res,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},precal\,res,i} + u^2_{V_{R,SC,precal\,res,i}} - 2\,u_{V_{R_{PC,precal\,res,i}}} u_{V_{R_{SC,precal\,res,i}}} \rho_{precal\,res,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	
$u_{VS,postcal,i}$	[m/s]	$u_{V_{R,PC,postcal,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},postcal,i} + u^2_{V_{R,SC,postcal,i}} - 2\,u_{V_{R_{PC,postcal,i}}} u_{V_{R_{SC,postcal,i}}} \rho_{postcal,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	
$u_{VS,class,i}$	[m/s]	$u_{V_{R,PC,class,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},class,i} + u^2_{V_{R,SC,class,i}} - 2\,u_{V_{R_{PC,class,i}}} u_{V_{R_{SC,class,i}}} \rho_{class,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	
$u_{VS,mnt,i}$	[m/s]	$u_{V_{R,PC,mnt,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},mnt,i} + u^2_{V_{R,SC,mnt,i}} - 2\,u_{V_{R_{PC,mnt,i}}} u_{V_{R_{SC,mnt,i}}} \rho_{mnt,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	
$u_{VS,lgt,i}$	[m/s]	$u_{V_{R,PC,lgt,i}}$	$f_{SC,i}(u^2_{V_{R_{PC}},lgt,i} + u^2_{V_{R,SC,lgt,i}} - 2\,u_{V_{R_{PC,lgt,i}}} u_{V_{R_{SC,lgt,i}}} \rho_{lgt,V_{R_{PC}}V_{R_{SC}}})^{0.5}$	
$u_{dVS,i}$	[m/s]	$u_{dV_{R,i}}$	$f_{SC,i}(u^2_{dV_{R_{PC}},i} + u^2_{dV_{R,SC,i}} - 2\,u_{dV_{R_{PC,i}}} u_{dV_{R_{SC,i}}} \rho_{dV_{R_{PC}}dV_{R_{SC}}})^{0.5}$	

Component	Unit	Without SC	With SC	Comments
$u_{V_{T,i}}$		2-3% V_i onshore 1-2% offshore	$u_{V_{T,precal,i}}$ $u_{V_{T,precal\,res,i}}$ $u_{V_{T,postcal,i}}$ $u_{V_{T,class,i}}$ $u_{V_{T,mnt,i}}$ $u_{V_{T,lgt,i}}$ $u_{dV_{T,i}}$ $u_{V_{T,rmv,i}}$ $u_{V_{T,coc,i}}$ or $u_{V_{T,model,i}}$ $u_{V_{T,sv,i}}$ s_{SC}	The components refer to the turbine mast of the SC, so they are directly representative for the uncertainty of the wind speed at the test turbine. **For turbines with active power control, these values shall be scaled by $(\frac{\rho_i}{\rho_o})^{1/3}$ before transforming them into power units through the sensitivity coefficient c_V.**
$u_{M,shear,i}$	[m/s]			These components include the bin-average value of the density-corrected wind speed, therefore **no scaling is required before transforming them into power units through the sensitivity coefficient c_V.**
$u_{M,shear,model,i}$	[m/s]			
$u_{M,veer,i}$	[m/s]			
$u_{M,veer,model,i}$	[m/s]			
$u_{M,upflow,i}$	[m/s]			
$u_{M,sfx,i}$	[m/s]			
$u_{M,cc,i}$	[m/s]			The component refers to the site calibrated speed wind speed. **For turbines with active power control, these values shall be scaled by $(\frac{\rho_i}{\rho_o})^{1/3}$ before transforming them into power units through the sensitivity coefficient c_V.**
$u_{M,TInorm,i}$	[kW]			The values are calculated from the density-normalized power curves. No scaling is required.
$u_{T,cal,oper}$	[K]			No scaling is required.
$u_{T,shield}$	[K]			
$u_{T,mnt}$	[K]			
u_{dT}	[K]			
$u_{B,cal,oper}$	[Pa]			These components refer to the measured pressure. They shall be multiplied by $exp\left(-g_n \frac{z_{hub}-z_{baro}}{R_0 T_{meas}}\right)$ to represent the uncertainty of the height-corrected pressure at hub height. Negligible effect is expected from the correction.
$u_{B,mnt}$	[Pa]			
u_{dB}	[Pa]			
$u_{RH,cal,oper}$	[%RH]			No scaling is required.
$u_{RH,mnt}$	[%RH]			
u_{dRH}	[%RH]			
$u_{AD,method,i}$	[m/s] [kW]	Pitch-controlled Stall		The uncertainty value is defined as a difference between measured (and site-calibrated as the case may be) and density-normalized values. Thus, no scaling is required.
$u_{P,i}$	[kW]			The values of the uncertainty components are by definition scaled according to the measured power value. Thus, in case of stall-regulated turbines, the components have to be scaled by $(\frac{\rho_o}{\rho_i})$
$u_{P,CT,i}$	[kW]			
$u_{P,VT,i}$	[kW]			
$u_{P,PT,i}$	[kW]			
u_{dP}	[kW]			

5 References

[1] IEC 61400-12-1, Edition 3.0, 2022-09 Power performance measurements of electricity producing turbines

[2] IEC 61400-12-3, Edition 1.0, 2022-08 Power performance – Measurement based site calibration

[3] IEC 61400-50-1, Edition 1.0, 2022-11 Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments

[4] Deutsche Windguard Report PP24009.A0 Cumulating Wind Speed Measurement Uncertainties Across Site Calibration and Power Curve Test, 03/2024, by A. Albers

[5] Deutsche Windguard Report PP23035.A2 Practical Aspects of Power Curve Testing Uncertainty Due to Turbulence Effects, 12/2023, by A. Albers

[6] WMO Field intercomparison of thermometer screens/shields and humidity measuring instruments, WMO Report No 16- Instruments and observing methods, WMO/TD-No 1579, 2011

[7] Guide to Meteorological Instruments and Methods of Observation, WMO-No 8, 2014 edition, updated in 2017, Chapter 2.5

[8] ISO/IEC 17025: 2017: General requirements for the competence of testing and calibration laboratories.

[9] MEASNET, Calibration Procedure for Transducers, Rev 01, April 2019

[10] MEASNET Project Report on Calibration Procedure for Transducers, June 2019

[11] 20PP01 IECRE External Report_v2, Power Performance Proficiency Test, March 2024

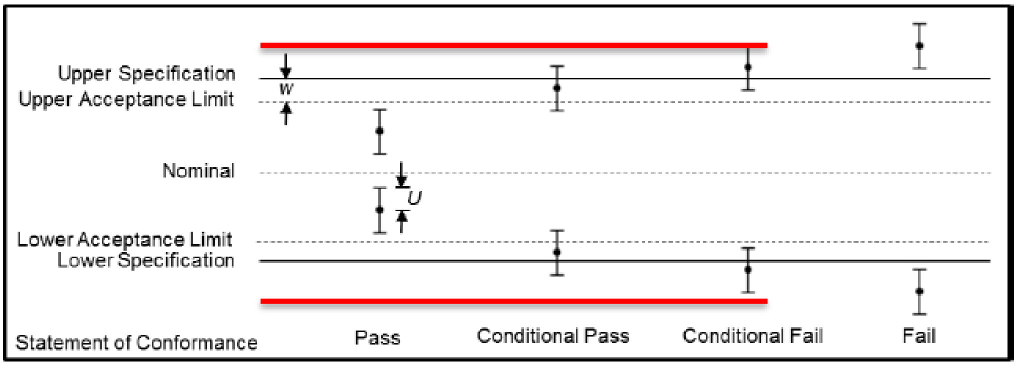
[12] ILAC-G8:09/2019 Guidelines on Decision Rules and Statements of Conformity

Annex 1 Assessing conformity to specifications based on laboratory calibrations

The thermometers, barometers, hygrometers, DAQ systems, power transducers and current transformers are tested in calibration facilities to verify that they operate within the specifications.

The relevant uncertainties are derived from the specifications unless the calibration results fail to comply with these.

The scheme to determine if the sensor operates within specifications or deviates from the latter is based on [12], specifically according to *Option 4.2.3 Non-binary Statement with Guard Band*.



The following adjustments/adaptations are applied:

i. The quantity U (expanded measurement uncertainty at 95%, k=2) is replaced by the standard uncertainty as derived from the calibration certificate.
ii. The guard band width w is assumed to equal u.

The upper/lower specification values (S) in the above Figure are assumed to represent standard uncertainties (e.g. accuracy/√3 or equivalent according to the Specification Sheet information).

The uncertainty components $u_{T,cal}$ etc. are calculated according to the following considerations, as relevant in the actual measurement range (e.g. range of temperature of the valid records of the power curve table):

Case	u_{cal}
All relevant calibration points are PASS	S
One or more calibration points are Conditional PASS or Conditional FAIL	S shall be increased by the required value to accommodate all the calibration points (see red line).
One or more points are FAIL	The sensor shall be rejected (not to be used)

When the FAIL case is observed for one or more points, it could be decided that by applying the calibration correction parameters (e.g. offset or linear regression parameters) the sensor is still reliable. In this case, the assessment of the applicable uncertainty shall be repeated for the corrected measurement value.

If such a sensor is used, it is mandatory to demonstrate the reliability by re-calibrating the sensor in the end of the measurement.

Annex 2 Correlation of calibration uncertainties for anemometers

This Annex aims to assist the estimation of the magnitude of the correlation of calibration uncertainties between anemometers calibrated in the same wind tunnel.

The starting point is the term $u^2_{V_{R_{PC}},precal} + u^2_{V_{R,SC,precal}} - 2\, u_{V_{R_{PC,precal}}} u_{V_{R_{SC,precal}}} \rho_{precal,V_{R_{PC}}V_{R_{SC}}}$ included in Equation (4.26). If the anemometer of the reference mast has not been changed between the SC and PC, this term becomes zero.

In the case that anemometer cup1 has been used in the SC while cup2 (same model) calibrated in the same wind tunnel has been used in the PC, an uncertainty arises for the flow corrected speed because the flow correction factor has been calculated using cup1 and then applied on the readings of cup2. This uncertainty is expressed by the term above.

An alternative way to quantify this uncertainty without including the correlation of uncertainties (difficult to calculate) is to consider the *repeatability* of calibrations in the specific wind tunnel. The *repeatability* provides a good measure of the uncertainty induced in the SC/PC process due to the use of different anemometers in the two campaigns.

The repeatability of calibrations in a wind tunnel depends on the anemometer model and the facility. When dealing with the same anemometer model, the repeatability depends only on the facility (including ambient conditions during calibrations). The repeatability for any specific wind tunnel is not reported, but wind tunnels compliant to Section 8 of [3] are subject to the following requirement:

"*The calibration setup shall undergo a detailed examination of the repeatability of anemometer calibrations. The calibration facility shall designate reference anemometers of representative size for use in these tests. The standard deviation and maximum deviation of the quality control anemometer output in the calibration speed range should be less than 0,2 % and 0,6 %, respectively, of the mean value*".

The repeatability for each wind speed bin in the 4 – 16 m/s range is further assumed to represent the uncertainty due to use of different anemometers in the SC and PC campaigns:

$$u^2_{V_{R_{PC}},precal} + u^2_{V_{R,SC,precal}} - 2\, u_{V_{R_{PC,precal}}} u_{V_{R_{SC,precal}}} \rho_{precal,V_{R_{PC}}V_{R_{SC}}} = (repeatability\ x\ V_{meas})^2$$

To simplify the calculations, it is reasonable to assume that $u_{V_{R_{PC,precal}}}$ equals $u_{V_{R_{SC,precal}}}$; their value is substituted by $u_{V_{R_{precal}}}$. The calibration uncertainty $u_{V_{R_{precal}}}$ may be written as:

$$u_{V_{R_{precal}}} = k_{cal} V_{meas}$$

Applying the assumptions we get:

$$2\left(1 - \rho_{precal,V_{R_{PC}}V_{R_{SC}}}\right)(k_{cal}V_{meas})^2 = (repeatability\ x\ V_{meas})^2 \Rightarrow$$

$$\rho_{precal,V_{R_{PC}}V_{R_{SC}}} = 1 - 0.5\,(\frac{repeatability}{k_{cal}})^2$$

An appropriate uncertainty budget of the anemometer calibration should implicitly “incorporate” the repeatability variation. Additionally, the repeatability should not be expected to “represent” a large proportion of the calibration uncertainty.

Taking a “typical value” of 0.2% for repeatability and a calibration uncertainty of 0.5% leads to $\frac{repeatability}{k_{cal}}$=0.4. The dependence of $\rho_{precal,V_{R_{PC}}V_{R_{SC}}}$ on the ratio $\frac{repeatability}{k_{cal}}$ (Figure A2.1) indicates that the assumption of $\rho_{precal,V_{R_{PC}}V_{R_{SC}}}$=*0.9* is a reasonable one (on the conservative side) when the repeatability is “kept” below ½ of the reported calibration uncertainty.

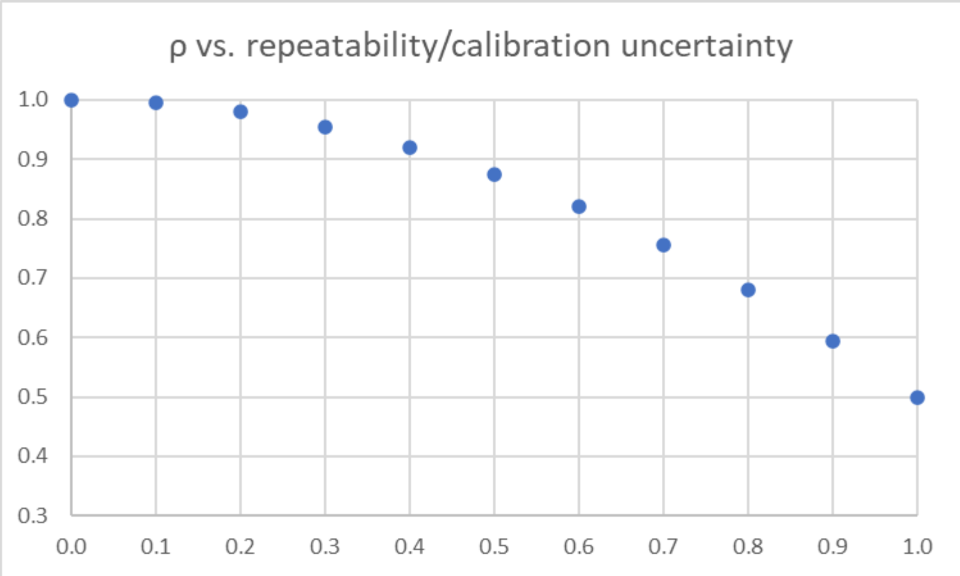


Figure A2.1

Annex 3 Alternative treatment of operational uncertainty in wind speed measurement

The 2nd term of the right hand side of Equation (4.29), $f_{SC}^2(u_{V_{R_{PC}},class}^2 + u_{V_{R,SC,class}}^2 - 2\, u_{V_{R_{PC,class}}} u_{V_{R_{SC,class}}} \rho_{class,V_{R_{PC}}V_{R_{SC}}})$, includes the correlation of operational uncertainties between the SC and PC datasets at the reference mast; this is an unknown value for which some reasonable value must be derived.

When the primary anemometer of the reference mast is the same model during the SC and PC, the value of the parenthesis can be substituted by a fraction of the operational uncertainty of the anemometer. Then, plausible values for $\rho_{class,V_{R_{PC}}V_{R_{SC}}}$ can be calculated based on the level of similarity of SC and PC ambient conditions at the reference mast.

Assume that the anemometer model has been classified as X. The classification is determined by assessing the anemometer response to wind speed, wind direction, air temperature T, turbulence TI, air density, flow inclination and turbulence structure. Each of these parameters spans a Class-specific range of values. The anemometer specific sensitivity on some of these parameters is graphically reported in the Classification reports. It can be linear or non-linear (e.g. tilt response).

The following procedure is proposed:

1. Calculate for each wind speed bin of the SC dataset the average values of T, TI, density and flow inclination at the reference mast. The calculation shall include only the direction bins which have been used in the power curve. The measured wind speed of the reference mast is used for the binning.
2. Calculate for each wind speed bin of the power curve the average values of T, TI, density and flow inclination at the reference mast. The measured wind speed of the reference mast is used for the binning.
3. Calculate for each wind speed bin the deviation of the average values of T, TI, density and flow inclination between the SC and PC.
4. Normalize (scale) for each wind speed bin the deviations of step 3 by the range of the respective parameter (e.g. T, TI etc.) as defined in the anemometer classification.
5. For each parameter find the maximum normalized value across all wind speed bins (4 to 16 m/s). Denote this value by $O_{p,k}$ (k=1 to 4).
6. The worst case would be that the deviations between the SC and PC are fully correlated in terms of the operational uncertainty. A plausible value would be to adopt the maximum value between the 4 parameters, so that the representative value for O_p would be $max\{O_{p,1}, O_{p,2}, O_{p,3}, O_{p,4}\}$. The factor O_p would be the scaling factor to be applied on Class X so as to describe the operational uncertainty due to the deviation of conditions between the SC and PC.

As an example, assume that T, TI, density and flow inclination were found to deviate by 10%, 15%, 10% and 5% of the respective Class range, respectively. Then O_p=15% and the “deviation class” would be O_p X. The value is applied for all wind speed bins according to the (0.05 m/s

+0.005 V_i) O_p X/$\sqrt{3}$ formula. The binning refers to the measured wind speed at the reference mast (not air density normalized, not-corrected for site calibration).

The modified version of Equation (4.29) would be:

$$u^2_{V_{final,class}} = u^2_{V_{TM,class}} + f^2_{SC} O^2_p u^2_{V_R,class} = u^2_{V_{TM,class}} + f^2_{SC} [\frac{(0.05+0.005V_{meas})O_p X}{\sqrt{3}}]^2 \quad \text{(A3.1)}$$

By assuming $u_{V_{TM}} = u_{V_{R_{PC,class}}} = u_{V_{R_{SC,class}}} = u_{V_{class}}$, the comparison of Equations (4.29) and (A3.1) leads to:

$$O_p = \sqrt{2(1 - \rho_{class,V_{R_{PC}}V_{R_{SC}}})} \quad \text{(A3.2)}$$

Some example values can be derived from Equation (A3.2):

Correlation	Op (% of class range)	Uncertainty $u_{V_{final,class}}$
ρ=1	0	$u_{V_{class}}$
ρ=0.95	32%	1.049 $u_{V_{class}}$
ρ=0.9	45%	1.095 $u_{V_{class}}$
ρ=0.75	71%	1.225 $u_{V_{class}}$
ρ=0.5	100%	1.414 $u_{V_{class}}$

Note: $u_{V_{class}}$ stands for the common Class B index of the anemometers at the reference and temporary masts, SC and PC. The last column is calculated with the additional assumption of $f_{SC} = 1$.

The example shows that the proposed/implied value of $\rho_{class,V_{R_{PC}}V_{R_{SC}}} = 0.9$ corresponds to a case when the conditions at the reference mast between the SC and the PC deviate by 45% of the parameter range for the anemometer class. It is thus a reasonably conservative assumption.

Annex 4 Rogowski coils

Key point: Applicability of Rogowski coils

Section 7.1 of [1] dictates that the electric power is measured with a power measurement device based on measurements of current and voltage on each phase. The class of current transformers shall meet the requirements of IEC 61689-2. The CTs shall be of class 0.5 or better.

When space and installation restrictions of a power curve test make it impossible to install a current transformer (split or solid), Rogowski coils (current transducers) may be applied. Rogowski coils are flexible, can measure a current range from a few A to kA with the same size, have good linearity and very high bandwidth. They are used in Power Quality measurements on wind turbines. Their signal is a very-low voltage which needs a conditioning unit.

Rogowski coils are sensitive to the centre-offset positioning[3], angle and deformation. They shall be calibrated according to the requirements set in *Measnet Calibration Procedure for Transducers* (Rev.01, 4/2019), particularly sections 6.2.1, 6.3, 7 and 8 [9].

Section 6.2 of [9] provides a Guide for the evaluation of uncertainty of the current transducers due to non-ideal installation. This is handled as an additional uncertainty beyond the value derived from the standard calibration certificates. The described procedures and calculations of [9] shall be followed.

The Rogowski coil shall be centred on the current conductors and kept perpendicular to them to enable high-accuracy measurements to be taken. Other precautions to be considered include the following:

- Signal integrators shall be subjected to sufficient ventilation to avoid overheating.
- Cables between the coil and the signal integrator shall be as short as reasonably possible. This may imply a separate cabinet for them.
- Ground conditions: Use of shielded cables, metal cabinets. Check signal ground against turbine ground potential.

Note 1: Manufacturer quoted values for Rogowski measurement uncertainty are typically around 1%[4]. This exceeds the CT class requirement and shall be reported as a deviation.

[3] There are devices which are recommended to be placed off-center by the manufacturer
[4] There are a number of models that claim to meet class 0.5; these have been only verified in laboratory tests.