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Wind ~~turbines~~ energy generation systems –
Part 12-1: Power performance measurements of electricity producing wind turbines

IEC 61400-12-1:2017-03 RLV(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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WIND ~~TURBINES~~ ENERGY GENERATION SYSTEMS –

Part 12-1: Power performance measurements of electricity producing wind turbines

FOREWORD

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International Standard IEC 61400-12-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This second edition cancels and replaces the first edition published in 2005. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

a) new definition of wind speed,
b) inclusion of wind shear and wind veer,
c) revision of air density correction,
d) revision of site calibration,
e) revision to definition of power curve,
f) interpolation to bin centre method,
g) revision of obstacle model,
h) clarification of topography requirements,
i) new annex on mast induced flow distortion,
j) revision to anemometer classifications,
k) inclusion of ultrasonic anemometers,
l) cold climate annex added,
m) database A changed to special database,
n) revision of uncertainty annex,
o) inclusion of remote sensing.

IEC 61400-12-2 is an addition to IEC 61400-12-1.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/610/FDIS	88/617/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

A list of all parts in the IEC 61400, published under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee recognizes that this revision represents a significant increase in complexity and perhaps greater difficulty to implement. However, it represents the committee's best attempt to address issues introduced by larger wind turbines operating in significant wind shear and complex terrain. The committee recommends that the new techniques introduced be validated immediately by test laboratories through inter-lab proficiency testing. The committee recommends a Review Report be written within three years of the release of this document which includes recommendations, clarifications and simplifications that will improve the practical implementation of this standard. If necessary a revision should be proposed at the same time to incorporate these recommendations, clarifications and simplifications.

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The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigenda of September 2019 and March 2020 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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INTRODUCTION

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. The standard has been prepared with the anticipation that it would be applied by:

a) a wind turbine manufacturer striving to meet well-defined power performance requirements and/or a possible declaration system;

b) a wind turbine purchaser in specifying such performance requirements;

c) a wind turbine operator who may be required to verify that stated, or required, power performance specifications are met for new or refurbished units;

d) a wind turbine planner or regulator who ~~must~~ shall be able to accurately and fairly define power performance characteristics of wind turbines in response to regulations or permit requirements for new or modified installations.

This document provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines. The document will benefit those parties involved in the manufacture, installation planning and permitting, operation, utilization, and regulation of wind turbines. The technically accurate measurement and analysis techniques recommended in this standard should be applied by all parties to ensure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to ~~environmental concerns~~ wind turbine performance. This document presents measurement and reporting procedures expected to provide accurate results that can be replicated by others. Meanwhile, a user of the standard should be aware of differences that arise from large variations in wind shear and turbulence~~, and from the chosen criteria for data selection~~. Therefore, a user should consider the influence of these differences and the data selection criteria in relation to the purpose of the test before contracting the power performance measurements.

A key element of power performance testing is the measurement of wind speed. This document prescribes the use of cup or sonic anemometers or remote sensing devices (RSD) in conjunction with anemometers to measure wind. Even though suitable ~~wind tunnel~~ procedures for calibration/validation and classification are adhered to, the ~~field flow conditions associated with the fluctuating wind vector, both in magnitude and direction, will~~ nature of the measurement principle of these devices may potentially cause them to perform differently. These instruments are robust and have been regarded as suitable for this kind of test with the limitation of some of them to certain classes of terrain.

Recognising that, as wind turbines become ever larger, a wind speed measured at a single height is increasingly unlikely to accurately represent the wind speed through the entire turbine rotor, this standard introduces an additional definition of wind speed. Whereas previously wind speed was defined as that measured at hub height only, this may now be supplemented with a so called Rotor Equivalent Wind Speed (REWS) defined by an arithmetic combination of simultaneous measurements of wind speed at a number of heights spanning the complete rotor diameter between lower tip and upper tip. The power curves defined by hub height wind speed and REWS are not the same and so the hub height wind speed power curve is always presented for comparison whenever a REWS power curve is measured. As a consequence of this difference in wind speed definition, the annual energy production (AEP) derived from the combination of a measured power curve with a wind speed distribution uses an identical definition of wind speed in both the power curve and the wind speed distribution.

~~Tools and~~ Procedures to classify cup anemometers and ultrasonic anemometers are given in Annexes I and J. ~~However there will always be a possibility that the result of the test can be influenced by the selection of the wind speed instrument.~~ Procedures to classify remote sensing devices are given in Annex L. Special care should be taken in the selection of the instruments chosen to measure the wind speed because it can influence the result of the test.

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WIND ~~TURBINES~~ ENERGY GENERATION SYSTEMS –

Part 12-1: Power performance measurements of electricity producing wind turbines

1 Scope

This part of IEC 61400 specifies a procedure for measuring the power performance characteristics of a single wind turbine and applies to the testing of wind turbines of all types and sizes connected to the electrical power network. In addition, this standard describes a procedure to be used to determine the power performance characteristics of small wind turbines (as defined in IEC 61400-2) when connected to either the electric power network or a battery bank. The procedure can be used for performance evaluation of specific wind turbines at specific locations, but equally the methodology can be used to make generic comparisons between different wind turbine models or different wind turbine settings when site-specific conditions and data filtering influences are taken into account.

The wind turbine power performance characteristics are determined by the measured power curve and the estimated annual energy production (AEP). The measured power curve, defined as the relationship between the wind speed and the wind turbine power output, is determined by collecting simultaneous measurements of meteorological variables (including wind speed), as well as wind turbine signals (including power output) at the test site for a period that is long enough to establish a statistically significant database over a range of wind speeds and under varying wind and atmospheric conditions. The AEP is calculated by applying the measured power curve to reference wind speed frequency distributions, assuming 100 % availability.

This document describes a measurement methodology that requires the measured power curve and derived energy production figures to be supplemented by an assessment of uncertainty sources and their combined effects.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

~~IEC 60044-1:1996, *Instrument transformers – Part 1: Current transformers*~~
~~Amendment 1 (2000)~~
~~Amendment 2 (2002)[1]~~

IEC 60688:~~1992~~ 2012, *Electrical measuring transducers for converting A.C. and D.C. electrical quantities to analogue or digital signals*
~~Amendment 1 (1997)~~
~~Amendment 2 (2001)[2]~~

~~IEC 61400-2:1996, *Wind turbine generator systems – Part 1: Safety of small wind turbines*~~

IEC 61400-12-2:2013, *Wind turbines – Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry*

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~~[1] There exists a consolidated edition 1.2 (2003) that includes edition 1 and its amendments 1 and 2.~~

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IEC 61869-1:2007, *Instrument transformers – Part 1: General requirements*

IEC 61869-2:2012, *Instrument transformers – Part 2: Additional requirements for current transformers*

IEC 61869-3:2011, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

ISO/IEC GUIDE 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

ISO/IEC 17043:2010, *Conformity assessment – General requirements for proficiency testing*

ISO 2533:1975, *Standard atmosphere*

ISO 3966:2008, *Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes*

~~ISO *Guide to the expression of uncertainty in measurement*, 1995, ISBN 92-67-10188-9~~

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accuracy
closeness of the agreement between the result of a measurement and a true value of the measurand

3.2
annual energy production
AEP
estimate of the total energy production of a wind turbine during a one-year period by applying the measured power curve to different reference wind speed frequency distributions at hub height, assuming 100 % availability

3.3
atmospheric stability
a measure of tendency of the wind to encourage or suppress vertical mixing

Note 1 to entry: Stable atmosphere is characterized by a high temperature gradient with altitude, high wind shear, possible wind veer and low turbulence relative to unstable conditions. Neutral and unstable atmosphere generally result in lower temperature gradients and low wind shear.

3.4
complex terrain
terrain surrounding the test site that features significant variations in topography and terrain obstacles (refer to 3.18) that may cause flow distortion

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3.5
cut-in wind speed
the lowest wind speed at which a wind turbine will begin to produce power

3.6
cut-out wind speed
the wind speed at which a wind turbine cuts out from the grid due to high wind speed

3.7
data set
a collection of data sampled over a continuous period

3.8
distance constant
indication of the response time of an anemometer, defined as the length of air that ~~must~~ shall pass the instrument for it to indicate 63 % of the final value for a step input in wind speed

3.9
extrapolated power curve
extension of the measured power curve by estimating power output from the maximum measured wind speed to cut-out wind speed

3.10
flow distortion
change in air flow caused by obstacles, topographical variations, or other wind turbines that results in ~~a deviation of the measured wind speed from the free stream wind speed and in a significant uncertainty~~ the wind speed at the measurement location to be different from the wind speed at the wind turbine location

3.11
hub height (of wind turbines)
height of the centre of the swept area of the wind turbine rotor above the ground at the tower

Note 1 to entry: For a vertical axis wind turbine the hub height is defined as the height of the ~~equator plane~~ centroid of the swept area of the rotor above the ground at the tower.

3.12
measured power curve
table and graph that represents the measured, corrected and normalized net power output of a wind turbine as a function of measured wind speed, measured under a well-defined measurement procedure

3.13
measurement period
period during which a statistically significant database has been collected for the power performance test

3.14
measurement sector
a sector of wind directions from which data are selected for the measured power curve

3.15
method of bins
data reduction procedure that groups test data for a certain parameter into ~~wind speed~~ intervals (bins)

Note 1 to entry: For each bin, the number of data sets or samples and their sum are recorded, and the average parameter value within each bin is calculated.

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3.16
net active electric power
measure of the wind turbine electric power output that is delivered to the electrical power network

3.17
normal maintenance
any intervention which is done according to a defined regular maintenance program, independent from the fact that a power performance test is being done, e.g. oil change, blade washing (if due anyway, i.e. independent from the power performance test) and any intervention which is out of the scope of the regular maintenance program (e.g. repair of a failed component) and which is not a machine configuration change

3.18
obstacles
~~things~~ obstructions that block the wind and create distortion of the flow, such as buildings and trees

3.19
pitch angle
angle between the chord line at a defined blade radial location (usually 100 % of the blade radius) and the rotor plane of rotation

3.20
power coefficient
ratio of the net electric power output of a wind turbine to the power available in the free stream wind over the rotor swept area

3.21
power performance
measure of the capability of a wind turbine to produce electric power and energy

3.22
rated power
quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

~~NOTE Maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating conditions.~~

3.23
rotor equivalent wind speed
wind speed corresponding to the kinetic energy flux through the swept rotor area when accounting for the variation of the wind speed with height, as represented in Equation (5)

3.24
special maintenance
any intervention which is out of the scope of the regular maintenance program and which is not a machine configuration change, i.e. any intervention which is done in order to improve the power performance during a test period, e.g. an unscheduled blade washing, any replacement of an essential component

3.25
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

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3.26
swept area
for a horizontal axis wind turbine, the projected area of the moving rotor upon a plane normal to axis of rotation

Note 1 to entry: For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft. For a vertical axis wind turbine, the projected area of the moving rotor upon a vertical plane.

3.27
test site
location of the wind turbine under test and its surroundings

3.28
uncertainty in measurement
parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand

3.29
wind measurement equipment
meteorological mast or remote sensing device

3.30
wind shear
change of wind speed with height across the wind turbine rotor

3.31
wind shear exponent
exponent α of the power law defining the variation of wind speed with height

Note 1 to entry: This parameter is used as a measure of the magnitude of wind shear for site calibration in Annex C and may be otherwise useful. The power law equation is

$$v_{zi} = v_h \left(\frac{z_i}{H} \right)^{\alpha} \quad (1)$$

where

v_h is the hub height wind speed;

H is the hub height (m);

v_{zi} is the wind speed at height z_i;

α is the wind shear exponent.

3.32
wind veer
change of wind direction with height across the wind turbine rotor

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4 Symbols and units

A	swept area of the wind turbine rotor	[m^2]
A_i	area of the i^{th} wind turbine rotor segment	[m^2]
A_w	Weibull scale factor	[m/s]
AEP	annual energy production	[Wh]
B	barometric pressure	[Pa]
B_{10min}	measured air pressure averaged over 10 min	[Pa]
Ch	pitot tube head coefficient	
$C_{P,i}$	power coefficient in bin i	
C_{QA}	generalized aerodynamic torque coefficient	
C_T	thrust coefficient	
c	sensitivity factor of a parameter (the partial differential)	
$c_{B,i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{d,i}$	sensitivity factor of data acquisition system in bin i	
c_{index}	sensitivity factor of index parameter	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{T,i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{V,i}$	sensitivity factor of wind speed in bin i	[Ws/m]
~~$c_{m,i}$~~ $c_{\rho,i}$	sensitivity factor of air density correction in bin i	[Wm^3/kg]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
Dn	rotor diameter of neighbouring and operating wind turbine	[m]
d	meteorological mast diameter	[m]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
f_i	the relative occurrence of wind speed in a wind speed interval	
$f_{r,MM}$	wind shear correction factor, measured using meteorological mast mounted instruments	
$f_{r,RSD}$	wind shear correction factor, measured using a remote sensing device	
H	hub height of wind turbine	[m]
h	height of obstacle ~~minus zero displacement~~	[m]
I	inertia of cup anemometer rotor	[kgm^2]
k	class number	
k	Weibull shape factor	
k_b	blockage correction factor	
k_c	wind tunnel calibration factor	
k_f	wind tunnel correction factor to other tunnels (only used in uncertainty estimate)	
k_ρ	humidity correction to density	
$K_{B,t}$	barometer sensitivity	[N/m^2V]
$K_{B,s}$	barometer gain	
$K_{B,d}$	barometer sampling conversion	
$K_{T,t}$	temperature transducer sensitivity	[K/A]
$K_{T,s}$	temperature transducer gain	[A/V]
$K_{T,d}$	temperature transducer sampling conversion	
$K_{p,t}$	pressure transducer sensitivity	
$K_{p,s}$	pressure transducer gain	

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$K_{p,d}$	pressure transducer sampling conversion	
~~L~~	~~leg distance of three legged mast~~	~~[m]~~
L_m	distance between adjacent legs of lattice meteorological mast	[m]
L	distance between the wind turbine and the ~~meteorological mast~~ wind measurement equipment	[m]
L_e	distance between the wind turbine or the ~~meteorological mast~~ wind measurement equipment and an obstacle	[m]
L_n	distance between the wind turbine or the ~~meteorological mast~~ wind measurement equipment and a neighbouring and operating wind turbine	[m]
l_h	height of obstacle	[m]
l_w	width of obstacle	[m]
M	number of uncertainty components in each bin	
M_A	number of category A uncertainty components	
M_B	number of category B uncertainty components	
N	number of bins	
N_h	number of hours in one year ≈ 8 760	[h]
N_i	number of 10 min data sets in wind speed bin i	
N_j	number of 10 min data sets in wind direction bin j	
n	number of samples within sampling interval	
~~n~~	~~velocity profile exponent (n=0,14)~~	
n_h	number of available measurement heights	
P_o	porosity of obstacle (0: solid, 1: no obstacle)	
P_i	normalized and averaged power output in bin i	[W]
P_n	normalized power output	[W]
$P_{n,i,j}$	normalized power output of data set j in bin i	[W]
P_{10min}	measured power averaged over 10 min	[W]
P_w	vapour pressure	[Pa]
Q_A	aerodynamic torque	[Nm]
Q_f	friction torque	[Nm]
R	~~distance to mast centre~~ rotor radius	[m]
R_0	gas constant of dry air (287,05)	[J/kgK]
R_d	distance to meteorological mast centre	[m]
R_w	gas constant of water vapour (461,5)	[J/kgK]
RSD	remote sensing device	
r	correlation coefficient	
s	category A standard uncertainty component	
s_A	category A standard uncertainty of tunnel wind speed time series	
$s_{k,i}$	category A standard uncertainty of component k in bin i	
s_i	combined category A uncertainties in bin i	
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
s_{sc}	category A standard uncertainty of site calibration	[m/s]
$s_{w,i}$	category A standard uncertainty of climatic variations ~~in bin i~~	[Wh]
$s_{\alpha,j}$	category A standard uncertainty of wind speed ratios in bin j	
~~t~~ S	meteorological mast solidity	
T	absolute temperature	[K]

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TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	[K]
t	time	[s]
U	wind speed	[m/s]
U_d	centreline wind speed deficit	[m/s]
U_{eq}	equivalent horizontal wind speed	[m/s]
~~U_h~~	~~free wind speed at height *h* of obstacle~~	~~[m/s]~~
U_i	wind speed in bin i	[m/s]
U_t	threshold wind speed	[m/s]
$\vec{U}$ U	wind speed vector	
~~u~~	~~longitudinal wind speed component~~	~~[m/s]~~
u	category B standard uncertainty component	
u_{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	[Pa]
$u_{c,i}$	combined standard uncertainty of the power in bin i	[W]
u_i	combined category B uncertainties in bin i	
u_{index}	category B standard uncertainty of index parameter	
$u_{k,i}$	category B standard uncertainty of component k in bin i	
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[m/s]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
$u_{\alpha,i,j}$	combined standard uncertainty of site calibration in wind speed bin i and wind direction bin j	[m/s]
~~$u_{m,i}$~~ $u_{\rho,i}$	category B standard uncertainty of air density correction in bin i	[kg/m^3]
V	wind speed	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_i	normalized and averaged wind speed in bin i	[m/s]
V_n	normalized wind speed	[m/s]
$V_{n,i,j}$	normalized wind speed of data set j in bin i	[m/s]
V_{10min}	measured wind speed averaged over 10 min	[m/s]
v	transversal wind speed component	[m/s]
$\overline{v}$	mean flow air speed	[m/s]
v_{eq}	measured equivalent wind speed	[m/s]
$v_{eq,final}$	final rotor equivalent wind speed	[m/s]
$v_{eq,MM}$	equivalent wind speed based on meteorological mast measurements	[m/s]
$v_{eq,RSD}$	equivalent wind speed based on remote sensing device measurements	[m/s]
v_h	hub height wind speed	[m/s]
$v_{h,MM}$	wind speed measured at hub height with meteorological mast	[m/s]
v_{hn}	hub height wind speed normalised for a specific wind shear profile	[m/s]
$v_{h,RSD}$	wind speed measured at hub height by the remote sensing device	[m/s]
v_i	wind speed measured at height i	[m/s]
v_{zi}	wind speed at height z_i	[m/s]
WME	wind measurement equipment	

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w	vertical wind speed component	[m/s]
w_i	weighting function to define deviation envelope	
X_k	parameter averaged over pre-processing time period	
X_{10min}	parameter averaged over 10 min	
x	distance downstream from obstacle to ~~met mast~~ wind measurement equipment or wind turbine	[m]
z	height above ground	[m]
z_i	height of the i^{th} wind turbine rotor segment	[m]
~~z_0~~	~~roughness height~~	~~[m]~~
~~α~~	~~disturbed sector~~	~~[°]~~
~~α~~	~~angle of attack~~	~~[°]~~
~~α_j~~	~~ratio of wind speeds in wind direction bin j (wind turbine position to meteorological mast position)~~	
~~ΔU_z~~	~~influence of an obstacle in wind speed difference~~	~~[m/s]~~
α	wind shear exponent from power law	[°]
$\varepsilon_{max,i}$	maximum deviation for any wind speed bin i in the wind speed range	[m/s]
θ	disturbed sector	[°]
κ	von Karman constant 0,4	
λ	speed ratio	
~~ρ~~	~~correlation coefficient~~	
ρ	air density	[kg/m^3]
ρ_0	reference air density	[kg/m^3]
ρ_{10min}	derived air density averaged over 10 min	[kg/m^3]
$\sigma_{P,i}$	standard deviation of the normalized power data in bin i	[W]
σ_{10min}	standard deviation of parameter averaged over 10 min	
$\sigma_u/\sigma_v/\sigma_w$	standard deviations of longitudinal/transversal/vertical wind speeds	
~~ϕ~~ Φ	relative humidity (range 0 % to 100 %)	
ω	angular speed	[s^{-1}]

5 Power performance method overview

The wind shear and wind veer may vary significantly over the rotor height of large wind turbines for atmospheric stability conditions and it is also dependent on topography at the site. The occurrence of extreme atmospheric stability conditions is a site specific issue, and if occurring during a power performance test, the power curve may vary significantly.

The power performance measurement method used in this standard is based on a definition of the power curve that expresses power produced versus the wind speed that represents effectively the kinetic energy flux in the wind flowing across the swept area of the rotor.

The kinetic energy flux (referring to a certain point in time or period of time, typically 10 min, assuming that the wind speed does not change within this time[2]) across the vertical capture area is in general terms expressed as:

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2 If the wind speed changes (i.e. if the turbulence intensity is >0) during a certain time period, then the kinetic power (averaged over this time period) is higher than in case of a constant wind speed, whereas a wind turbine

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$$P_{\text{kin}} = \int_A \frac{1}{2}\rho V^3 \, \mathrm{d}A \tag{2}$$

Here the wind speed V, measured at a point in space over the rotor area, is the horizontal wind speed[3]. The horizontal wind speed is defined as the average magnitude of the horizontal component of the instantaneous wind velocity vector, including only the longitudinal and lateral (but not the vertical) components. When we consider a horizontal axis wind turbine the wind veer is also taken into account and the kinetic energy in the wind is corrected according to the wind direction at hub height:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho \left(V \cos\left(\varphi - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A \tag{3}$$

Here φ_{hub} is the wind direction at hub height. The wind veer may vary significantly over the rotor height of large wind turbines for extreme atmospheric stability conditions and it is also dependent on topography at the site.

In this standard we do not consider wind shear and wind veer in the horizontal plane. Thus the energy equivalent wind speed that corresponds to the kinetic energy in the wind as derived from the expression of kinetic energy in Equation (3) in general is described as:

$$V_{\text{eq}} = \left(\frac{1}{A} \int_i \left(V_i \cos\left(\varphi_i - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A_i \right)^{1/3} \tag{4}$$

Here the index i refers to the height within the rotor area[4].

Although horizontal wind speed is considered to be the influential wind speed parameter, on sites with significant non-horizontal flow (up or down-flow), there is additional uncertainty associated with both the measurement of the horizontal wind speed and the response of the wind turbine.

At sites with low and homogeneous wind shear and wind veer over the rotor (and for turbines with small rotor diameters in possibly more complex wind flow conditions), the wind speed measured at hub height can be a good representation of the kinetic energy to be captured by the rotor. Hub height wind speed is the wind speed upon which power curves have historically been defined in all previous editions of this standard. For that reason, the wind speed measured at hub height is the default definition of wind speed and shall always be measured and reported, even when more comprehensive measurements of wind speed are available over the rotor height.

At sites and seasons where extreme atmospheric stability conditions are expected to be frequent, it is recommended always to measure wind shear.

If wind shear and wind veer are not measured over the full height of the rotor, there is added uncertainty in the equivalent wind speed. This uncertainty decreases as more wind speed and

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has only a limited possibility to transform this additional kinetic power into additional electric power. This issue is not taken into further consideration here. As a simplification, the Equations (2), (3) , (4) are considered valid here, even in case of a turbulence intensity >0. The impact of wind speed changes on the time averaged kinetic power and the associated impact on the wind turbine power curve is treated by the turbulence normalisation procedure as included in Annex M.

[3] Wind turbine power seems to correlate better with the horizontal wind speed definition than with a vector wind speed definition for a one point hub height wind speed measurement.

[4] However when wind speed is mentioned in the document, it is by default referring to the hub height wind speed definition unless specifically stated to be this energy equivalent wind speed definition.

wind direction measurement heights are used. If measurements are limited to only hub height and there is no measurement of wind shear over the most significant parts of the rotor then this implies an uncertainty in determination of the equivalent wind speed.

For small wind turbines[5], where the influence of the wind shear and wind veer are insignificant, the wind speed shall be represented by a hub height wind speed measurement alone without adding uncertainty due to lack of wind shear and wind veer measurements.

For vertical axis wind turbines, where the influence of the wind veer is not present, the wind veer shall be neglected.

As the wind conditions at the position of the test turbine and at the position of the wind measurement may differ significantly if the test turbine or the wind measurement is located in wakes of any wind turbines, such situations shall be excluded from the test.

The air density ρ also varies over the height of a large wind turbine rotor. However, this variation is small. For practical implementation of the power performance measurement method, it is sufficient to define and determine the air density only at hub height. The power curve is normalized to the average air density at the measurement site over the measurement period or to a pre-defined reference air density.

Power curves are also influenced by the turbulence at the test site, and turbulence may vary over the rotor. In this standard, only the site turbulence at hub height is considered. High turbulence increases the radius of curvature of the power curve at cut-in and at the start of power regulation at nominal power while low turbulence will make these corners of the power curve sharper. Site turbulence shall be measured and presented as a supplement to the power curve. If needed, a normalisation to a specified turbulence can be done using the method of Annex M.

In summary, the power curve according to this standard is a climate specific power curve, where:

a) the wind speed at a point in space is defined as the horizontal wind speed;

b) the wind speed of a power curve is defined as the hub height wind speed. This definition may be supplemented with the equivalent wind speed, as defined in Equation (4), taking account of vertical wind shear and wind veer[6];

c) air density is measured at hub height and the power curve is normalized to a site average air density during the measurement period or to a pre-defined reference air density;

d) turbulence is measured at hub height and the power curve is presented without a turbulence normalization;

e) the power curve can be normalized to a broader range of climatic conditions (e.g. specific air density, turbulence intensity, vertical shear and veer)[7].

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5 Small turbines, refer to IEC 61400-2.

6 For vertical axis wind turbines, the wind veer is omitted in Equation (3) (setting $\varphi_i = \varphi_{\text{hub}}$).

7 The power curve normalization is only valid for limited ranges of climatic conditions from the actual site conditions.

In this standard, all necessary procedures for measurements, calibration, classification, data correction, data normalization and determination of uncertainties are provided. However, if not all parameters are sufficiently measured, then uncertainty shall be applied due to the lack of measurement. This applies, for example, to the measurement of a power curve of a large wind turbine with only a hub height wind speed sensor. In this case, an uncertainty shall be applied for the variability of the wind shear and of the wind veer.

The best results from the use of the standard are achieved by measurement of all required parameters and use of all relevant procedures. However, if this is not possible, there are options both for the measurement setup and for the use of the procedures. These options are described in Table 1. The options refer to the use of wind measurement equipment, the applied normalizations, and additional uncertainties connected to the lack of measurements.

Table 1 – Overview of wind measurement configurations for power curve measurements that meet the requirements of this standard

Wind measurement configuration	1. Meteorology mast to hub height and remote sensing to all heights	2. Meteorology mast below hub height and remote sensing to all heights	3. Meteorology mast above hub height	4, Meteorology mast to hub height
Typical application	Large wind turbines[8] in flat terrain (see Annex B)	Large wind turbines in flat terrain (see Annex B)	Large and small wind turbines in all types of terrain	Large and small wind turbines in all types of terrain
Wind measurement sensors	7.2.3, 7.2.5	7.2.3, 7.2.5	7.2.3, 7.2.4	7.2.3
Normalisation procedures for climate specific power curve determination	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density; 9.1.5
Additional uncertainty due to lack of wind shear measurement	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	Additional gross uncertainty for large wind turbines due to lack of vertical wind shear; E.11.2.2
Optional normalization procedures[9]	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4. Meteorological mast flow distortion; 9.1.2, Site calibration; Annex C.	Turbulence and upflow angle; 9.1.6. Site calibration; Annex C.

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8 Refer to IEC 61400 -2 for definition of large and small wind turbines.

9 Upflow influences the power curve and can be measured with 3D sonic anemometers or upflow vanes. If an upflow angle normalization is applied then the method should be documented (uncertainty on upflow is considered in Annex E). However, no specific procedure is described in this standard on how to normalise for upflow angle.

6 Preparation for performance test

6.1 General

The specific test conditions related to the power performance measurement of the wind turbine shall be well-defined and documented in the test report, as detailed in Clause 10.

6.2 Wind turbine and electrical connection

As detailed in Clause 10, the wind turbine and electrical connection shall be described and documented to identify uniquely the specific machine configuration that is tested.

6.3 Test site

6.3.1 General

At the test site ~~a meteorological mast~~ wind measurement equipment shall be set up in the neighbourhood of the wind turbine to determine the wind speed that drives the wind turbine.

Wind shear and atmospheric stability characteristics of the site may have significant influences on the wind measurement and the ~~measured~~ actual power performance of the wind turbine. Often there is a diurnal cycle of atmospheric stability, with stable atmosphere forming at night and neutral or unstable atmosphere during the day as the sun heats the ground, increasing turbulence and mixing in the boundary layer. Wind shear, wind veer, and turbulence are all a function of atmospheric stability and impact the relationship between the hub height wind speed to the rotor equivalent wind speed and unusual profiles may impact a wind turbine's energy conversion. In addition, flow distortion effects may cause the wind speed at the ~~meteorological mast~~ position of the wind speed measurement and wind turbine to be different, though correlated.

The test site shall be assessed for sources of wind flow distortion in order to:

a) choose the position of the ~~meteorological mast~~ wind measurement equipment;

b) define a suitable measurement sector;

~~c) estimate appropriate flow correction factors;~~

c) determine if a site calibration is required then determine the appropriate flow corrections by measurement according to Annex C;

d) evaluate the uncertainty due to wind flow distortion.

The following factors shall be considered, in particular:

1) topographical variations and roughness;

2) other wind turbines;

3) obstacles (buildings, trees, etc.).

The test site shall be documented as detailed in Clause 10.

6.3.2 Location of the ~~meteorological mast~~ wind measurement equipment

Care shall be taken in locating the ~~meteorological mast~~ wind measurement equipment. The wind measurement equipment shall not be located too close to the wind turbine, since the wind speed will be influenced ~~/changed/affected~~ in front of the wind turbine. Also, it shall not be located too far from the wind turbine, since the correlation between wind speed and electric power output will be reduced. The ~~meteorological mast~~ wind speed measurement instrumentation shall be positioned at a distance from the wind turbine of between 2 and 4 times the rotor diameter D of the wind turbine. A distance of 2,5 times the rotor diameter D is recommended. In the case of a vertical axis wind turbine, ~~D is equivalently defined as $2\sqrt{A/\pi}$, where A is the swept area of the rotor, and distance is~~

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~~defined as L+0,5D, where L is the distance between the centre of the turbine tower and the mast of an equivalent horizontal axis wind turbine~~ refer to Clause H.4.

Prior to carrying out the power performance ~~evaluation~~ test and in helping to select the location for the ~~meteorological mast~~ wind measurement equipment, account should be taken of the need to exclude measurements from all sectors in which either the ~~mast~~ wind measurement equipment or the wind turbine will be subject to flow disturbance.

In most cases, the best location for the ~~meteorological mast~~ wind measurement equipment will be upwind of the wind turbine in the direction from which most valid wind is expected to come during the test. In other cases, however, it may be more appropriate to place the ~~mast~~ wind measurement equipment alongside the wind turbine as the wind conditions will be more similar, for example for a wind turbine sited on a ridge.

6.3.3 Measurement sector

The measurement sector(s) shall exclude directions having significant obstacles and other wind turbines, as seen from both the wind turbine under test and the ~~meteorological mast~~ wind measurement equipment.

For all neighbouring wind turbines and significant obstacles, the directions to be excluded due to wake effects shall be determined using the procedure in Annex A. The disturbed sectors to be excluded due to the ~~meteorological mast~~ wind measuring equipment being in the wake of the wind turbine under test are shown in Figure 1 for distances of 2D, 2,5D and 4D. Reasons to reduce the measurement sector(s) might be special topographic conditions or unexpected measurement data ~~achieved~~ from directions with complicated structures. All reasons for reducing the measurement sector shall be clearly documented.

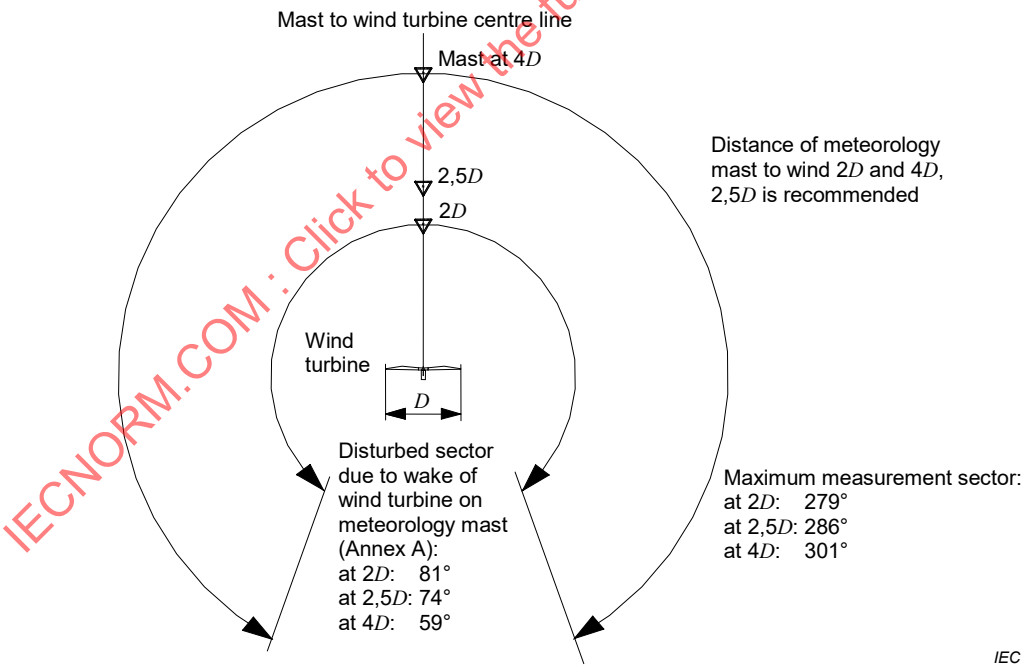

Figure 1 – Requirements as to distance of the ~~meteorological mast~~ wind measurement equipment and maximum allowed measurement sectors

6.3.4 Correction factors and uncertainty due to flow distortion originating from topography

The test site shall be assessed for sources of wind flow distortion due to topographical variations. The assessment in Annex B shall identify whether the power curve can be

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measured without a ~~required~~ site calibration. If the criteria of Annex B are met, the wind flow regime of the site does not need a site calibration. However, in assuming that no flow correction ~~factors are~~ is necessary, the applied uncertainty due to flow distortion of the test site shall be a minimum of 2 % of the measured wind speed if the ~~meteorological mast~~ wind measurement equipment is positioned at a distance between 2 and 3 times the rotor diameter of the wind turbine and 3 % or greater if the distance is between 3 and 4 times the rotor diameter[10], unless objective evidence can be provided quantifying a different uncertainty.

If the criteria of Annex B are not met, or a smaller uncertainty due to flow distortion of the test site is desired, then an experimental site calibration shall be undertaken in accordance with Annex C. ~~If an experimental test site calibration is undertaken Annex C shall be used.~~ The measured flow correction factors for each sector shall be used.

7 Test equipment

7.1 Electric power

The net electric power of the wind turbine shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase.

The class of the current transformers shall meet the requirements of IEC ~~60044-1~~ 61869-2 and the class of the voltage transformers, if used, shall meet the requirements of IEC ~~60186~~ 61869-3. They shall be of class 0,5 or better.

The accuracy of the power measurement device, if it is a power transducer, shall meet the requirements of IEC 60688 and shall be class 0,5 or better. If the power measurement device is not a power transducer then the accuracy should be equivalent to class 0,5 power transducers. The operating range of the power measurement device shall be set to measure all positive and negative instantaneous power peaks generated by the wind turbine. As a guide for MW-size active control regulated wind turbines, the full-scale range of the power measurement device should be set to ~~–50 % to +200 %~~ –25% to +125% of the wind turbine rated power[11]. All data shall be periodically reviewed during the test to ensure that the range limits of the power measurement device have not been exceeded. The power transducer shall be calibrated to traceable standards. The power measurement device shall be mounted between the wind turbine and the electrical connection to ensure that only the net active electric power (i.e. reduced by self-consumption) is measured. It shall be stated whether the measurements are made on the wind turbine side or the network side of the transformer.

7.2 Wind speed

7.2.1 General

~~Wind speed measurements shall be made with a cup anemometer that meets the requirements in Annex I. For power performance measurements an anemometer with a class better than 1,7A shall be used. Additionally, in terrain that does not meet the requirements of Annex B for not requiring a site calibration, it is recommended that a class better than class 2,5B or 1,7S be used. The wind speed to be measured is defined as the average magnitude of the horizontal component of the instantaneous wind velocity vector[12], including only the~~

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[10] These uncertainties were derived from a WAsP (Wind Atlas Analysis and Application Program, DTU Wind Energy) analysis of a Gaussian hill meeting the terrain requirements of Annex B.

[11] In other cases, a higher range may be necessary. This has to be checked individually.

[12] ~~It is believed that, by using instruments that are able to measure the wind speed according to this definition consistent power curves will be obtained in most field conditions. Consistent in this context means that the power curves measured in inclined flow are essentially similar to the power curves measured under non-inclined flow conditions. Special care should be taken to achieve a proper mounting (align the instrument) and special care should also be taken to inspect the anemometer for distorted cups. Improper mounting or distorted cups may introduce severely biased results.~~

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~~longitudinal and lateral, but not the vertical, turbulence components. Consequently, the angular response of the cup anemometer should be cosine shaped (see Annex J). All reported wind speeds, and all uncertainties connected to operational characteristics shall be related to this wind speed definition.~~

~~The cup anemometer shall be calibrated before and recalibrated after the measurement campaign. The difference between the regression lines of calibration and recalibration shall be within ±0,1 m/s in the range 6m/s to 12 m/s. Only the calibration before the measurement campaign shall be used for the performance test. Calibration of the cup anemometer shall be made according to the procedure of Annex F. During calibration the cup anemometer shall be mounted on a vertical tube configuration similar to the one being used during the power performance test.~~

~~As an inferior alternative to the recalibration, it shall be documented that the cup anemometer maintains its calibration over the duration of the measurement period. The procedure in Annex K should be used.~~

~~The cup anemometer shall be mounted at hub height of ±2,5 %, relative to the ground at the meteorological mast. The requirements given in Annex G with respect to mounting shall be used.~~

~~The uncertainty in wind speed measurement derives from three sources (see Table D.1): the calibration of the instrument, the operational characteristics of the anemometer and flow distortion due to instrument mounting effects. Uncertainty in calibration shall be derived from Annex F. Uncertainty due to operational characteristics shall be derived from Annex I on classification of anemometry. Uncertainty due to mounting effects shall be derived from Annex G.~~

The wind speed measured at Hub Height only (HH) is the default wind speed definition and shall always be used. This may be considered the limiting case of the rotor equivalent wind speed where there is only one measurement height and additional uncertainty due to the lack of a wind shear or wind veer profile measurement (see E.11.2.2). It is recommended that the hub height wind speed measurement is supplemented with wind shear measurements in the lower half of the rotor to reduce the wind speed uncertainty. To further reduce the wind speed uncertainty, the Rotor Equivalent Wind Speed (REWS), see 9.1.3.2 and Annex Q, should be used as the wind speed input variable to the power curve.

The wind speed measurement configurations are summarized in Table 2 which takes account of the current limitations of each measurement technology with respect to the terrain complexity classification. Remote sensing devices that assume horizontal flow uniformity through the scanned volume limit the application of these technologies to non-complex terrain conditions for power performance testing. Thus only configurations based on Table 2 shall be applied.

Table 2 – Wind speed measurement configurations (X indicates allowable configuration)

Wind speed measurement	HH	HH	REWS	REWS
Terrain type	Non-complex	Complex	Non-complex	Complex
Hub height meteorological mast	X	X		
Hub height meteorological mast + RSD	X	X	X	
RSD + non-hub height meteorological mast	X		X	
Meteorological mast covering heights above HH + 2/3 R	X	X	X	X

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The different possible sensor configurations comprise meteorological mast top-mounted anemometers, meteorological mast side-mounted anemometers and remote sensing devices and these provide measurements of hub height wind speed, rotor equivalent wind speed and wind shear profile. Subclauses 7.2.3 to 7.2.5 describe the general, common requirements of top-mounted, side-mounted and remote sensing sensor configurations whilst 7.2.6 to 7.2.8 describe the application specific details for the measurements using these sensor configurations.

7.2.2 General requirements for meteorological mast mounted anemometers

The following requirements apply to all cup and sonic anemometer applications described in Subclauses 7.2.3 to 7.2.8.

The sensor shall meet the requirements in Annex I for cup and sonic anemometers. For power performance measurements an anemometer with a class better than 1,7A or 1,7C shall be used. Additionally, in terrain that requires a site calibration, it is recommended that a class better than class 2,5B, 2,5D or 1,7S shall be used, see Annex I and Annex J.

The anemometer shall be calibrated before and, if required, calibrated again after the measurement campaign (post-calibration). It is mandatory to check and document that the anemometer maintains the validity of its calibration throughout the measurement period. This can be achieved by either comparing the initial calibration results with the outcome of the post-calibration or as an alternative, the in-situ anemometer comparison following Annex K is permissible.

Where a post-calibration is carried out, the difference between the regression lines of calibration and post-calibration shall be within ± 0,1 m/s in the range 4 m/s to 12 m/s. Only the calibration before the measurement campaign shall be used for the performance test. Calibration of the anemometer shall be made according to the procedure of Annex F. If the maximum difference between the regression lines of calibration and post-calibration is outside of ± 0,1 m/s in the range of 4 m/s to 12 m/s, then the standard uncertainty of the anemometer calibration $u_{VS,precal,i}$ shall be increased (at least to this max. difference, but not to more than ± 0,2 m/s). If the difference is above ± 0,2 m/s, then the in-situ anemometer comparison of Annex K is to be used to identify the point in time when the deviation in the data occurred and the subsequent faulty data shall be rejected. If the in-situ test cannot determine the point at which the deviation began then the post-calibration difference is added as an uncertainty.

As an alternative, the in-situ calibration procedure of Annex K shall be used to check the anemometer integrity throughout the measurement period. In this procedure a control anemometer is used to monitor the primary anemometer. Where a cup anemometer is used as the primary anemometer, then either a cup anemometer or a sonic anemometer may be used as the control anemometer. Where a sonic anemometer is used as the primary anemometer, then the control anemometer shall be a cup anemometer. In the case where a REWS derived power curve is obtained from taller than hub height meteorological mast measurements, there shall be a side mounted primary anemometer at hub height on the mast with an associated control anemometer satisfying the mounting requirements from Annex G.

The uncertainty in wind speed measurement derives from several sources of uncertainty as specified in Table D.1 Uncertainty in calibration shall be derived from Annex F. Uncertainty due to operational characteristics shall be derived from Annex I on classification of anemometry. Uncertainty due to mounting effects shall be derived from Annex G.

7.2.3 Top-mounted anemometers

Where wind speed measurements are made with a top-mounted anemometer the requirements given in Annex G with respect to mounting shall be adhered to. The installed

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height of the sensor above ground level[13] shall be verified by measurement and the measurement method and its standard uncertainty documented[14]. The standard uncertainty of the measurement of the height of the wind speed sensor above the estimated ground level shall be less than or equal to 0,2 m. The control anemometer shall be mounted according to the requirements of Annex G.

7.2.4 Side-mounted anemometers

The mounting shall follow the requirement for side mounted anemometers according to Annex G. The installed height of the side-mounted anemometers above ground level (see footnote 11) shall be verified by measurement and the measurement method and its uncertainty documented. The height measurement standard uncertainty shall be less than or equal to 0,2 m.

Correction of side-mounted anemometers for meteorological mast flow distortion is permitted and further described in 9.1.2 and Annex S. The technical basis for the correction and the effect of the correction shall be documented. The booms shall have identical orientations to ensure similarity of flow distortion between different heights. The meteorological mast and boom design should have similar flow distortion effect at the sensor with a maximum allowed difference in wind speed distortion of 1 % between all different heights. The meteorological mast cross-sectional dimensions should be consistent at each elevation, thus in the case of free-standing meteorological masts where the meteorological mast cross-sectional area is larger at the lower elevations, special care should be taken following the recommendations in Annex G. An alternative option is to mount a second anemometer at each measurement height on a separate boom and to limit the measurement sector such that the wind speed measurements do not deviate by more than 1 %.

7.2.5 Remote sensing device (RSD)

Remote sensing devices that assume horizontal flow uniformity through the scanned volume limit the application of these technologies to non-complex terrain conditions for power performance testing as defined by Annex B. The remote sensing device shall be verified before the measurement campaign or in-situ according to Clause L.3. The remote sensing device can be used to measure hub height wind speed, wind shear profile, wind veer and/or the rotor equivalent wind speed based on measurements at more than one height (see 7.2.8). In any case, the remote sensing device shall be simultaneously compared with a top-mounted anemometer on a meteorological mast at a height not less than the minimum of the wind turbine rotor lower tip-height or 40 m as defined in Clause L.1. Requirements on the top-mounted anemometer are identical to those described in 7.2.3.

The uncertainty of the RSD wind speed measurements shall be derived according to Annex L.

7.2.6 Rotor equivalent wind speed measurement

If the wind speed is measured at three or more heights across the wind turbine rotor as defined in 7.2.8, then the rotor equivalent wind speed can be calculated according to 9.1.3. Note that more than three measurement heights are recommended. There are three options for measuring the rotor equivalent wind speed as described below.

a) Where a hub height top-mounted anemometer satisfying the requirements of 7.2.3 is used together with an RSD satisfying the requirements of 7.2.5 and the terrain meets the

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[13] For the purpose of defining ground level, an estimate of the mean elevation over a radius of 2 m around the mast base or 5 m radius around the turbine base can be made. The sensor height measurement uncertainty should exclude the uncertainty of the ground level estimate. For offshore conditions, ground level should be considered as mean sea level.

[14] The measurement can be performed by means of measurement device with a traceable calibration for example a theodolite able to derive heights from an angle measurement in the vertical plane.

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requirements of Annex B then the measurements from the hub height anemometer and RSD are combined to determine the rotor equivalent wind speed according to 9.1.3.

b) Where an anemometer not at hub height but otherwise satisfying the requirements for top-mounted anemometers of 7.2.3 is used with an RSD satisfying the requirements of 7.2.5 and the terrain meets the requirements of Annex B then the RSD measurements are used directly to determine the rotor equivalent wind speed according to 9.1.3.

c) Where a taller than hub height meteorological mast is used with side-mounted measurements distributed across the rotor height, including an anemometer at hub height, then the side-mounted anemometer wind speed measurements may be used directly to measure the rotor equivalent wind speed according to 9.1.3.

7.2.7 Hub height wind speed measurement

There are three options for measuring hub height wind speed as described below.

a) Where a hub height meteorological mast is used, the hub height wind speed measurements shall meet the requirements described in 7.2.3.

b) If the terrain meets the requirements of Annex B, then the hub height wind speed can be measured with an RSD meeting the requirements of 7.2.5 and noting specifically the requirement to compare the RSD against a simultaneous top-mounted anemometer.

c) A meteorological mast that is taller than the hub height may be used to better capture the wind speeds across the rotor area. In this case, the hub height wind speed shall be measured with a side-mounted sensor on a boom following the requirements described in 7.2.4.

For the hub height definition of wind speed, the lack of knowledge of the vertical wind shear or wind veer across the wind turbine rotor shall be accounted for by adding an uncertainty term according to Annex E based on the estimated or measured wind shear or wind veer. Where only a hub height wind speed measurement is available, an estimated wind shear or wind veer based on site characteristics (e.g. roughness) or prior measurement or modelling at the site (e.g. during a resource assessment campaign) shall be used as input to the uncertainty analysis. Where the hub height wind speed is determined using an RSD or taller than hub height meteorological mast with side-mounted wind speed measurements across the rotor or where below hub height side-mounted instruments are present and satisfying the minimum requirements described in 7.2.8, then wind shear or wind veer derived from the RSD or side-mounted instruments shall be used as input to the uncertainty assessment.

7.2.8 Wind shear measurements

Where wind speed measurements are available over a range of heights wind shear shall be measured and used for the rotor equivalent wind speed or for wind shear exponent determination.

Wind shear measurements shall either be performed using side-mounted anemometers as described in 7.2.4 or by a single remote sensing instrument as described in 7.2.5. Further specifications on wind shear measurement using remote sensing instruments or meteorological mast measurements are given in Annex L and Annex G respectively.

The rotor equivalent wind speed measurement shall include wind speed measurements above hub height. To apply a measurement-based wind shear correction, there shall be at least three wind speed measurements distributed over the rotor swept area. However, to minimise wind speed uncertainty, it is recommended to have as many measurement heights as possible. Measurement heights should be distributed symmetrically around hub height and evenly over the vertical range of the rotor swept area.

The measurement heights shall include the following heights as a minimum:

a) hub height ±1,0 %;

b) between $H - R$ and $H - 2/3R$;

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c) between $H + 2/3R$ and $H + R$,

where H is the hub height of the wind turbine and R the radius of the rotor swept area, see Figure 2.

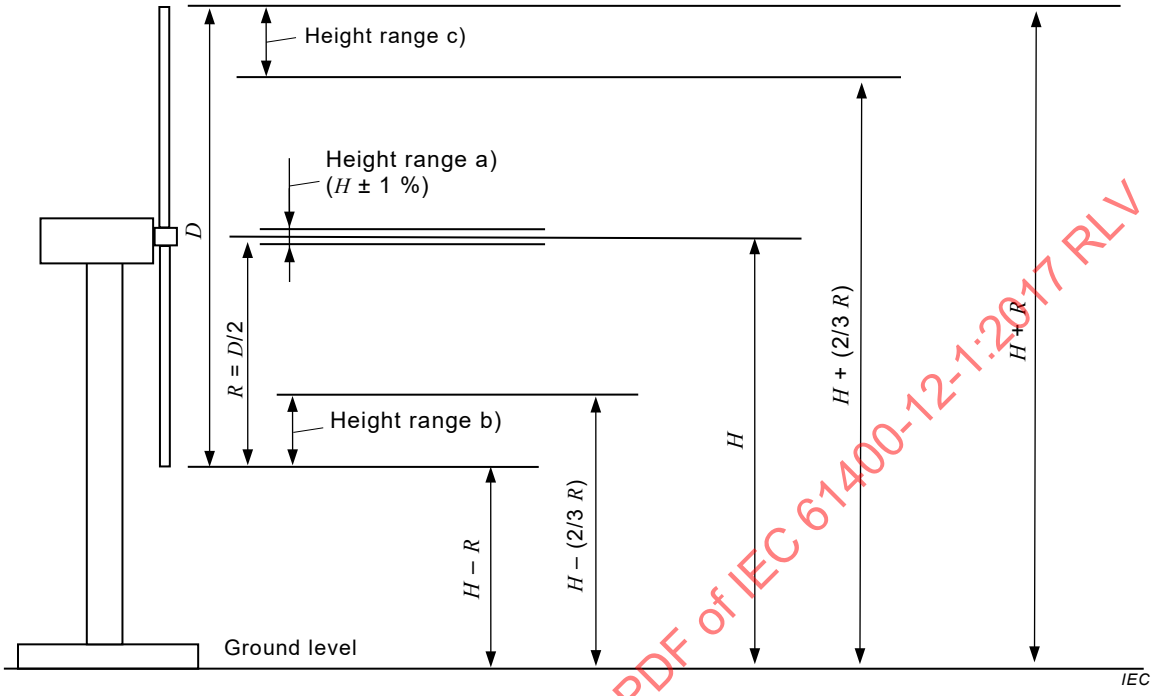

Figure 2 – Wind shear measurement heights appropriate to measurement of rotor equivalent wind speed

If the meteorological mast is hub height or a little above, then no wind speed measurements above hub height may be available for wind shear measurement. In that case, the measurements used to derive wind shear shall include at least the following heights:

a) a side-mounted anemometer as close to hub height satisfying the requirements of Annex G for separation from the top-mounted anemometer,

b) between $H - R$ and $H - 2/3R$ and satisfying the requirements of Annex G for side mounted anemometers.

where H is the hub height of the wind turbine and R the radius of the rotor swept area, see Figure 3.

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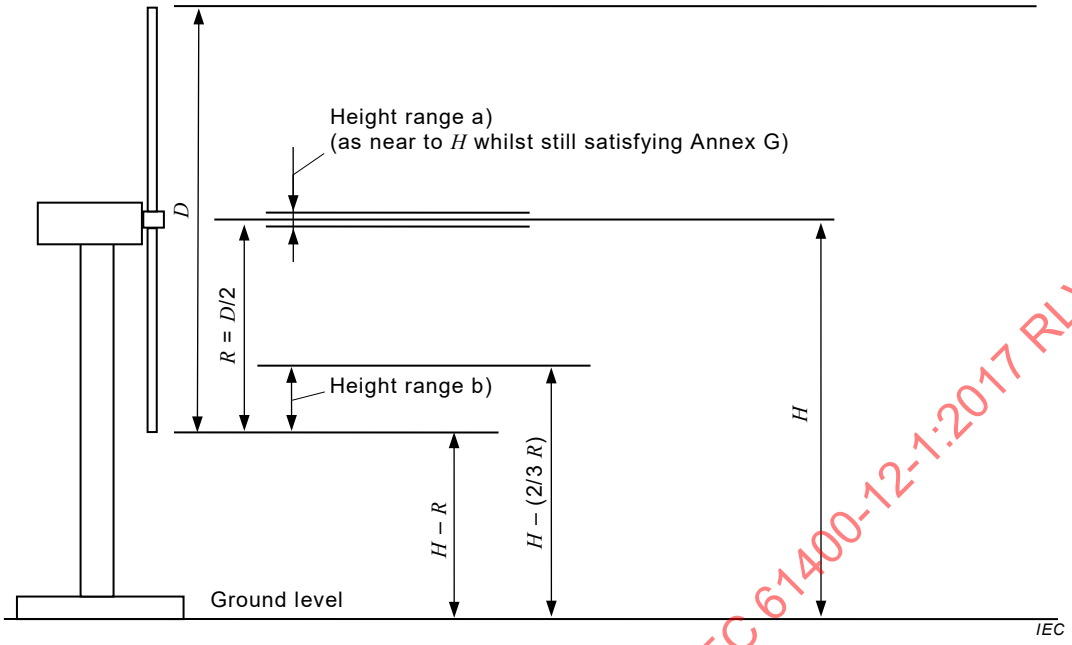

Figure 3 – Wind shear measurement heights when no wind speed measurements above hub height are available (for wind shear exponent determination only)

7.3 Wind direction

Wind direction measurements are used as an input to the site calibration, for filtering data to the valid direction sector and for determining wind veer. Wind direction ~~should~~ shall be measured with a wind ~~vane~~ direction sensor. ~~A wind vane used for this purpose shall be mounted on the meteorological mast on a boom, as described in Annex G. The combined calibration, operation, and orientation uncertainty of the wind direction measurement should be less than 5º.~~ This may be a wind vane or a 2D or 3D sonic anemometer or an RSD. Where a sonic anemometer is used it shall be used in conjunction with a conventional wind vane as a control. If an RSD is used, it should be subjected to a verification test on the wind direction according to Annex L.

The instantaneous horizontal wind direction shall be determined and averaged over 10 min. Vector averaging (averaging of cosine and sine components of instantaneous wind direction values taking arc tan of the average values and adjusted to the 0° to 360° scale) is one method for deriving the average wind direction. Another method is to extend the wind direction scale for values above 360° and calculating the 10 min average, then adjusting the average value to the 0° to 360° range. Data measured within the dead band of a wind vane, usually at the north mark of the wind direction sensor body, are usually not defined (open circuit or short circuit) and shall be excluded. The combined calibration, operation, and orientation standard uncertainty of the wind direction measurement shall be less than 5°. The wind direction sensor shall be calibrated. Annex N provides guidance.

7.4 Air density

Air density shall be derived from measurement of air temperature, air pressure ~~using equation (1)~~ and relative humidity. As an alternative to the humidity measurement, an assumed value of 50 % relative humidity may be used if humidity is not measured. The air density shall be calculated using Equation (12) in 9.1.5.

~~At high temperatures, it is recommended also that relative humidity be measured and corrected for. The correction for the density effect of the air humidity shall be performed using equation (F.1).~~

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The air temperature sensor~~, and the humidity sensor if used,~~ shall be mounted within 10 m of hub height to represent the air temperature at the wind turbine rotor centreline. Refer to Annex G for temperature sensor mounting requirements where a meteorological mast shorter than hub height is used.

The air pressure sensor should be mounted ~~on the meteorological mast close to~~ within 10 m of hub height to represent the ~~air~~ barometric pressure at the wind turbine rotor centreline. ~~If the air pressure sensor is not mounted close to the hub height,~~ Air pressure measurements shall be always corrected to the appropriate hub height according to ISO 2533.

The humidity sensor should be mounted within 10 m of hub height to represent the humidity at the wind turbine rotor centreline.

7.5 Rotational speed and pitch angle

Rotational speed and pitch angle should be measured throughout the test if there is a specific need for it. For example if there is a need to apply the measurements in connection with acoustic noise tests. If measured, the measurements shall be reported according to Clause 10.

7.6 Blade condition

The condition of the blades may influence the power curve particularly for stall regulated wind turbines. It may be useful in understanding the characteristics of the wind turbine to monitor the factors that ~~might~~ affect blade condition including precipitation, icing and bug and dirt accretion.

7.7 Wind turbine control system

Sufficient status signals shall be identified, verified and monitored to allow the rejection criteria of 8.4 to be applied. Obtaining these parameters from the wind turbine controller's data system~~, if available,~~ is adequate[15]. The definition of each status signal shall be reported.

7.8 Data acquisition system

A digital data acquisition system having a sampling rate per channel of at least 1 Hz shall be used to collect measurements and store ~~pre-processed data~~ either sampled data or statistics of the data sets as described in 8.3.

The calibration and accuracy of the data system chain (transmission, signal conditioning and data recording) shall be verified by injecting known signals from a traceable, calibrated source at the transducer ends and comparing these inputs against the recorded readings. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors.

8 Measurement procedure

8.1 General

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria to ensure that the data are of sufficient quantity and quality to determine the power performance characteristics of the wind turbine accurately. The measurement procedure shall be documented, as detailed in Clause 10, so that every procedural step and test condition can be reviewed and, if necessary, repeated.

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[15] A status signal on generator cut-in is adequate to verify cut-out hysteresis control algorithm.

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Accuracy of the measurements shall be expressed in terms of ~~measurement~~ standard uncertainty, as described in Annex D. During the measurement period, data should be periodically ~~checked~~ validated to ensure high quality ~~and repeatability of the test results~~. Test logs shall be maintained to document all important events during the power performance test.

8.2 Wind turbine operation

During the measurement period, the wind turbine shall be in normal operation, as prescribed in the wind turbine operations manual, and the machine configuration ~~may~~ shall not be changed. The operational status of the wind turbine shall be reported ~~by the status signals~~ as described in Clause 10. Normal maintenance of the wind turbine shall be carried out throughout the measurement period, but such work shall be noted in the test log. Any special maintenance actions, such as frequent blade washing, which ensure good performance during the test shall in particular be noted. Such special maintenance actions ~~shall by default not be made, unless agreed by contractual parties prior to commencement of the test~~ should be avoided.

8.3 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or higher. Air temperature, air pressure~~, wind turbine status~~ and humidity and precipitation, if measured, may be sampled at a slower rate, but at least once per minute.

The data acquisition system shall store either sampled data or statistics of data sets as follows:

a) mean value;

b) standard deviation;

c) maximum value;

d) minimum value.

Selected data sets shall be based on 10-min periods derived from contiguous measured data. Data shall be collected until the requirements defined in 8.5 are satisfied.

8.4 Data rejection

To ensure only data obtained during normal operation of the wind turbine are used in the analysis, and to ensure data are not corrupted, data sets shall be excluded from the database under the following circumstances:

a) external conditions other than wind speed are out of the operating range of the wind turbine;

b) the wind turbine cannot operate because of a wind turbine fault condition;

c) the wind turbine is manually shut down or in a test or maintenance operating mode;

d) failure or degradation (e.g. due to icing) of ~~test~~ measurement equipment;

e) wind direction outside the measurement sector(s) as defined in 6.3.3;

f) wind directions outside valid (complete) site calibration sectors;

g) any special atmospheric condition filtered during the site calibration shall also be filtered during the power curve test.

Any other rejection criteria shall be clearly reported.

The effect on the power curve of a large hysteresis loop in the cut-out control algorithm may be considerable. ~~The power curve shall capture the effect of hysteresis at the cut-in control algorithm, as well as the effect of parasitic losses below cut-in. In case cut-out behaviour has been reached during the measurement period, two data sets shall therefore be presented. One data set shall include all data points in the database (database A). The other data set~~

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~~shall exclude all data sets where the turbine has stopped generating power due to cut-out at high wind speed (database B)[16].~~

This effect shall not be included in the power curve, and all data sets where the wind turbine has stopped generating power due to cut-out at high wind speed shall be excluded. If cut-out behaviour has been reached during the measurement period, the measurements may be presented in a special database that includes all data points in the database. The power curve shall capture the effect of hysteresis at the cut-in control algorithm, as well as the effect of parasitic losses below cut-in. Cut-out hysteresis affects the higher wind speed bins and neglecting it may therefore lead to overestimation of energy production especially for scenarios with higher annual average wind speeds.

Subsets of the database collected under special operational conditions (e.g. high blade roughness due to dust, salt, insects and ice or if grid conditions vary significantly) or atmospheric conditions (e.g. precipitation, wind shear) that occur during the measurement period may be selected as special databases.

~~If the grid frequency varies on the order of two or more hertz, it might be appropriate to select the power performance at different frequency levels as a special database. In this case, the grid frequencies should be divided into frequency bins, centred on integer values of the grid frequency.~~

~~**8.5 Data correction**~~

~~For the selected data sets wind speeds shall be corrected for flow distortion from site calibration (see 5.2) and air pressure shall be corrected if measured at a height other than close to hub height (see 6.4).~~

8.5 Database

After data normalisation (see 9.1) the selected data sets shall be sorted using the “method of bins” procedure, see 9.2. The wind speed range shall be divided into 0,5 m/s contiguous bins centred on multiples of 0,5 m/s. The selected data sets shall at least cover a wind speed range extending from 1 m/s below cut-in to 1,5 times the wind speed at 85 % of the rated power of the wind turbine. Alternatively, the wind speed range shall extend from 1 m/s below cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated" (see 9.3), where “AEP-measured” and “AEP-extrapolated” are defined using the appropriate, consistent definitions of wind speed (i.e. the hub height wind speed derived power curve and wind speed distribution and, in the case where REWS is derived, by the REWS derived power curve and wind speed distribution). For active pitch controlled wind turbines, the power curve may also be considered complete when the rated power has been reached and the average power does not change by more than the larger of 0,5 % of the power or 5 kW for three consecutive wind speed bins and there is not a trend of increasing power across these three bin-averages. The report shall state which of the three wind speed range criteria has been used.

~~The report shall state which of the two definitions has been used to determine the range of the measured power curve. The wind speed range shall be divided into 0,5 m/s contiguous bins centred on multiples of 0,5 m/s.~~

The database shall be considered complete when it has met the following criteria:

a) each bin includes a minimum of 30 min of sampled data;

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~~[16] A power curve based on database A can be used to estimate the impact of cut-out behaviour of a turbine. While accurate for the location and period of the test, it may differ from the behaviour seen at other periods or locations. A power curve based on database B, which does not include power loss due to cut-out hysteresis, can be used to compare or verify power curves in a more generic way.~~

b) the database includes a minimum of 180 h of sampled data.

Should a single incomplete bin be preventing completion of the test, then that bin value can be estimated by linear interpolation from the two adjacent complete bins. ~~In order to complete the power curve at high wind speeds the following procedure can be used:~~

~~– for wind speeds above 1,6 times the wind speed at 85 % of rated power the measurement sector can be opened.~~

~~The following condition has to be fulfilled by using these two measures: AEP measured by extended procedures deviates less than 1 % from AEP extrapolated up to the highest complete wind speed bin for the extended procedures (for the Rayleigh distribution in 8.3).~~

The database shall be presented in the test report as detailed in Clause 10.

9 Derived results

9.1 Data normalisation

9.1.1 General

In the following subclauses, three methods of normalisation are described for the main atmospheric drivers on the power curve results: air density, wind shear and turbulence intensity.

The purpose of these normalisations is to improve the accuracy of the results by means of concrete formulations for each variable. This will to some extent allow the comparison of results from different data sets bringing them to similar scale.

The various normalisations should be applied as indicated in the flow chart in Figure 4.

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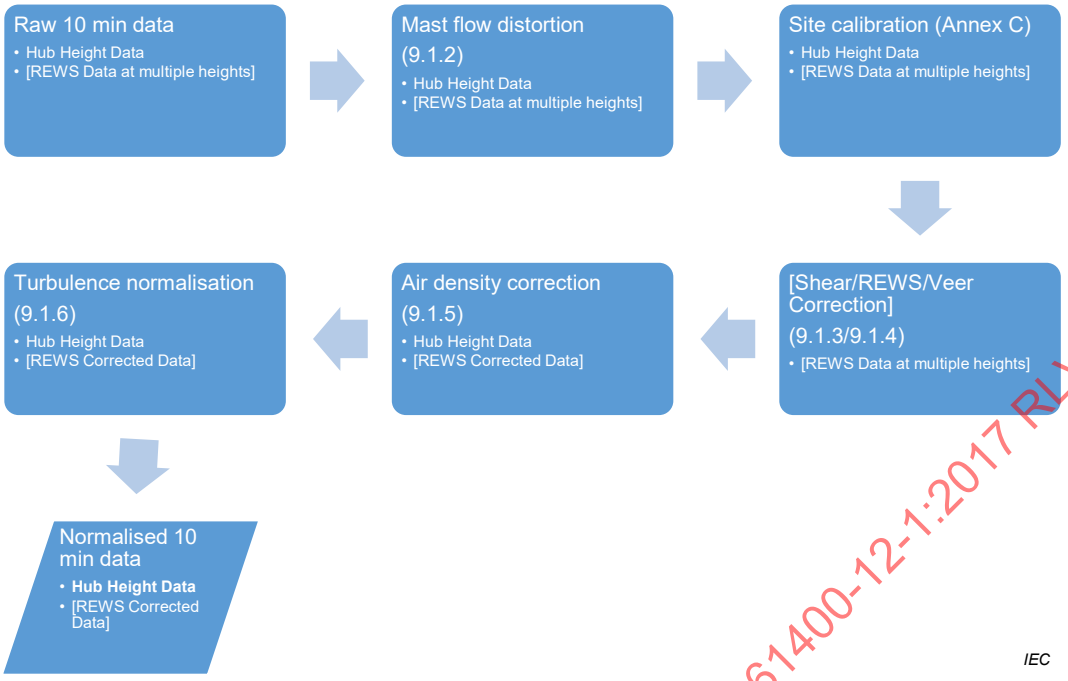

Figure 4 – Process of application of the various normalisations[17]

9.1.2 Correction for meteorological mast flow distortion of side-mounted anemometer

Correction of the wind speeds from side mounted anemometers for meteorological mast flow distortion is permitted (the requirement from Annex G for a maximum of 1 % meteorological mast flow distortion before application of the correction is still required). Any correction method shall be documented and reported following the requirements of 10.

The impact of the meteorological mast flow distortion on the wind shear measurement may be minimized by reducing the measurement sector where meteorological mast flow distortion is below a certain limit. The technical basis for any such reduction in sector width shall be documented. Annex S gives a possible method for determining the flow distortion correction for a lattice mast.

9.1.3 Wind shear correction (when REWS measurements available)

9.1.3.1 General

If the wind speed over the wind turbine rotor area is constant, the wind speed at hub height would be representative of the wind speed over the wind turbine rotor and the use of the hub height wind speed would be justified. However, the assumption of a point wind speed such as at hub height representing the wind speed over the wind turbine rotor area may not be representative for large wind turbines. It is therefore necessary to introduce corrections that account for the wind speed at hub height and the variations introduced by the wind shear over the wind turbine rotor. In the following, three quantities are defined:

a) the rotor equivalent wind speed;

b) the wind shear correction factor;

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17 Where the optional REWS measurements are available, the REWS data follow a normalisation path parallel to the default hub height data normalisations as indicated by the terms in square brackets. The normalisation of the REWS data is carried out separately at each measurement height for all normalisation steps up to the step where the results from each height are combined into the wind shear/REWS/veer correction. A single REWS corrected value is derived for each 10-minute data point at each subsequent step in parallel to the corrections applied to each hub height data point.

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c) the wind shear corrected wind speed.

The wind shear correction factor may be used to derive a climate specific power curve as explained in Annex P. However, this correction is based on the assumption that a wind turbine is able to convert all of the available kinetic energy.

9.1.3.2 Rotor equivalent wind speed

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. Where the wind speed for at least three measurement heights are available (see 7.2.6), the rotor equivalent wind speed is defined as:

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n_{\mathrm{h}}} v_i^3 \frac{A_i}{A} \right)^{1/3} \tag{5}$$

where

n_{h} is the number of available measurement heights ($n_{\mathrm{h}} \geq 3$);

v_i is the wind speed measured at height i;

A is the complete area swept by the rotor (i.e. πR^2 with radius R);

A_i is the area of the i^{th} segment, i.e. the segment the wind speed v_i is representative for, derived from Equation (6).

The segments (with areas A_i) shall be chosen in the way that the horizontal separation line between two segments lies in the middle of two measurement points. The segment areas are then derived according to Equation (6):

$$A_i = \int_{z_i}^{z_{i+1}} c(z)\,\mathrm{d}z = g(z_{i+1}) - g(z_i) \tag{6}$$

where

z_i is the height of the i^{th} segment separation line ($H-R<z_i<H+R$), numbered in the same order as v_i (either top down or bottom up).

The rotor width at height z is:

$$c(z) = 2\sqrt{R^2 - (z-H)^2} \tag{7}$$

where

R is the rotor radius;

H is the hub height.

The integrated function is:

$$g(z) = (z-H)\sqrt{R^2 - (z-H)^2} + R^2 \arctan\left(\frac{z-H}{\sqrt{R^2 - (z-H)^2}} \right) \tag{8}$$

Example of REWS calculation for one 10 minute wind speed profile

In this example, a wind turbine is assumed to have a hub height of 80 m and a rotor diameter of 100 m. The wind speed was measured at 5 heights with a meteorological mast. If the heights could have been chosen, ideally they would have been evenly distributed (40 m,

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60 m, 80 m, 100 m and 120 m). This example shows a case where the heights were fixed independently from the REWS evaluation purpose. The segment limits were set in the middle of two consecutive measurements. The resulting REWS is equal to 9,38 m/s, see Table 3.

Table 3 – Example of REWS calculation

Measurement Heights [m]	Wind speed [m/s]	Segment weighting* [%]	Segment inferior limit height (z_i) [m]	Segment superior limit height (z_{i+1}) [m]	Segment height [m]
116	11,46	16,31	108	130	22
100	10,43	21,04	90	108	18
80	9,24	25,29	70	90	20
60	7,81	23,12	50	70	20
40	6,05	14,24	30	50	20

* Segment weighting is defined as the ratio between the segment area and the total swept rotor area.

9.1.3.3 Wind shear correction factor

9.1.3.3.1 Case 1: Hub height meteorological mast with remote sensing device or remote sensing device with short (below hub height) meteorological mast

A wind shear correction factor measured using a remote sensing device is defined as the ratio of the rotor equivalent wind speed relative to the wind speed measured at hub height according to Equation (9):

$$f_{r,RSD} = v_{eq,RSD} / v_{h,RSD} \quad (9)$$

where

$v_{eq,RSD}$ is the rotor equivalent wind speed measured by the remote sensing device, as defined in Equation (5);

$v_{h,RSD}$ is the wind speed measured at hub height by the remote sensing device.

9.1.3.3.2 Case 2: Meteorological mast above hub height

A wind shear correction factor measured using a meteorological mast is defined as the ratio of the rotor equivalent wind speed to the wind speed measured at hub height according to Equation (10)[18]:

$$f_{r,MM} = v_{eq,MM} / v_{h,MM} \quad (10)$$

where

$v_{eq,MM}$ is the rotor equivalent wind speed measured by the anemometers on the meteorological mast, as defined in Equation (5);

$v_{h,MM}$ is the wind speed measured by the anemometer at hub height.

18 Note that $f_{r,MM}$ is for reporting purposes only.

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9.1.3.4 Wind shear correction of wind speed

If the hub height wind speed and the wind shear are measured with the same type of WME, the rotor equivalent wind speed is calculated according to Equation (5).

If the hub height wind speed is measured using an anemometer mounted on a meteorological mast and the wind shear measurement with an RSD, the final rotor equivalent wind speed is calculated according to Equation (11):

$$v_{\text{eq,final}} = f_{\text{r,RSD}} v_{\text{h,MM}} \tag{11}$$

9.1.4 Wind veer correction

As explained in Annex Q, the change of wind direction over the rotor height range (wind veer) can have a significant impact on the wind turbine power output. In the case of large wind turbine rotors, it is recommended to apply the extended definition of equivalent wind speed including wind veer.

9.1.5 Air density normalisation

The air density shall be determined from measured air temperature, air pressure and relative humidity according to the Equation (12):

$$\rho_{10\text{min}} = \frac{1}{T_{10\text{min}}}\left(\frac{B_{10\text{min}}}{R_0} - \Phi P_{\text{w}}\left(\frac{1}{R_0} - \frac{1}{R_{\text{w}}}\right)\right) \tag{12}$$

where

$\rho_{10\text{min}}$ is the derived 10 min averaged air density;

$T_{10\text{min}}$ is the measured absolute air temperature averaged over 10 min [K];

$B_{10\text{min}}$ is the air pressure corrected to hub height averaged over 10 min [Pa];

R_0 is the gas constant of dry air 287,05 [J/kgK];

Φ is the relative humidity (range 0 % to 100 %);

R_{w} is the gas constant of water vapour 461,5 [J/kgK];

P_{w} is the vapour pressure equal to 0,000 020 5 exp(0,0631 846 $T_{10\text{min}}$) [Pa];

Vapour pressure P_{w} depends on mean air temperature over the 10 min.

The selected data sets shall be normalised to ~~two~~ at least one reference air density. ~~One shall be the sea level air density, referring to ISO standard atmosphere (1,225 kg/m^3).~~ The ~~other~~ reference air density shall be the average of the measured air density ~~data~~ of the valid collected data at the site during the test period (see 8.4), or alternatively a pre-defined nominal air density for the site. The average measured air density shall be rounded to the nearest ~~0,05~~ 0,01 kg/m^3 and reported in accordance with 10.

~~No air density normalization to actual average air density is needed when the actual average air density is within 1,225 ± 0,05 kg/m^3. Alternatively, the other normalization may be carried out to a nominal air density pre-defined for the site. The air density may be determined from measured air temperature and air pressure according to the equation:~~

$$\rho_{10\,\text{min}} = \frac{B_{10\,\text{min}}}{R_0 \cdot T_{10\,\text{min}}} \tag{1}$$

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~~where~~

$\rho_{10\,min}$ ~~is the derived 10 min averaged air density;~~

$T_{10\,min}$ ~~is the measured absolute air temperature averaged over 10 min;~~

B_{10min} ~~is the measured air pressure averaged over 10 min;~~

R_0 ~~is the gas constant of dry air 287,05 J/(kg × K).~~

For a stall-regulated wind turbine with constant pitch and constant rotational speed, data normalisation shall be applied to the measured power output according to Equation (13):

$$P_n = P_{10min}\left(\frac{\rho_0}{\rho_{10min}}\right) \quad (13)$$

where

P_n is the normalised power output;

P_{10min} is the measured power averaged over 10 min;

ρ_0 is the reference air density;

ρ_{10min} is the air density derived according to Equation (12) averaged over 10 min.

For a wind turbine with active power control, the normalisation shall be applied to the wind speed according to Equation (14):

$$V_n = V_{10\,min}\left(\frac{\rho_{10\,min}}{\rho_0}\right)^{1/3} \quad (14)$$

where

V_n is the normalised wind speed;

V_{10min} is the measured wind speed averaged over 10 min.

9.1.6 Turbulence normalisation

Wind turbine power curve measurements are influenced by the turbulence intensity. A significant part of the turbulence intensity effect is caused by the averaging of the measured power output and the measured wind speed over 10-minute periods. It is recommended to remove this effect from the measurements by normalising the power curve data to a reference turbulence intensity according to Annex M. The reference turbulence intensity shall be defined prior to the power curve test. It may be defined as a function of the wind speed at hub height. If not defined otherwise, a reference turbulence intensity of 10 % shall be applied. The uncertainty of the turbulence normalisation shall be accounted for. If no turbulence normalisation of the power curve data is performed, the uncertainty of the power curve due to turbulence effects shall be estimated. As a recommendation use the uncertainty method described in Annex M[19].

9.2 Determination of the measured power curve

The power curve shall be determined based on the hub height wind speed and, if measured, the rotor equivalent wind speed. However, it should be remembered that the uncertainty in a power curve derived from hub height measurements only is subject to higher uncertainty due to the lack of knowledge of other influential wind condition parameters. Therefore to account for the vertical wind shear, wind veer and turbulence intensity and to reduce power curve measurement uncertainty, it is recommended to consider the rotor equivalent wind speed as the representative wind speed and the turbulence normalised power output according to

[19] It should be noted that turbulence intensity measured by cup anemometers, remote sensing devices and ultra sonic anemometers are measured differently. This should be considered when interpreting the results.

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Annex M as the relevant power output. The derivation of power curves based on wind speed normalised for a specific wind shear profile (see Annex P) and the turbulence normalised power output are options that are recommended if a comparison between different power curves is wanted or if the power curves are applied for wind resource assessment.

To indicate single 10-min averages, a further index j should be added to the respective wind speeds.

The measured power curve is determined by applying the "method of bins" for the normalized data sets, using 0,5 m/s wind speed bins and by calculation of the mean values of the normalized wind speed and normalized power output for each wind speed bin according to Equations (15) and (16):

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{\mathrm{n},i,j} \tag{15}$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{\mathrm{n},i,j} \tag{16}$$

where

V_i is the normalized and averaged wind speed in bin i;

$V_{\mathrm{n},i,j}$ is the normalized wind speed of data set j in bin i;

P_i is the normalized and averaged power output in bin i;

$P_{\mathrm{n},i,j}$ is the normalized power output of data set j in bin i;

N_i is the number of 10 min data sets in bin i.

The measured power curve shall be presented as detailed in Clause 10 and where REWS power curves are measured, the hub height wind speed power curve shall also be presented. ~~In case cut-out behaviour has been reached during the measurement period two power curves shall be presented. Power curve A shall be based on database A and power curve B shall be based on database B, as described in 7.4. Both power curves shall be presented as detailed in Clause 9.~~

9.3 Annual energy production (*AEP*)

The *AEP* shall be calculated in two ways, one designated "*AEP*-measured", the other "*AEP*-extrapolated". If the measured power curve does not include data up to cut-out wind speed, the power curve shall be extrapolated from the maximum complete measured wind speed up to cut-out wind speed.

Furthermore, *AEP* may be defined as generic *AEP* or site specific *AEP*. Generic *AEP* is estimated by applying the measured power curve to different reference wind speed frequency distributions. For a specific development, nominal site conditions specifying the wind climate of the site may be known. If so, a site specific *AEP* may, additionally, be reported and computed based on this site specific information.

It is emphasised that a power curve derived from hub height wind speed measurements shall only be combined with a wind speed frequency distribution based on the hub height wind speed definition to derive *AEP* whereas a power curve derived from REWS measurements shall only be combined with a REWS frequency distribution to derive *AEP*. The *AEP* derived from combining a REWS power curve with a hub height wind speed frequency distribution (and vice versa) is not a valid calculation. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. *AEP* estimations shall be made for hub height annual average wind speeds of 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, 10 m/s and 11 m/s according to Equation (17):

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$$AEP = N_h \sum_{i=1}^{N} [F(V_i) - F(V_{i-1})] \left(\frac{P_{i-1} + P_i}{2} \right) \quad (17)$$

where

AEP is the annual energy production;

N_h is the number of hours in one year ≈ 8 760;

N is the number of bins;

V_i is the normalized and averaged wind speed in bin i;

P_i is the normalized and averaged power output in bin i.

$$F(V) = 1 - \exp\left(-\frac{\pi}{4} \left(\frac{V}{V_{ave}} \right)^2 \right) \quad (18)$$

where

$F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;

V_{ave} is the annual average wind speed ~~at hub height~~;

V is the wind speed.

The summation is initiated by setting V_{i-1} equal to V_i – 0,5 m/s and P_{i-1} equal to 0,0 kW.

For a specific ~~development~~ site, nominal site conditions specifying the wind climate of the site may be known. If so, a site specific AEP may, additionally, be reported and computed based on this site specific information.

~~The AEP shall be calculated in two ways, one designated "AEP-measured", the other "AEP-extrapolated". If the measured power curve does not include data up to cut-out wind speed, the power curve shall be extrapolated from the maximum complete measured wind speed up to cut-out wind speed.~~

If the site specific wind distribution is known and is present in tabular form, the site-specific AEP may be calculated by first transforming the wind distribution to the corresponding cumulative distribution. The amount of hours up to each measured wind speed of the measured power curve will be derived by linear interpolation between two adjacent values of the cumulative distribution. The hours will be divided by the sum of hours in the table, which is typically the nominal number of hours within a calendar year. Finally the AEP will be calculated by using Equation (17). The tabular wind speed distribution shall use the same definition of wind speed (hub height or REWS) as the measured power curve otherwise a valid AEP cannot be derived.

If the site specific wind distribution is presented as a Weibull distribution with known shape and scale factors, then the AEP may be calculated with Equation (17) and substituting the cumulative Rayleigh distribution Equation (18) with the Weibull distribution Equation (19):

$$F(V) = 1 - e^{-\left(\frac{V}{A_W}\right)^k} \quad (19)$$

where

$F(V)$ is now the Weibull cumulative probability distribution function for wind speed;

V is the wind speed;

A_W is the Weibull scale factor;

k is the Weibull shape factor;

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AEP-measured shall be obtained from the measured power curve by assuming zero power for all wind speeds above and below the range of the measured power curve and carrying out the summation according to Equation (17).

AEP -extrapolated shall be obtained from the measured power curve by assuming zero power for all wind speeds below the lowest wind speed in the measured power curve and constant power for wind between the highest wind speed in the measured power curve and the cut-out wind speed. 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.

AEP -measured and AEP -extrapolated shall be presented in the test report, as detailed in Clause 10. For all AEP calculations, the availability of the wind turbine shall be set to 100 %. For given annual average wind speeds, estimations of AEP -measured shall be labelled as "incomplete" when calculations show that the AEP -measured is less than 95 % of the AEP -extrapolated.

Estimations of measurement uncertainty in terms of standard uncertainty of the AEP according to Annex D, shall be reported for the AEP -measured for all ~~given annual average~~ the used wind speed distributions.

The uncertainties in AEP, described above, only deal with uncertainties originating from the power performance test and do not take into account uncertainties due to other important factors relating to actual energy production for a given installation.

9.4 Power coefficient

The power coefficient, C_P, of the wind turbine shall be added to the test results and presented as detailed in Clause 10. C_P shall be determined from the measured power curve according to Equation (20):

$$C_{P,i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \tag{20}$$

where

$C_{P,i}$ is the power coefficient in bin i;

V_i is the normalized and averaged wind speed in bin i (matching the defined wind speed as either rotor equivalent wind speed or hub height wind speed);

P_i is the normalized and averaged power output in bin i;

A is the swept area of the wind turbine rotor;

ρ_0 is the reference air density.

10 Reporting format

The test report shall contain the following information:

a) Identification and description of the specific wind turbine configuration under test (see 6.2), including:

   1) wind turbine make, type, serial number, production year;

   2) rotor diameter and a description of the verification method used or reference to rotor diameter documentation;

   3) rotor speed or rotor speed range;

   4) rated power and rated wind speed;

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5) blade data: make, type, serial numbers, number of blades, fixed or variable pitch, and pitch angle(s);

6) hub height and tower type;

7) description of the control system (device and software version) and documentation of status signals being used for data reduction;

8) description of grid conditions at the wind turbine, i.e. voltage, frequency and their tolerances, and a drawing indicating where the power transducer is connected, specifically in relation to an internal or external transformer and self-consumption of power;

b) A description of the test site (see 6.3), including:

1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;

2) a test site map showing the surrounding area covering a radial distance of at least 20 times the wind turbine rotor diameter and indicating the topography, location of the wind turbine, ~~meteorological mast~~ wind measurement equipment, significant obstacles, other wind turbines, and measurement sector;

3) results of site assessment, i.e. the limits of the valid measurement sector(s);

4) if site calibration is undertaken, the limits of the final measurement sector(s) shall also be reported, including the rationale for any changes from the results of the site assessment;

5) a table of the coordinates and elevation of the test wind turbine, wind measurement equipment and any significant obstacles considered in the assessment of obstacles;

c) A description of the test equipment (see Clause 7):

1) identification of all sensors, wind measurement equipment and data acquisition system, including documentation of calibrations of sensors, wind measurement equipment, transmission lines, and data acquisition system;

~~2) description of the arrangement of cup anemometers on the meteorological mast, following the requirements and descriptions in Annex G;~~

2) sketch of the arrangement of the meteorological mast showing ~~principle~~ dimensions of the ~~tower~~ mast and instrument mounting ~~fixtures~~, to document compliance with Annex G;

3) description of method to ~~maintain~~ ensure the ~~anemometer~~ calibration of the wind measurement equipment was maintained over the duration of the measurement period and documentation of results that show that the calibration is maintained;

d) A description of the measurement procedure (see Clause 8):

1) documentation of the procedural steps, test conditions, sampling rate, averaging time, and measurement period including;

– documentation of the calibrations, corrections or transfer functions applied by the data logger and/or by post-processing;

2) a test log book that records all important events during the power performance test, including:

– a listing of all maintenance activities that occurred during the test;

– a listing of any special actions (such as blade washing) that were completed to ensure good performance;

~~3) identification of any data rejection criteria beyond those listed in 7.4.~~

3) a complete list of all filter criteria used to produce the reported result, including:

– the parameter, measurement or time period or combination of parameters being filtered on;

– the range or logical criteria for the filter;

– the justification for the filter;

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- the order that the filters were applied shall be reported with the number of points removed each iteration. Alternatively, the number of data points the filter would remove from the database by itself;
- the starting number of datasets in the database and the final number of datasets after all filters have been applied;

e) Presentation of measured data (see 8.3 to 8.5). Data from each selected data set shall be presented in both tabular and graphical formats, providing statistics of measured power output as a function of wind speed and of important meteorological parameters including (where REWS measurements are available, the measured data shall be presented separately for both the hub height data and the REWS data):

1) scatter plots of mean, standard deviation, maximum, and minimum power output as a function of wind speed (plots ~~must~~ shall include information on sample frequency). An example is shown in Figure 5;
2) scatter plots of mean wind speed and turbulence intensity as a function of wind direction;
3) scatter plots of the turbulence intensity as a function of wind speed, and the average turbulence intensity in each wind speed bin shall be presented;
4) special databases consisting of data collected under special operational or atmospheric conditions should also be presented as described above;
5) if measured, rotational speed and pitch angle shall be presented with a scatter plot including binned values versus wind speed and a table with the binned values;
6) definition of status signals and plots of status signals during the measurement period;
7) scatter plots of air density as a function of wind direction and wind speed including average per bin;
8) scatter plot of the wind shear exponent vs. time of day and as function of wind speed. The wind shear exponent in the lower rotor half and in the upper rotor half shall be presented separately. In addition, the average values of both wind shear exponents per wind speed bin shall be represented;
9) the average wind shear exponent or equivalent representation of the site wind shear conditions during the test;
10) wind shear correction factor according to 9.1.3.3, if applicable based on measurement set up (use Equation (9) or Equation (10) depending on measurement configuration);
11) the average air density measured during the test;

f) Presentation of measured power curve for the reference air density ~~at sea level~~ (see 9.1 and 9.2) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:

1) the power curve shall be presented in a table similar to Table 4[20]. For each wind speed bin, the table shall list:
   - normalized and averaged wind speed;
   - normalized and averaged power output;
   - number of data sets;
   - calculated C_P value;
   - standard uncertainties of category A (see Annex D and Annex E);
   - standard uncertainties of category B (see Annex D and Annex E);
   - combined standard uncertainty (see Annex D and Annex E);

[20] In addition to presenting the measured power curve in a table according to f) 1), the measured power curve can be presented as bin-centre values. The recommended method is to use a cubic spline for interpolation between the bin-values in the table to represent the measured wind speed, power and power coefficient values at the bin centre.

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2) the power curve shall be presented in a graph similar to Figure 6. The graph shall show the following as a function of normalized and averaged wind speed:
   – normalized and averaged power output;
   – combined standard uncertainty;
3) the C_P curve shall be presented in a graph similar to Figure 7;
4) both the graph and the table shall state the ~~sea level~~ reference air density ~~1,225 kg/m^3~~ used for the normalisation;
5) if cut-out wind speed has been reached during the measurement period, the power curve and C_P curve, or the parts of the curves influenced by the cut-out hysteresis, ~~shall~~ can be presented in a similar way to items 1), 2), 3) and 4).

~~g) Presentation of measured power curve for site specific air density (see 8.1 and 8.2):~~

~~if the site average air density is not within 0,05 kg/m^3 of 1,225 kg/m^3, or if a pre-defined nominal air density is required, then a second presentation of the measured power curve shall be made. This presentation shall be the same as for sea level air density but shall show the power curve results obtained by normalization to the site specific air density.~~

g) Presentation of measured power curves collected under special operational and atmospheric conditions ~~(see 7.5)~~:
   1) power curves derived from subsets of the database for special operational or atmospheric conditions may also be reported. If this is the case, a power curve should be reported ~~as for sea level air density, but with clear indication in all plots and tables of the special operational and/or atmospheric conditions~~ in the same way as for the reference air density but with the density derived from the average of the measured air density of the subsets of the database or alternatively using a pre-defined nominal air density for the site.

h) Presentation of estimated annual energy production for the reference air density ~~at sea level~~ (see 9.3) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:
   1) a table similar to Table 5 for each annual average hub height wind speed shall include:
      – AEP-measured;
      – standard uncertainty of AEP-measured (see Annex D and Annex E);
      – AEP-extrapolated;
   2) the table shall also state:
      – reference air density;
      – cut-out wind speed;
   3) if at any annual average wind speed AEP-measured is less than 95 % of AEP-extrapolated, the table shall also include the label “incomplete” in the column of values of AEP-measured;
   ~~4) in case cut-out wind speed has been reached during the measurement period the estimated annual energy production, including the cut-out hysteresis, shall additionally be presented similar to items 1), and 3); the table shall also state the reference air density.~~

~~j) Presentation of estimated annual energy production for site specific air density (see 8.3):~~

~~if the site average air density is not within 0,05 kg/m^3 of 1,225 kg/m^3, or if it is desired that a pre-defined nominal air density be used, then a second table of AEP shall be presented. This presentation shall be the same as for sea level air density, but shall show AEP results obtained by normalization to the site specific air density.~~

i) Presentation of measured power coefficient (see 9.4):
   1) measured power coefficient should be presented as a function of wind speed in a table and a graph in which the swept area of the rotor shall be indicated;

j) Presentation of results of site calibration (see Annex C for reporting requirements):

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1) if a site calibration is undertaken, it shall be presented in the report as a table ~~and a graph~~;
2) the table shall for each wind direction bin present:
   - minimum and maximum wind direction limits;
   - the bin-averaged wind direction;
   - ~~the bin-averaged ratio of wind speeds;~~
   - the characteristics of the wind speed correction;
   - number of hours of data;
   - combined standard uncertainty of the wind speed ratio for 6 m/s, 10 m/s and 14 m/s;

~~3) the graph (see Figure 5) shall present:~~

- ~~the bin-averaged ratio of wind speeds with standard deviation S_{ab} versus wind direction.~~

3) the report shall furthermore include graphs and tables as required in Annex C;

k) Uncertainty of measurement (see Annex D):
   1) uncertainty assumptions on all uncertainty components shall be provided;
l) Deviations from the procedure:
   1) any deviations from the requirements of this standard shall be clearly documented in a separate clause. Each deviation shall be supported with the technical rationale and an estimate of its effect on test results.

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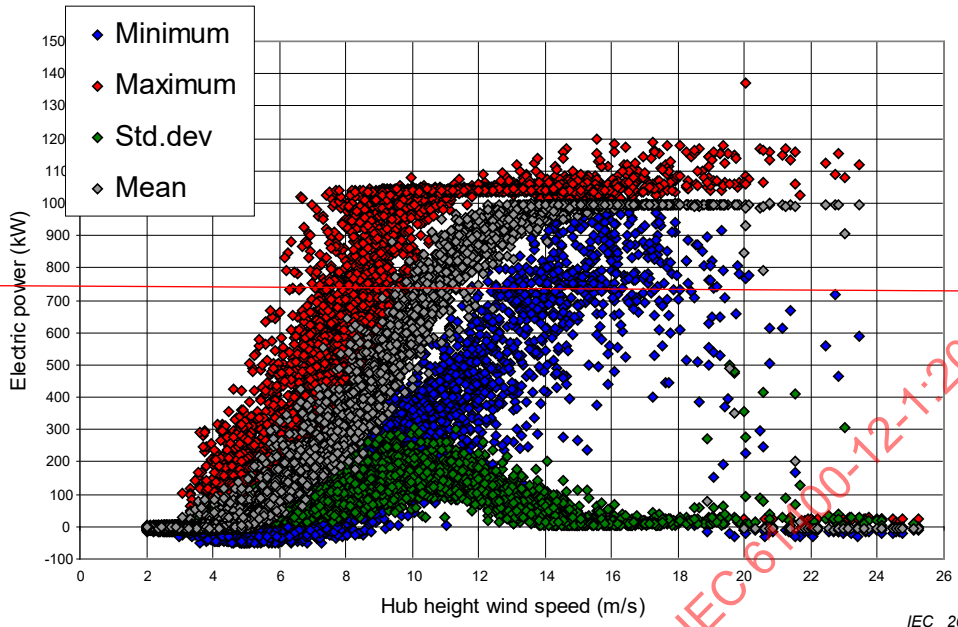
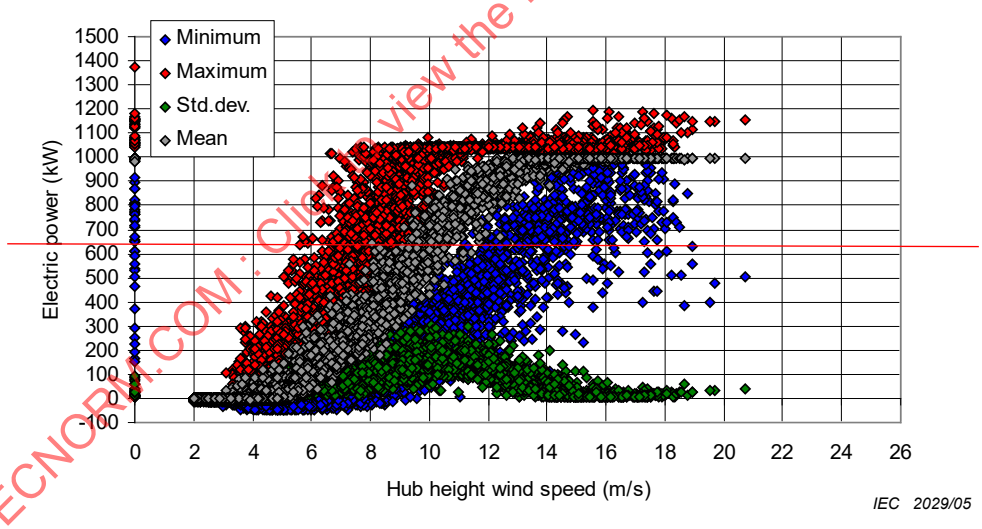
Scatter plot of measured power output (database A)



Scatter plot of measured power output (database B)



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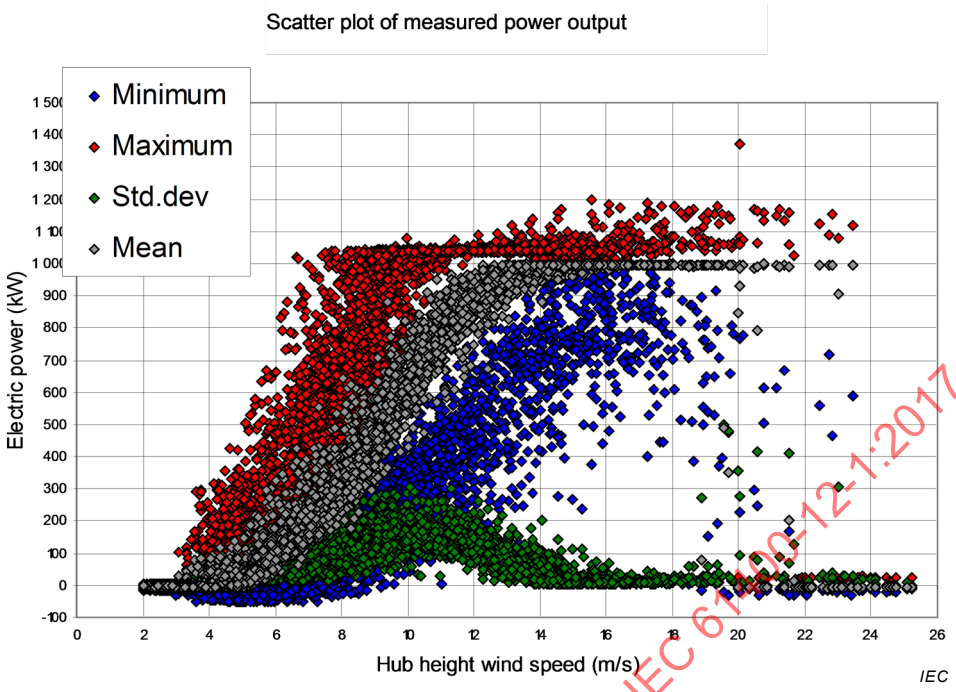

Figure 5 – Presentation of example database ~~A and B~~: power performance test scatter plot sampled at 1 Hz (mean values averaged over 10 min)

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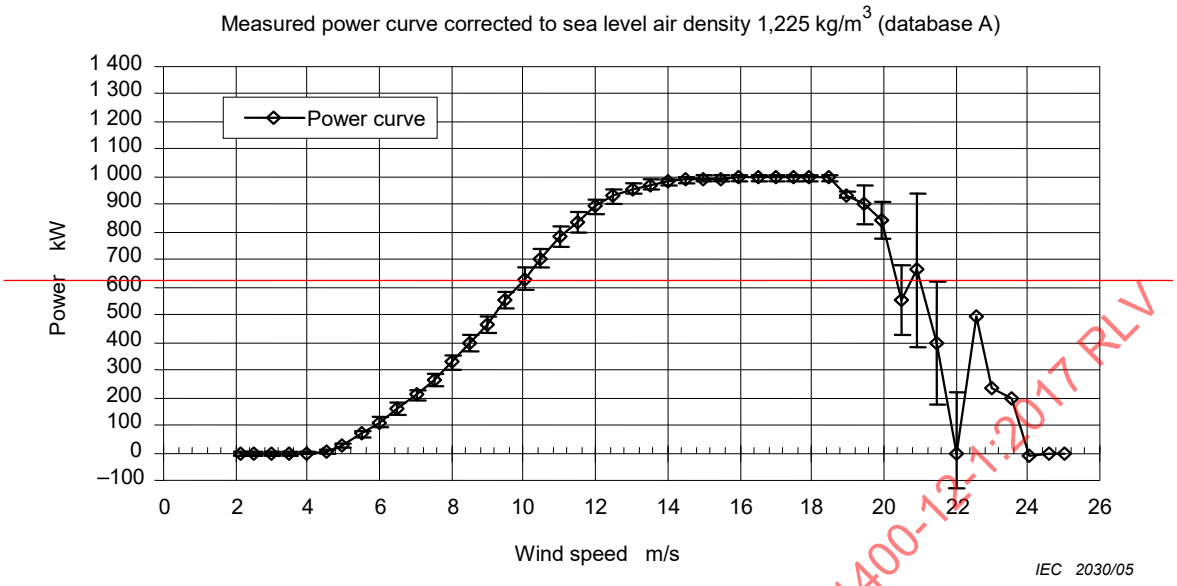

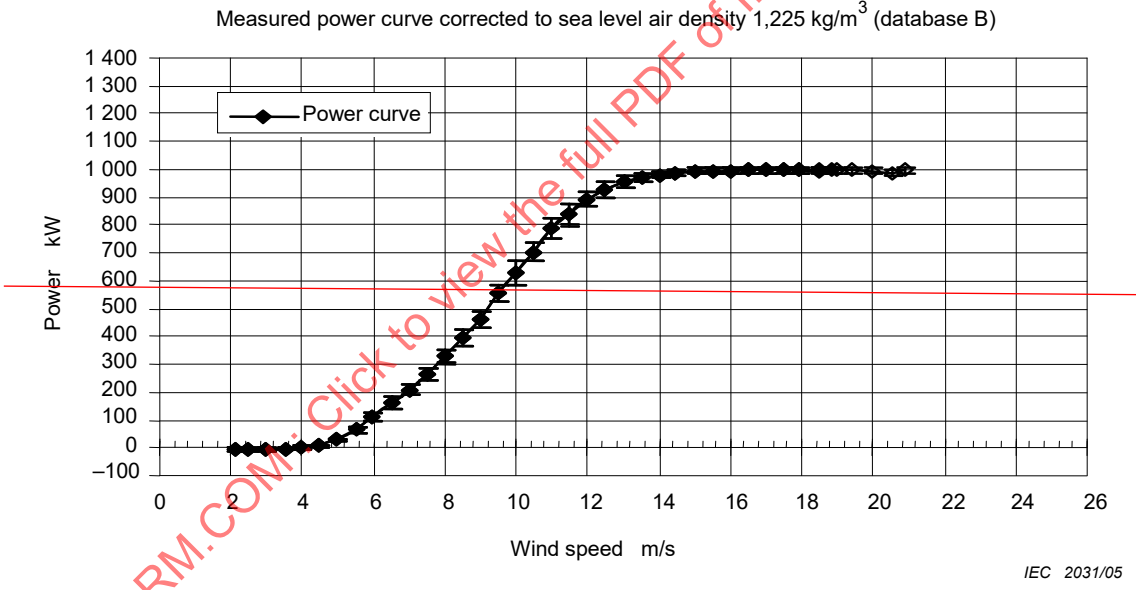

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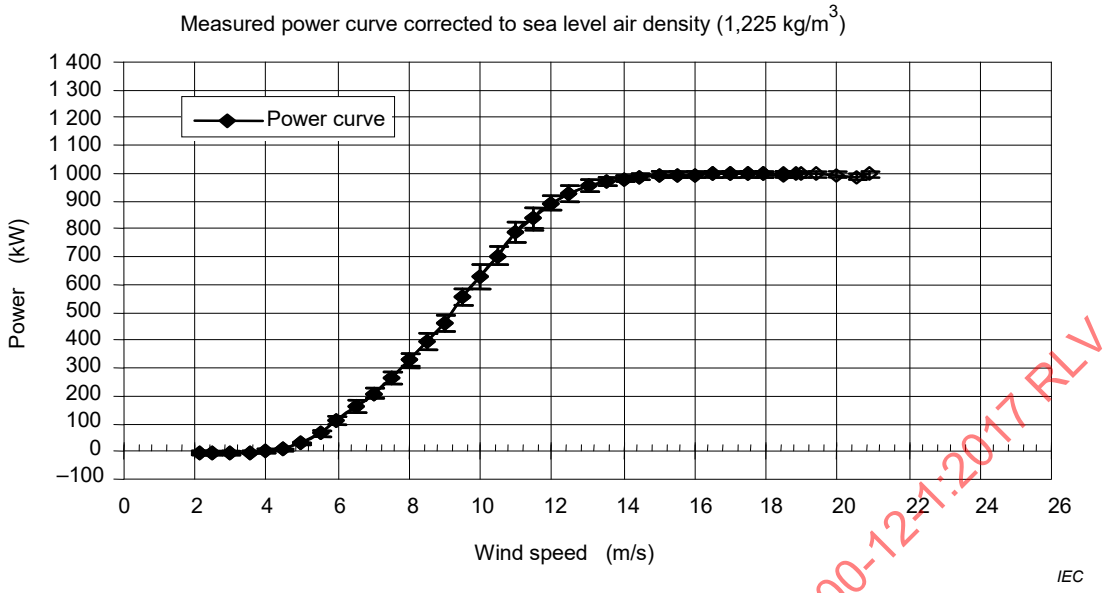

Figure 6 – Presentation of example measured power curve ~~for databases A and B~~

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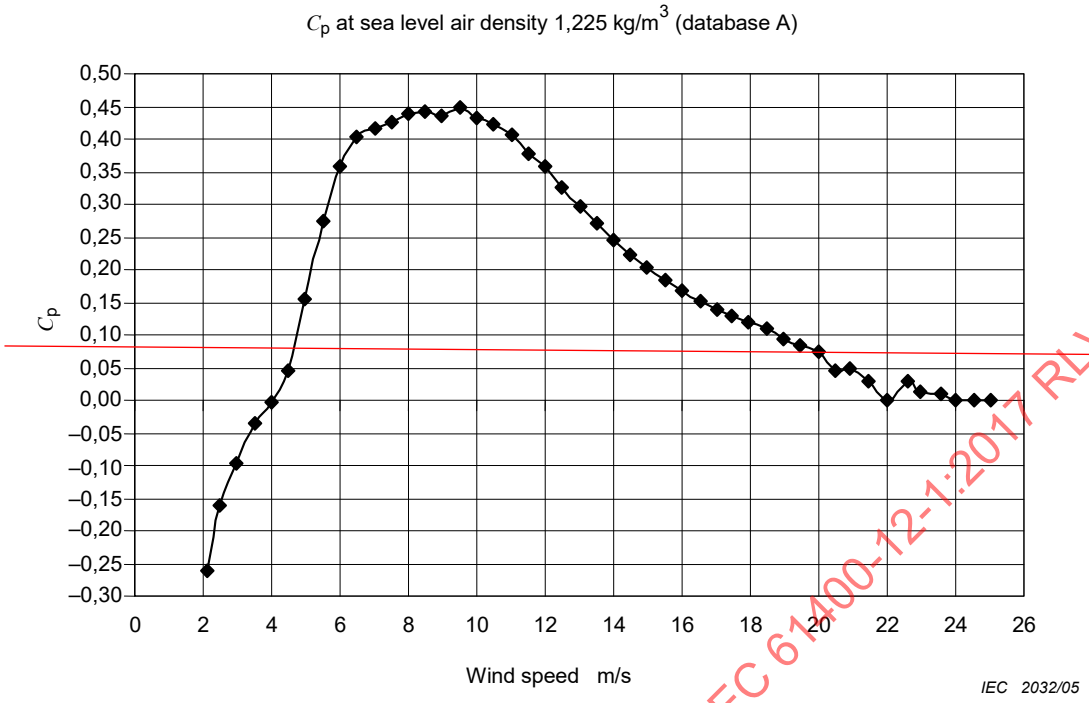

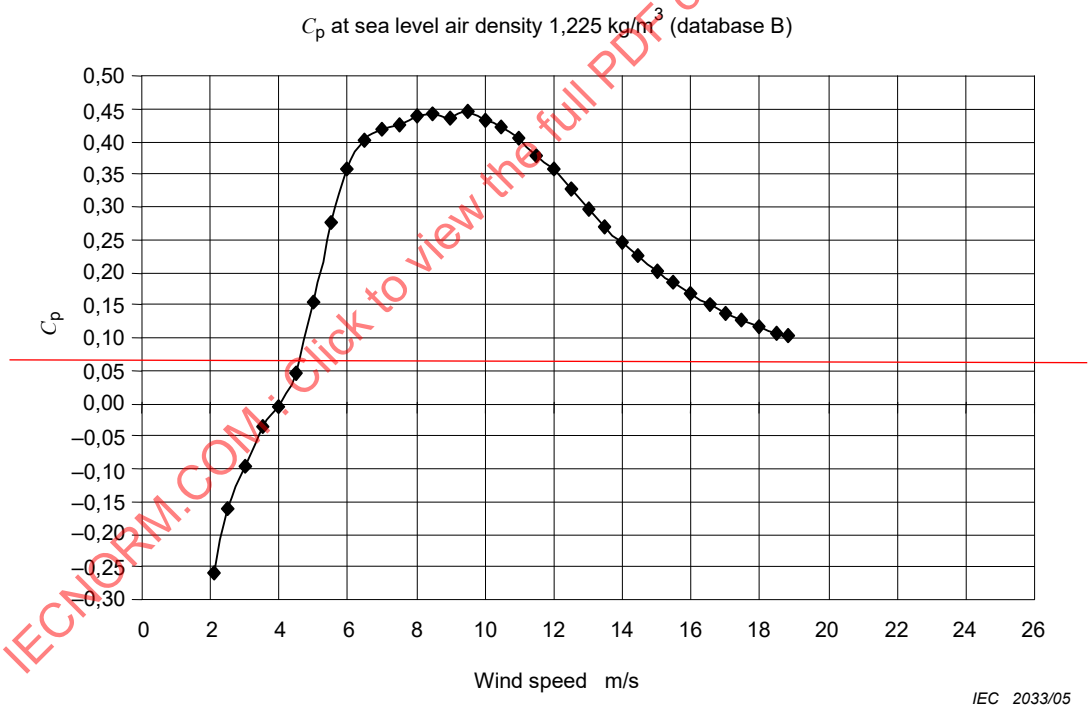

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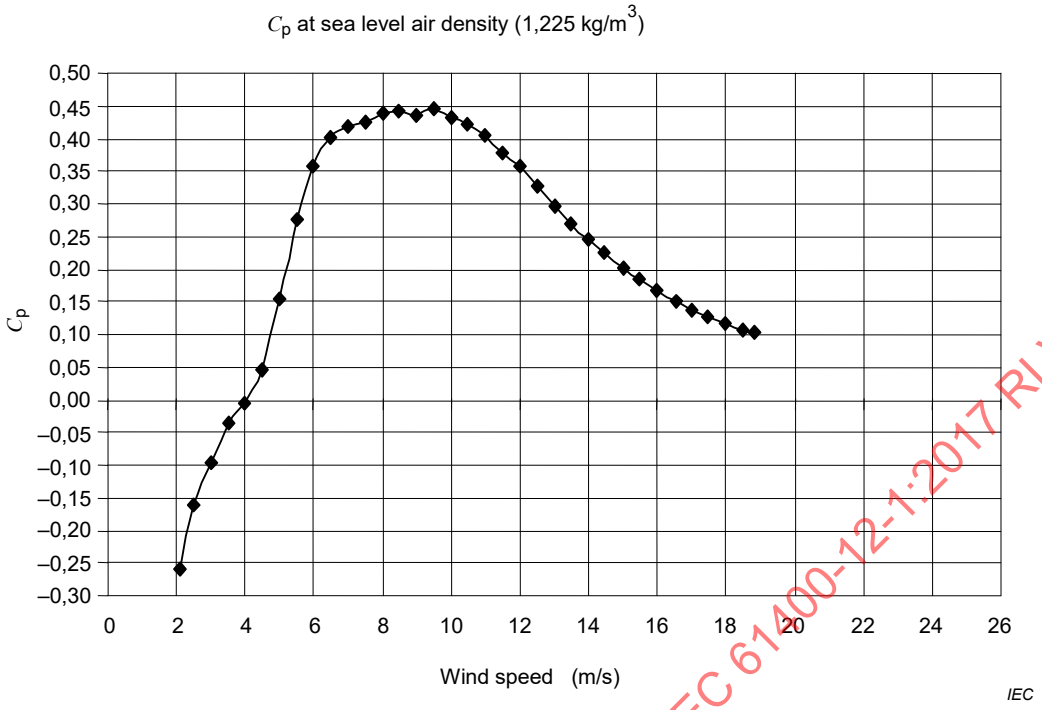
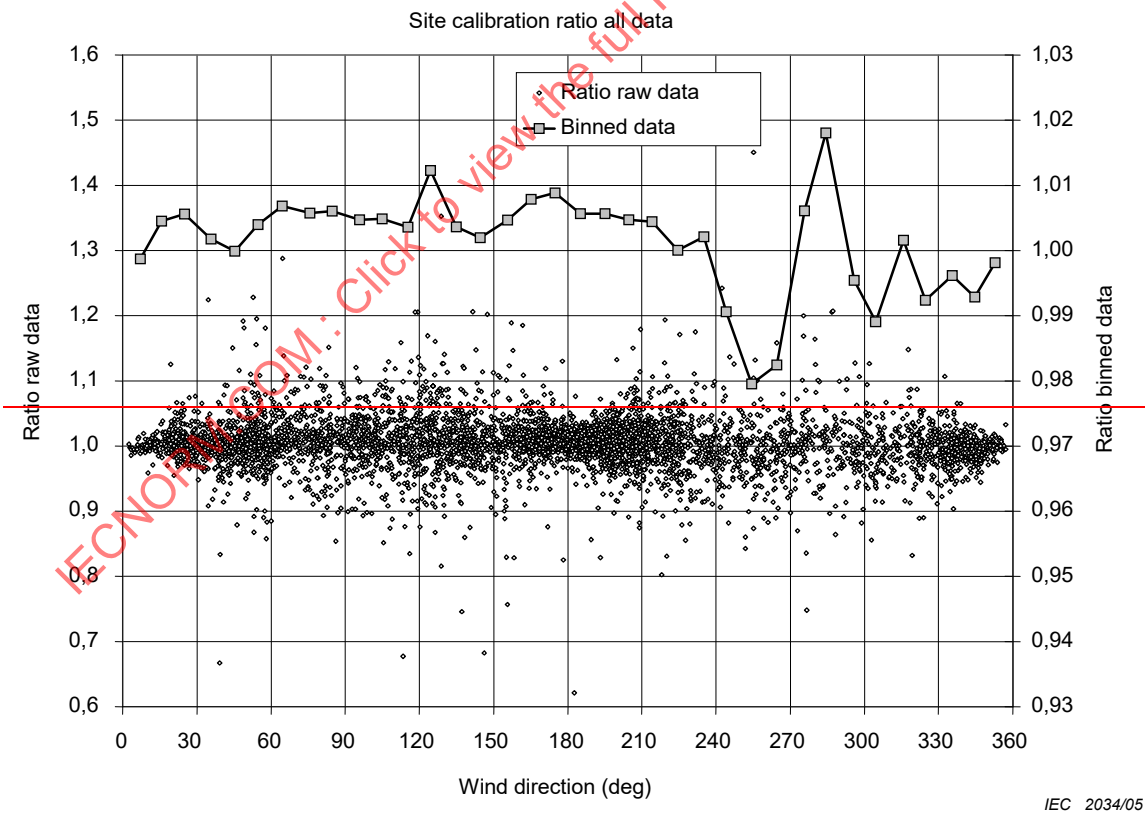


Figure 7 – Presentation of example C_P curve ~~for databases A and B~~



~~Figure 5 – Presentation of example site calibration (only the sectors 20° to 30°, 40° to 60°, 160° to 210° and 330° to 350° are valid sectors)~~

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Table 1 – Example of presentation of a measured power curve for database A

Measured power curve (database A)							
Reference air density: 1,225 kg/m³					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed	Power output	C_p	No. of data sets	Standard uncertainty s_i	Standard uncertainty u_i	Standard uncertainty u_{ci}
	m/s	kW		(10 min. avg.)	kW	kW	kW
4	2,1	–3,6	–0,26	138	0,05	6,3	6,3
5	2,5	–3,6	–0,16	275	0,04	6,3	6,3
6	3,0	–3,8	–0,10	270	0,13	6,3	6,3
7	3,5	–2,2	–0,03	320	0,56	6,3	6,3
8	4,0	–0,4	0,00	347	0,56	6,3	6,3
9	4,5	6,0	0,05	362	0,67	6,3	6,4
10	5,0	27,7	0,15	333	1,09	6,8	6,9
11	5,5	67,4	0,28	285	1,65	10,9	11,0
12	6,0	111,3	0,36	262	2,26	16,1	16,3
13	6,5	160,9	0,40	265	3,08	20,1	20,3
14	7,0	209,4	0,42	286	3,22	20,4	20,7
15	7,5	262,0	0,43	287	3,23	20,7	20,9
16	8,0	327,6	0,44	248	3,28	23,3	23,5
17	8,5	395,2	0,44	215	4,38	28,6	28,9
18	9,0	462,0	0,44	179	4,94	29,8	30,2
19	9,5	556,1	0,45	183	5,02	29,9	30,3
20	10,0	629,8	0,43	133	5,83	41,5	41,9
21	10,5	703,1	0,42	127	6,82	32,8	33,5
22	11,0	786,5	0,41	119	6,75	36,1	36,7
23	11,5	836,5	0,38	101	6,65	36,5	37,1
24	12,0	893,5	0,36	94	7,27	25,2	26,2
25	12,5	928,6	0,33	74	5,59	28,8	29,3
26	13,0	956,4	0,30	70	6,38	19,5	20,5
27	13,5	971,3	0,27	63	4,66	16,5	17,1
28	14,0	980,9	0,25	71	3,19	13,5	13,8
29	14,5	988,2	0,22	77	2,53	12,2	12,4
30	15,0	993,5	0,20	64	1,37	11,9	11,9
31	15,5	993,7	0,18	47	0,84	11,6	11,6
32	16,0	995,7	0,17	54	0,83	11,3	11,3
33	16,5	996,2	0,15	33	0,42	11,4	11,4
34	17,0	996,4	0,14	23	0,23	11,3	11,3
35	17,5	996,5	0,13	30	0,24	11,3	11,3
36	18,0	996,5	0,12	13	0,18	11,3	11,3
37	18,5	995,7	0,11	11	0,21	11,3	11,3
38	19,0	935,5	0,09	15	0,70	11,3	11,4
39	19,5	900,5	0,08	12	61,11	36,8	71,3
40	20,0	842,5	0,07	8	65,05	23,0	69,0
41	20,5	551,2	0,04	5	122,70	33,9	127,3
42	20,9	661,2	0,05	6	230,33	159,9	280,4
43	21,5	396,5	0,03	8	211,08	77,3	224,8
44	22,0	–6,3	0,00	6	176,06	144,4	227,7
45	22,6	494,3	0,03	4	0,03	224,5	224,5
49	24,6	–6,3	0,00	3	0,19	125,4	125,4
50	25,0	–6,3	0,00	3	0,04	6,3	6,3

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Table 2 – Example of presentation of a measured power curve for database B

Measured power curve (database B)							
Reference air density: 1,225 kg/m³					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed	Power output	C_p	No. of data sets	Standard uncertainty s_i	Standard uncertainty u_i	Standard uncertainty u_{ci}
	[m/s]	[kW]		(10 min. avg.)	[kW]	[kW]	[kW]
4	2,1	–3,6	–0,26	138	0,05	6,3	6,3
5	2,5	–3,6	–0,16	275	0,04	6,3	6,3
6	3,0	–3,8	–0,10	270	0,13	6,3	6,3
7	3,5	–2,2	–0,03	320	0,56	6,3	6,3
8	4,0	–0,4	0,00	347	0,56	6,3	6,3
9	4,5	6,0	0,05	362	0,67	6,3	6,4
10	5,0	27,7	0,15	333	1,09	6,8	6,9
11	5,5	67,4	0,28	285	1,65	10,9	11,0
12	6,0	111,3	0,36	262	2,26	16,1	16,3
13	6,5	160,9	0,40	265	3,08	20,1	20,3
14	7,0	209,4	0,42	286	3,22	20,4	20,7
15	7,5	262,0	0,43	287	3,23	20,7	20,9
16	8,0	327,6	0,44	248	3,28	23,3	23,5
17	8,5	395,2	0,44	215	4,38	28,6	28,9
18	9,0	462,0	0,44	179	4,94	29,8	30,2
19	9,5	556,1	0,45	183	5,02	29,9	30,3
20	10,0	629,8	0,43	133	5,83	41,5	41,9
21	10,5	703,1	0,42	127	6,82	32,8	33,5
22	11,0	786,5	0,41	119	6,75	36,1	36,7
23	11,5	836,5	0,38	101	6,65	36,5	37,1
24	12,0	893,5	0,36	94	7,27	25,2	26,2
25	12,5	928,6	0,33	74	5,59	28,8	29,3
26	13,0	956,4	0,30	70	6,38	19,5	20,5
27	13,5	971,3	0,27	63	4,66	16,5	17,1
28	14,0	980,9	0,25	71	3,19	13,5	13,8
29	14,5	988,2	0,22	77	2,53	12,2	12,4
30	15,0	993,5	0,20	64	1,37	11,9	11,9
31	15,5	993,7	0,18	47	0,84	11,6	11,6
32	16,0	995,7	0,17	54	0,83	11,3	11,3
33	16,5	996,2	0,15	33	0,42	11,4	11,4
34	17,0	996,4	0,14	23	0,23	11,3	11,3
35	17,5	996,5	0,13	30	0,24	11,3	11,3
36	18,0	996,5	0,12	13	0,18	11,3	11,3
37	18,5	995,7	0,11	11	0,21	11,3	11,3
38	19,0	996,6	0,10	14	0,59	11,3	11,3
39	19,4	996,1	0,09	10	0,21	11,3	11,3
40	20,0	994,1	0,09	5	0,41	11,3	11,3
41	20,5	987,4	0,08	2	2,67	11,4	11,7
42	20,9	996,9	0,08	3	3,38	11,8	12,3

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Table 4 – Example of presentation of a measured power curve

Measured power curve							
Reference air density: 1,225 kg/m^3					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed	Power output	C_P	No. of data sets	Standard uncertainty s_i	Standard uncertainty u_i	Standard uncertainty u_{ci}
	[m/s]	[kW]		(10 min. avg.)	[kW]	[kW]	[kW]
4	2,1	–3,6	–0,26	138	0,05	6,3	6,3
5	2,5	–3,6	–0,16	275	0,04	6,3	6,3
6	3,0	–3,8	–0,10	270	0,13	6,3	6,3
7	3,5	–2,2	–0,03	320	0,56	6,3	6,3
8	4,0	–0,4	0,00	347	0,56	6,3	6,3
9	4,5	6,0	0,05	362	0,67	6,3	6,4
10	5,0	27,7	0,15	333	1,09	6,8	6,9
11	5,5	67,4	0,28	285	1,65	10,9	11,0
12	6,0	111,3	0,36	262	2,26	16,1	16,3
13	6,5	160,9	0,40	265	3,06	20,1	20,3
14	7,0	209,4	0,42	286	3,22	20,4	20,7
15	7,5	262,0	0,43	287	3,23	20,7	20,9
16	8,0	327,6	0,44	248	3,28	23,3	23,5
17	8,5	395,2	0,44	215	4,38	28,6	28,9
18	9,0	462,0	0,44	179	4,94	29,8	30,2
19	9,5	556,1	0,45	183	5,02	29,9	30,3
20	10,0	629,8	0,43	133	5,83	41,5	41,9
21	10,5	703,1	0,42	127	6,82	32,8	33,5
22	11,0	786,5	0,41	119	6,75	36,1	36,7
23	11,5	836,5	0,38	101	6,65	36,5	37,1
24	12,0	893,5	0,36	94	7,27	25,2	26,2
25	12,5	928,6	0,33	74	5,59	28,8	29,3
26	13,0	956,4	0,30	70	6,38	19,5	20,5
27	13,5	971,3	0,27	63	4,66	16,5	17,1
28	14,0	980,9	0,25	71	3,19	13,5	13,8
29	14,5	988,2	0,22	77	2,53	12,2	12,4
30	15,0	993,5	0,20	64	1,37	11,9	11,9
31	15,5	993,7	0,18	47	0,84	11,6	11,6
32	16,0	995,7	0,17	54	0,83	11,3	11,3
33	16,5	996,2	0,15	33	0,42	11,4	11,4
34	17,0	996,4	0,14	23	0,23	11,3	11,3
35	17,5	996,5	0,13	30	0,24	11,3	11,3
36	18,0	996,5	0,12	13	0,18	11,3	11,3
37	18,5	995,7	0,11	11	0,21	11,3	11,3
38	19,0	996,6	0,10	14	0,59	11,3	11,3
39	19,4	996,1	0,09	10	0,21	11,3	11,3

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Measured power curve							
Reference air density: 1,225 kg/m^3					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed	Power output	C_P	No. of data sets	Standard uncertainty s_i	Standard uncertainty u_i	Standard uncertainty u_{ci}
	[m/s]	[kW]		(10 min. avg.)	[kW]	[kW]	[kW]
40	20,0	994,1	0,09	5	0,41	11,3	11,3
41	20,5	987,4[21]	0,08	2	2,67	11,4	11,7
42	20,9	996,9	0,08	3	3,38	11,8	12,3

~~**Table 3 – Example of presentation of estimated annual energy production (database A)**~~

~~Estimated annual energy production (database A) Reference air density: 1,225 kg/m^3 Cut-out wind speed 25 m/s (extrapolation by constant power from last bin)~~					
~~Hub height annual average wind speed (Rayleigh)~~	~~*AEP*-measured (measured power curve)~~	~~Standard uncertainty in *AEP*~~	~~Standard uncertainty in *AEP*~~	~~*AEP*-extrapolated (extrapolated power curve)~~	
~~m/s~~	~~MWh~~	~~MWh~~	~~%~~	~~MWh~~	
~~4~~	~~481~~	~~99~~	~~21~~	~~481~~	
~~5~~	~~1083~~	~~129~~	~~12~~	~~1083~~	
~~6~~	~~1825~~	~~152~~	~~8~~	~~1825~~	
~~7~~	~~2596~~	~~168~~	~~7~~	~~2596~~	
~~8~~	~~3305~~	~~181~~	~~6~~	~~3305~~	
~~9~~	~~3892~~	~~197~~	~~5~~	~~3892~~	
~~10~~	~~4329~~	~~216~~	~~5~~	~~4329~~	
~~11~~	~~4615~~	~~238~~	~~5~~	~~4615~~	

~~**Table 4 – Example of presentation of estimated annual energy production (database B)**~~

~~Estimated annual energy production (database B) Reference air density: 1,225 kg/m^3 Cut-out wind speed 25 m/s (extrapolation by constant power from last bin)~~					
~~Hub height annual average wind speed (Rayleigh)~~	~~*AEP*-measured (measured power curve)~~	~~Standard uncertainty in *AEP*~~	~~Standard uncertainty in *AEP*~~	~~*AEP*-extrapolated (extrapolated power curve)~~	
~~m/s~~	~~MWh~~	~~MWh~~	~~%~~	~~MWh~~	
~~4~~	~~481~~	~~99~~	~~21~~	~~495~~	

[21] The dataset in bin 41 is incomplete (less than three data sets), therefore, the power value in bin 41 for *AEP* calculation is interpolated as 995,7.

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~~5~~	~~1083~~	~~129~~	~~12~~	~~1097~~	
~~6~~	~~1825~~	~~152~~	~~8~~	~~1841~~	
~~7~~	~~2597~~	~~165~~	~~6~~	~~2621~~	
~~8~~	~~3307~~	~~170~~	~~5~~	~~3362~~	
~~9~~	~~3890~~	~~169~~	~~5~~	~~4026~~	
~~10~~	~~4318~~	~~163~~	~~4~~	~~4590~~	~~Incomplete~~
~~11~~	~~4591~~	~~156~~	~~4~~	~~5045~~	~~Incomplete~~

Table 5 – Example of presentation of estimated annual energy production

Estimated annual energy production **Reference air density: 1,225 kg/m^3** **Cut-out wind speed: 25 m/s** **(extrapolation by constant power from last bin)**					
Hub height annual average wind speed (Rayleigh)	***AEP*-measured (measured power curve)**	**Standard uncertainty in *AEP***	**Standard uncertainty in *AEP***	***AEP*-extrapolated (extrapolated power curve)**	
m/s	MWh	MWh	%	MWh	
4	480	82	17	480	
5	1081	113	10	1 081	
6	1 824	138	8	1 824	
7	2 595	155	6	2 603	
8	3 305	163	5	3 342	
9	3 889	165	4	3 995	
10	4 318	162	4	4 536	
11	4 592	157	3	4 954	Incomplete

NOTE The standard uncertainty figures in the above tables are based on a coverage factor of 1. This implies that the level of confidence (percentage of times in repeated power curve measurements the intervals will contain the "true" *AEP* value) is in the order of 58 % to 68 %. The level of confidence is only an estimate since detailed knowledge of the probability distribution of the measurand is normally not known. The upper value (68 %) applies to normal distributions and the lower value (58 %) applies to rectangular distributions.

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Annex A
(normative)

Assessment of influences caused by wind turbines and obstacles at the test site

A.1 General

Annex A describes a procedure to determine one or more sectors which are not usable for the test because the flow at the wind turbine under test and/or the flow at the position of the wind measurement equipment (WME: a meteorological mast or a remote sensing device) might be affected by an operating wind turbine and/or by an obstacle.

The procedure consists of two steps, to be applied in the following order[22]:

a) evaluation of influences caused by operating wind turbines (wind turbine under test, as well as neighbouring and operating wind turbines), as described in Clause A.2;

b) evaluation of influences caused by obstacles, as described in Clause A.3 (under consideration of the special requirements for extended obstacles, as described in Clause A.5).

The valid sector which remains after this procedure shall be used for the terrain assessment according to Annex B.

The purpose of site calibration is generally to measure the change in the boundary layer as it follows the orography, which is generally attached flow, whereas obstacles often generate more turbulent wakes associated with them, which are affected by sharp edges and vertical surfaces that may trigger flow separation. A site calibration does not typically work well for correcting the effects of flow separation. This should be considered when deciding whether to treat an object as an obstacle or as terrain as flow separation and highly turbulent wakes are to be avoided. With this in mind, it is recommended that an object (including orographic elements which satisfy the dimensional criteria) whose height is more than half of its width be treated as an obstacle.

A.2 Requirements regarding neighbouring and operating wind turbines

The WME shall not be influenced by the wind turbine under test. The wind turbine under test and the ~~meteorological mast~~ WME shall not be influenced by neighbouring operating wind turbines. If a neighbouring wind turbine is operated at any time during the power performance test, its wake shall be determined and accounted for as described in this annex (using the calculation given in Clause A.4). Small wind turbines of total height less than (2/3)(H – D/2) shall be treated as obstacles, and accounted for as described in Clause A.3.

If a wind turbine is stopped at all times during the power performance test, it shall be considered as an obstacle and accounted for as described in Clause A.3.

The minimum distance from the wind turbine under test and the ~~meteorological mast to~~ neighbouring and operating wind turbines shall be two rotor diameters D_n of the neighbouring wind turbine ~~or two rotor diameters of the wind turbine under test if it has a larger diameter~~. The minimum distance from the WME to any neighbouring and operating wind turbine shall be two rotor diameters of the respective wind turbine. The sectors to exclude due to wakes from neighbouring and operating wind turbines shall be taken from Figure A.1. The dimensions to be taken into account are the actual distance L_n and the rotor diameter D_n of the neighbouring

22 Note that step b) requires the preliminary measurement sector, which is the result of step a).

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and operating wind turbine. The sectors to be excluded shall be derived for both the wind turbine under test and the ~~meteorological mast~~ WME, and they shall be centred on the direction from the neighbouring and operating wind turbine to the ~~meteorological mast~~ wind measurement equipment or the wind turbine. An example is shown in Figure A.2.

A.3 Requirements regarding obstacles

Obstacles near the wind turbine under test or near the WME shall be evaluated. Each obstacle shall be evaluated either as part of the orography (as described in Annex B[23]), or – alternatively – according to the procedure which is described here as follows.

No significant obstacles (e.g. buildings, trees, parked wind turbines) shall exist in the measurement sector within a reasonable distance from the wind turbine ~~and meteorological mast~~ or from the WME. Only small buildings, connected to the wind turbine operation or the wind measurement equipment, are acceptable. Where significant obstacles are present then the measurement sector shall be reduced as described in Clause A.4 and A.5.

The criterion for the significance of an obstacle (with respect to the wind turbine under test and/or with respect to the WME) is to exceed one or more of the limits given in Table A.1, where Table A.1 shall be applied for all locations:

a) for the evaluation of the surroundings of the wind turbine under test (i.e. using the centre of the wind turbine under test as centre of the $2L$, $4L$, $8L$, and $16L$ circles);

b) for the evaluation of the surroundings of the WME (i.e. using the position(s) of the equipment as centre of the $2L$, $4L$, $8L$, and $16L$ circles)

Table A.1 – Obstacle requirements: relevance of obstacles

Distance[a]	Sector[b]	Maximum obstacle height from terrain surface[c]
$<2L$	360°	$<1/3\ (H - 0{,}5\ D)$
$\geq 2L$ and $< 4L$	Preliminary measurement sector	$<2/3\ (H - 0{,}5\ D)$
$\geq 4L$ and $<8L$	Preliminary measurement sector	$<(H - 0{,}5\ D)$
$\geq 8L$ and $<16L$	Preliminary measurement sector	$<4/3\ (H - 0{,}5\ D)$
$\geq 2L$ and $<16L$	Clearly outside preliminary measurement sector by 40° or more	No limit to height

a from obstacle to wind turbine under test, respectively from obstacle to WME – whereas L is the horizontal distance between wind turbine under test and wind measurement equipment.

b *Preliminary measurement sector* shall be understood here as the valid sector which remains after evaluation of neighbouring operating wind turbines (as described in Clause A.2, using the calculation described in Clause A.4), whereas all directions which are less than 40° outside shall also be considered.

c H is the hub height and D is the rotor diameter of the wind turbine under test.

~~The influence of an obstacle on the met mast or turbine position at the height z is estimated by~~

$$\Delta U_z / U_h = -9{,}75\ (1 - P_0)\frac{h}{x}\eta \exp\left(-0{,}67\eta^{1{,}5}\right) \qquad \text{(A.1)}$$

23 The consideration of an obstacle in this way will typically increase mainly the terrain variation, whereas the effect on the slope might be very small (except for extended obstacles, e.g. forests).

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~~An obstacle model is used to predict the influence of obstacles upon the mast and the turbine position at hub height. The criteria for determining a significant obstacle is that the flow is affected by 1 % or more between the turbine position at hub height and the met mast at hub height for any wind direction in the measurement sector.~~

$$\eta = \frac{H}{h}\left(K\frac{x}{h}\right)^{\frac{-1}{n+2}} \quad \text{(A.2)}$$

$$K = \frac{2\kappa^2}{\ln\frac{h}{z_0}} \quad \text{(A.3)}$$

~~where~~

~~x distance downstream obstacle to met mast or wind turbine [m]~~

~~h height of obstacle [m]~~

~~U_h free wind speed at height h of obstacle [m/s]~~

~~n velocity profile exponent (n=0,14)~~

~~P_0 porosity of obstacle (0: solid, 1: no obstacle)~~

~~H hub height [m]~~

~~z_0 roughness length [m]~~

~~κ von Karman constant 0,4~~

A.4 Method for calculation of sectors to exclude

The wind turbine under test shall always be evaluated according to Figure A.1 with respect to its wake influence on the WME.

A neighbouring and operating wind turbine shall always be evaluated according to Figure A.1 with respect to its wake influence on the wind turbine under test and also with respect to its wake influence on the WME.

With respect to operating wind turbines, the dimensions to be taken into account are the actual distance L_n (from centre of wind turbine under test to the position of the WME) and the rotor diameter D_n of the wind turbine that causes the wake[24].

An obstacle shall be evaluated according to Figure A.1 with respect to its wake influence on the wind turbine under test if the obstacle is significant with respect to the wind turbine under test according to Table A.1.

An obstacle shall be evaluated according to Figure A.1 with respect to its wake influence on the WME if the obstacle is significant with respect to the WME according to Table A.1.

~~Sectors with a significant obstacle shall be excluded with reference to Figure A.1. The dimensions to be taken into account are the actual distance L_e and an equivalent rotor diameter D_e of the obstacle.~~ With respect to obstacles, the dimensions to be taken into account are the actual horizontal distance L_e (from the centre of wind turbine under test or

[24] The influence of the turbine under test on the WME is evaluated by means of L (distance between turbine under test and wind measurement equipment) and D (rotor diameter of turbine under test).

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from the position of the WME as appropriate) and an equivalent rotor diameter D_e of the obstacle. A stopped neighbouring wind turbine may be treated as a cylinder with a diameter equal to the tower base diameter and a height equal to the upper tip height. The equivalent rotor diameter of the obstacle shall be defined as:

$$D_e = \frac{2 l_h l_w}{l_h + l_w} \quad \text{(A.1)}$$

where

D_e is the equivalent rotor diameter;

l_h is the height of obstacle;

l_w is the width of obstacle as seen from the wind turbine under test or from the WME.

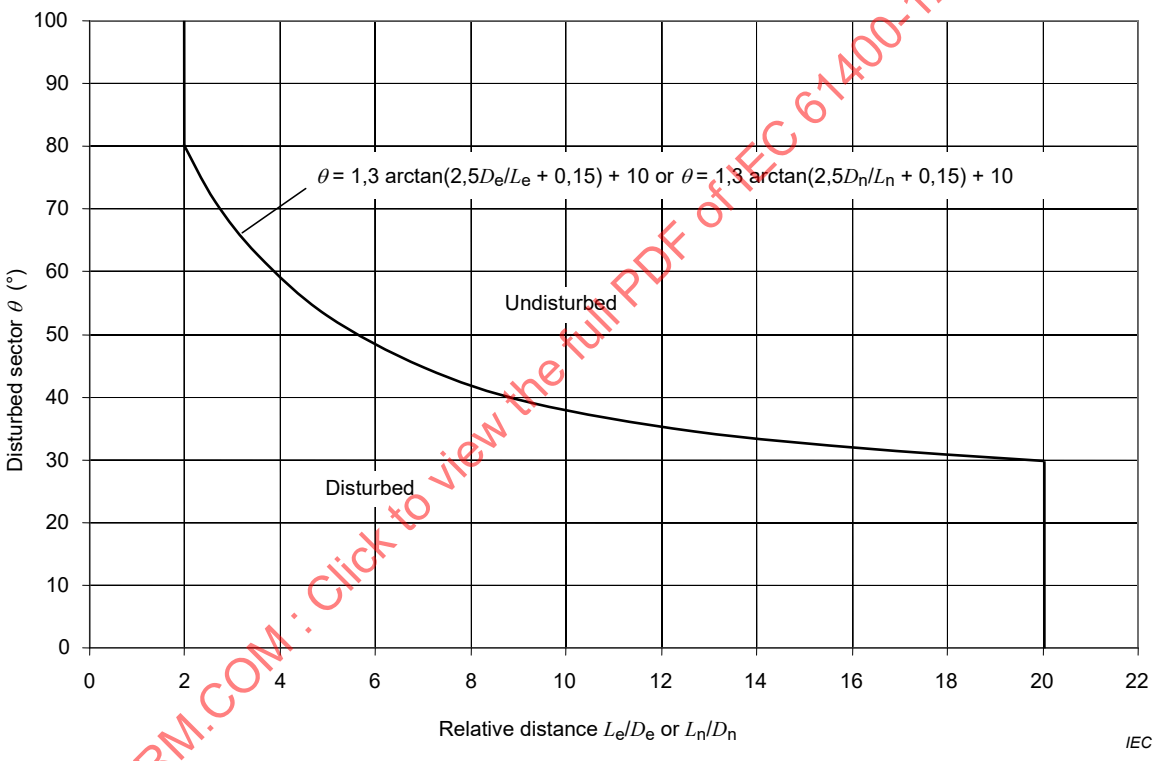

Figure A.1 – Sectors to exclude due to wakes of neighbouring and operating wind turbines and significant obstacles

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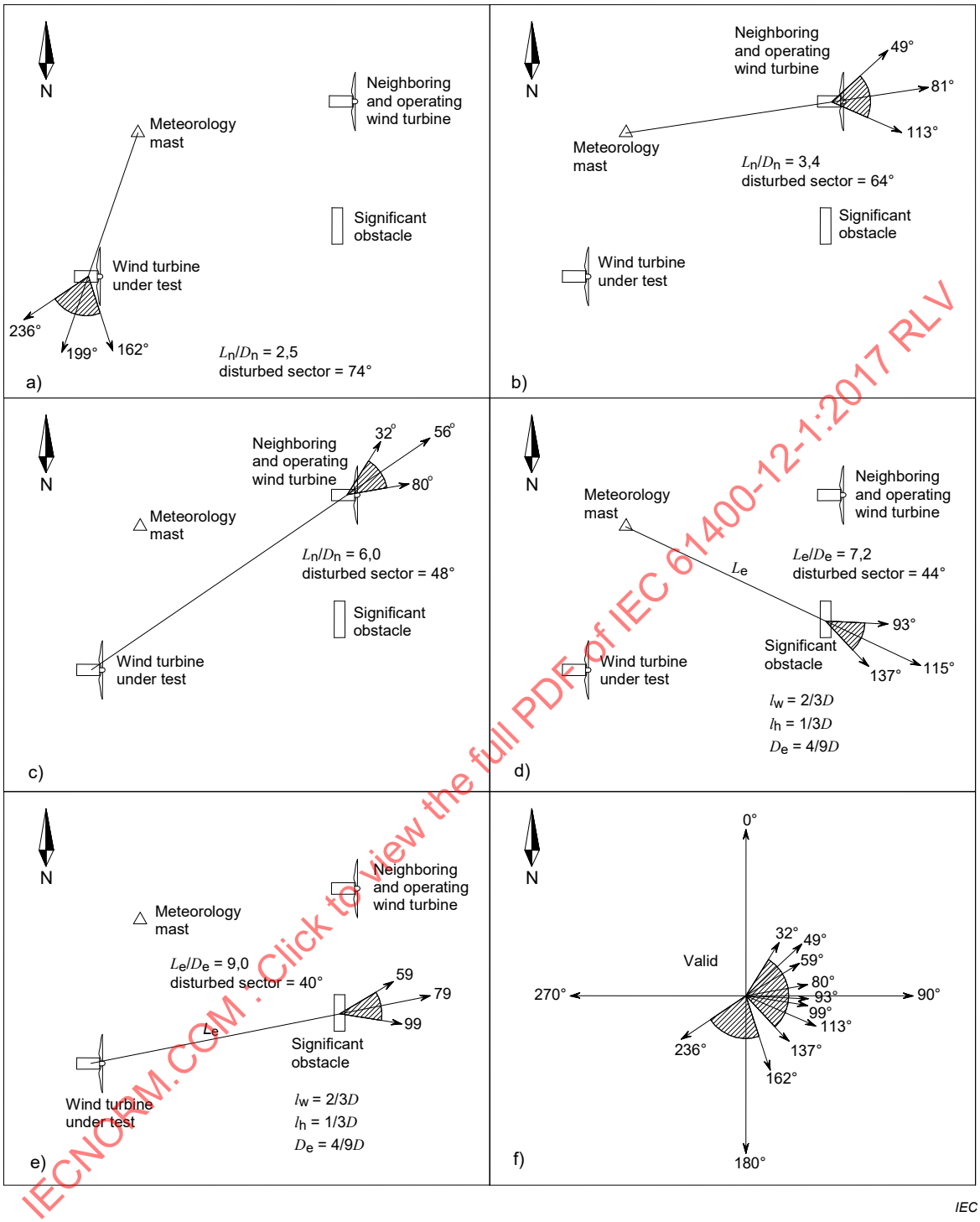

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Figure A.2 – An example of sectors to exclude due to wakes of the wind turbine under test, a neighbouring and operating wind turbine and a significant obstacle

The figures show the sectors to exclude if:

a) the WME (meteorological mast or remote sensing device) is in the wake of the wind turbine under test;

b) the ~~meteorological mast~~ WME is in the wake of the neighbouring and operating wind turbine;

c) the wind turbine under test is in the wake of the neighbouring and operating wind turbine;

d) the ~~meteorological mast~~ WME is in the wake of the significant obstacle;

e) the wind turbine under test is in the wake of the significant obstacle;

f) all of the above effects a) to e) are combined.

NOTE The example shown in Figure A.2 is based on the assumption that the obstacle is significant (according to Table A.1) with respect to the wind turbine under test and also significant with respect to the wind measurement equipment.

A.5 Special requirements for extended obstacles

Obstacles within a distance of less than $4L$ (from centre of the wind turbine under test or from the wind measurement equipment) which extend more than 50 m in any horizontal direction shall be divided into partial obstacles that do not extend more than 50 m in any horizontal direction and exactly 50 m in any dimension that is more than 50 m. These partial obstacles may overlap each other. The combination of these partial obstacles shall at least[25] cover the original obstacle completely. Each partial obstacle shall be evaluated separately. The significance of each partial obstacle shall be assessed, and if it is found to be significant, the sector to be excluded shall be determined. For example:

a) An obstacle 90 m by 90 m is divided into 4 partial obstacles 50 m by 50 m each. These partial obstacles are chosen such that they overlap each other by 10 m so that the set union of the 4 partial obstacles is identical to the original obstacle.

b) An obstacle 70 m by 10 m is divided into 2 partial obstacles 50 m by 10 m each. These partial obstacles are chosen such that they overlap each other by 30 m so that the set union of the 2 partial obstacles is identical to the original obstacle.

A grouping of trees or forest shall be treated in this way.

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25 For practical purposes, it makes sense to create partial obstacles which all have the same shape (e.g. squares of 50 m x 50 m). This is a conservative approach and therefore permitted. (In this case, the set union of all partial obstacles covers a larger area than the original obstacle.)

Annex B
(normative)

Assessment of terrain at the test site

For testing without a site calibration (in terrain which is defined as “flat terrain”), ~~the terrain at the test site may only show minor variations from a plane, which passes both through the base of the tower of the wind turbine, and the terrain within the sectors~~ the following criteria shall be kept (see Figure B.1 and Table B.1 for details):

– orography at the test site may only show minor variations from a plane, which passes both through the base of the tower of the wind turbine, and the terrain within the respective sector;

– each of these planes shall not exceed a certain limit for the slope.

The assessment of the terrain shall be made using a digital model of the terrain with a grid resolution of 30 m or finer.

Table B.1 shall be applied for the locations below for the measurement sector:

a) for the evaluation of the surrounding of the wind turbine under test (i.e. using the centre of the wind turbine under test as centre of the $2L$, $4L$, $8L$, and $16L$ circles);

b) for the evaluation of the surrounding of the WME (i.e. using the position of the equipment as centre of the $2L$, $4L$, $8L$, and $16L$ circles).

If the terrain complies with all of the requirements of Table B.1 in both cases, then no site calibration is required[26] due to orography. Otherwise the terrain is defined as “complex terrain” and a site calibration measurement is required.

~~If the terrain characteristics are within an additional 50 % of the limits of the maximum slopes shown in Table B.1, then a flow model can be used to determine if a site calibration measurement can be avoided. The flow model shall be validated for the type of terrain. If the flow model shows a difference in wind speed between the anemometer position and the turbine's hub less than 1 % at 10 m/s for the measurement sectors, then no site calibration measurement is required.~~

In Table B.1, L is the distance between the wind turbine and the WME, H is the hub height and D is the rotor diameter (of the wind turbine under test).

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26 Nevertheless, other aspects of the terrain such as roughness, distance to the sea coast, or other considerations, may lead to the conclusion that a site calibration is recommended.

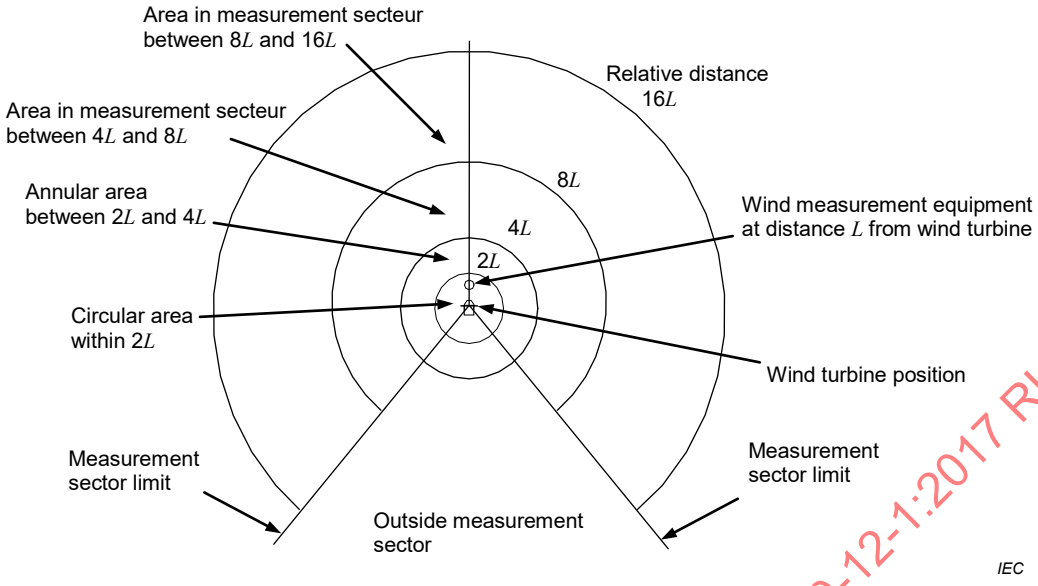

Figure B.1 – Illustration of area to be assessed, top view

Table B.1 – Test site requirements: topographical variations

Distance	Sector[a]	Maximum slope %	Maximum terrain variation from plane
<2L	360°	<3[b]	~~<0,04 $(H+D)$~~ <1/3 $(H - 0,5\ D)$
≥2L and < 4L	Measurement sector	<5[b]	~~<0,08 $(H+D)$~~ <2/3 $(H - 0,5\ D)$
≥2L and <4L	Outside measurement sector	<10[c]	Not applicable
≥4L and <8L	Measurement sector	<10[b]	~~<0,13$(H+D)$~~ < $(H - 0,5\ D)$
≥8L and <16L	Measurement sector	<10[c]	Not applicable

a Measurement sector is understood here by default as the remaining valid sector after execution of the procedure defined in Annex A, whereas it is also allowed to use a smaller measurement sector[27].

b The maximum slope of the plane, which provides the best fit to the terrain in the sector being considered and passes through the tower base. See Figure B.2 for an example.

c The line of steepest slope that connects the tower base to individual terrain points on the surface of the terrain within the sector. See Figure B.3 for an example.

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27 It is additionally recommended to check if significant terrain variation exists slightly outside the borders of this sector. If this is the case, the final sector which is considered for the power performance test should keep a clear directional distance to these critical directions.

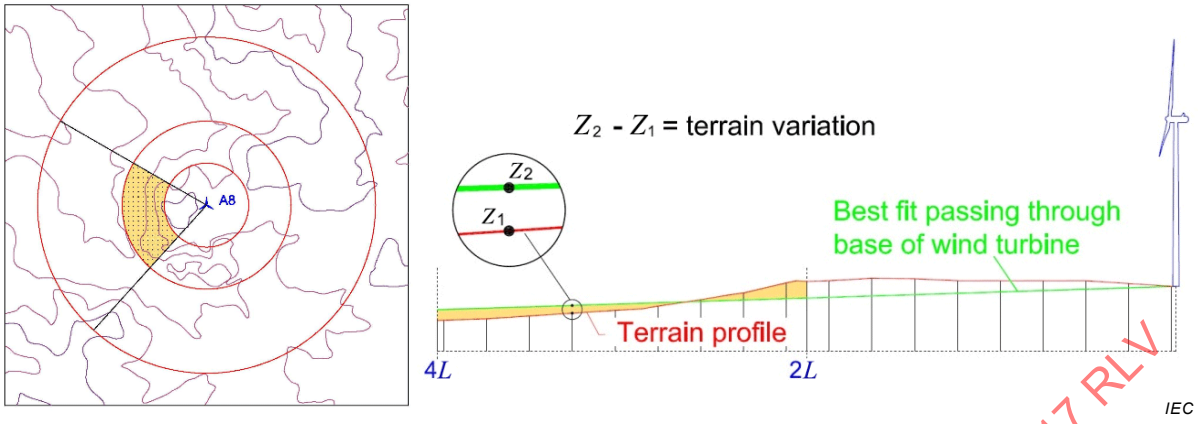

Figure B.2 – Example of determination of slope and terrain variation from the best-fit plane: "2*L* to 4*L*" and the case "measurement sector" (Table B.1, line 2)

NOTE 1 This figure shows just one direction. All directions within the measurement sector are considered for the calculation of the plane which provides the best fit, and then the maximum terrain variation against this plane is determined by analysing all directions as shown above.

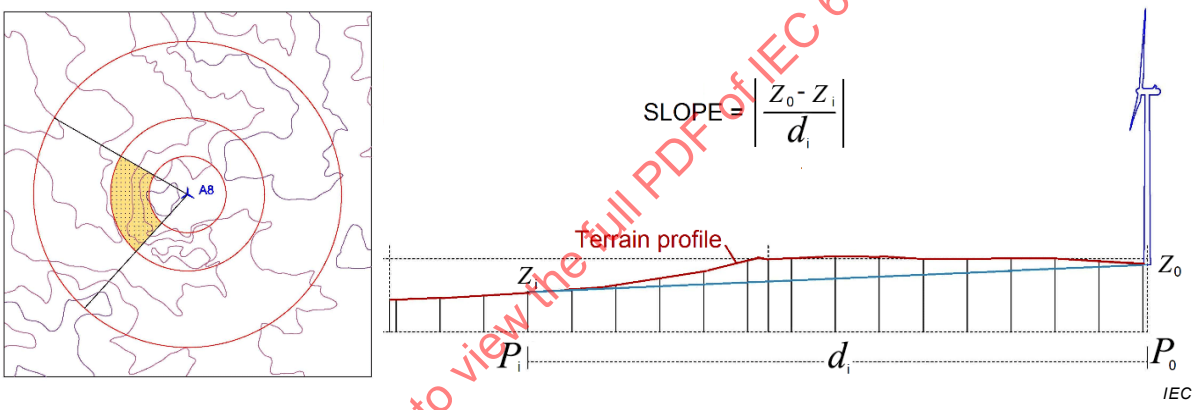

Figure B.3 – Determination of slope for the distance "2*L* to 4*L*" and "8*L* to 16*L*" and the case "outside measurement sector" (Table B.1, line 3 and line 5)

NOTE 2 This figure shows just one direction. All directions outside the measurement sector are analysed in the same way, and the worst-case result (i.e. highest slope) is considered.

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Annex C
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Site calibration procedure

C.1 General

A site calibration quantifies and potentially reduces the effects of terrain ~~and obstacles~~ on the power performance measurement. Terrain ~~and obstacles~~ may cause a systematic difference in wind speed between the position on the meteorological mast where the power performance anemometer is mounted and the equivalent height above ground at the centre of the turbine rotor at the turbine position. In addition, the relationship between the reference meteorological mast wind speed and the wind speed at the turbine position may also be affected by changes in atmospheric stability and/or the shear profile. Wind shear, which is the change in wind speed with height above the ground, may be also an influential parameter on this relationship as different shear profiles may cause a different relationship between the measurement points, especially if the turbine and met mast are at different elevations.

~~A key result of a site calibration test is a table of flow correction factors for all wind directions in the measurement sector. Another result is an estimate of the uncertainty of these correction factors. The test may provide information that justifies a change to the allowable measurement sector.~~

Seasonal considerations: atmospheric stability, turbulence and wind shear can be related to different seasonal conditions. There are also concerns of the effects of changes in roughness due to changes in the vegetation in the testing area or other roughness changes directly caused by different seasonal surface characteristics (water/land vs. ice/land, snow, crops, etc.…). In light of these considerations, the site calibration and power curve measurement should be conducted during the same season or seasons. If the measurements are conducted in different seasons, additional uncertainty shall be applied as discussed in Clause C.7.

The outputs of the site calibration are:

a) a table of flow corrections for all wind directions within the measurement sector(s) and

b) an estimate of the standard uncertainty of these flow corrections.

There are two distinct methods in which the site calibration may be evaluated. Only one method is required, where the method is chosen by evaluating the data to assess shear as discussed in C.5.1. The output for each method is:

1) Subclause C.5.2 Site calibration with shear: the flow corrections consist of a matrix of wind direction bins and wind shear bins where a single wind speed ratio correction factor is calculated for each point in the matrix.

2) Subclause C.5.3 Site calibration where shear is not a significant influence: the flow corrections consist of a slope and an intercept value for each wind direction bin. The coefficient of determination, r^2, value for the regression shall also be reported.

This procedure is given for the wind speed defined as the hub height wind speed. This is so that the procedure does not mandate upper tip height meteorological masts, which are expensive and may be impractical, as remote sensing devices may not be suitable for measurements in complex terrain. However, where a power curve is to be derived for the REWS definition of wind speed, then the procedure is repeated for each pair of measurement heights rather than just for the hub height on each meteorological mast.

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C.2 Overview of the procedure

Prior to the installation of the wind turbine (or after the removal of it if already existing) two meteorological masts shall be erected. One meteorological mast is the reference position meteorological mast, which will also be used for the power performance test. The second meteorological mast is a wind turbine meteorological mast at the wind turbine position.

This procedure intends to characterize the correlation of the wind speeds between the two positions. Further recommendations for the selection of these positions are provided in C.3.1.

The flowchart in Figure C.1 provides a general overview of the preparation and analysis process.

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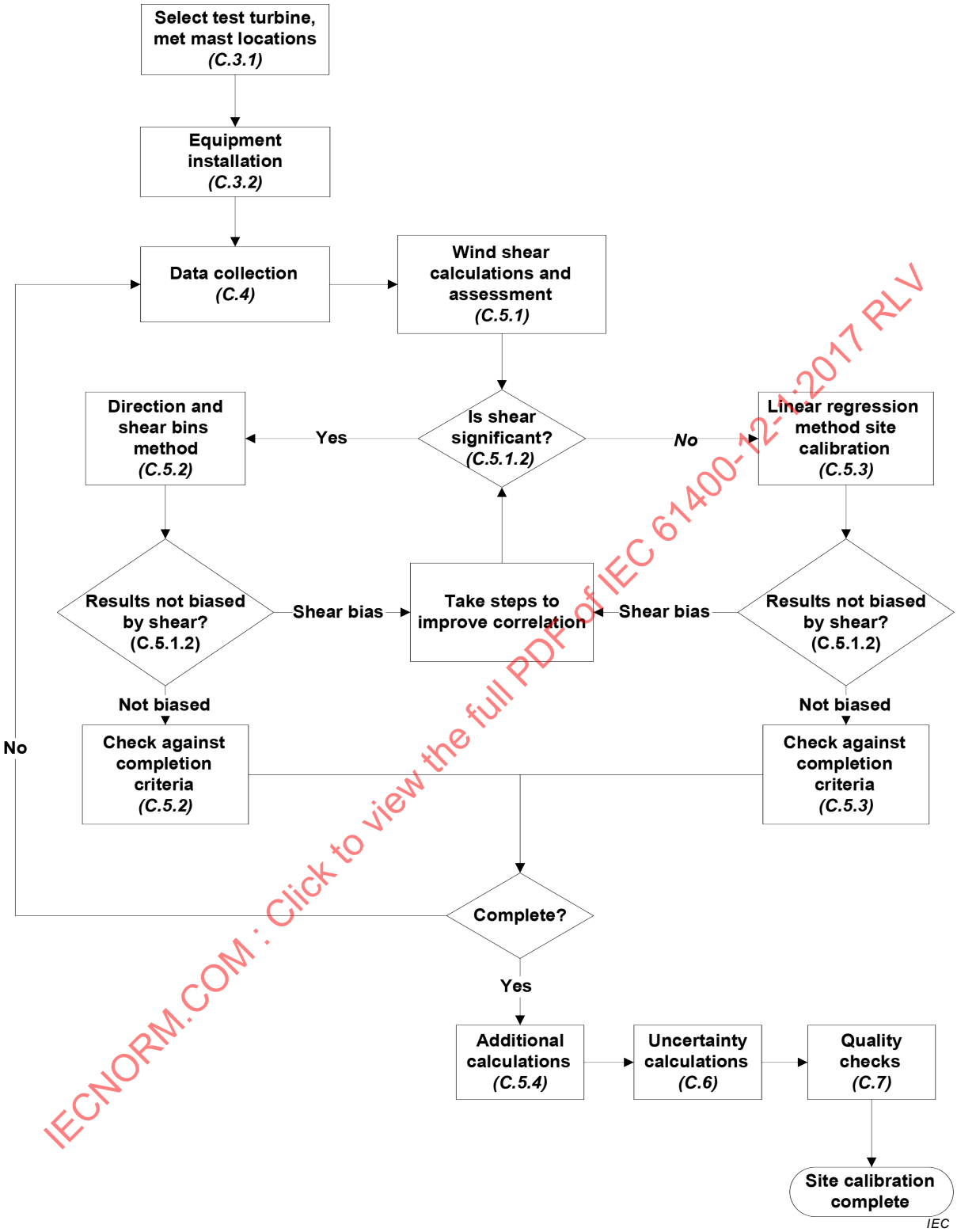

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Figure C.1 – Site calibration flow chart

C.3 Test set-up

C.3.1 Considerations for selection of the test wind turbine and location of the meteorological mast

~~Prior to the installation or after removal of the wind turbine two meteorological masts shall be erected. One mast is the reference position meteorological mast to be used also for the power performance test. The second mast is the turbine position mast. The test set-up requires two anemometers, a wind vane and a data processing/recording system. The reference position anemometer and the wind vane shall be mounted on the meteorological mast that is also used for power performance testing. The turbine position anemometer shall be mounted on a temporary mast as close as possible to the position where the turbine's hub will be or was located. This anemometer shall be within 2,5 % of hub height and the mast as close as possible to the turbine tower centre-line but no more than 0,2 H from the centre-line where H is the turbine hub height. A second wind vane may be mounted on the temporary mast at the turbine position to provide additional information on flow distortion at the site.~~

~~Sensors used in the site calibration test shall meet the requirements of Clause 6. The anemometers shall be of the same type with the same operating characteristics. The anemometers shall be calibrated during the same anemometer calibration campaign. The meteorological mast instrumentation should be the same for the power curve measurement as for site calibration. If this is not the case, the added uncertainty shall be taken into account.~~

The reference meteorological mast shall be the same meteorological mast that is used for power curve measurement. The wind turbine meteorological mast shall be located as close as possible to the position where the test wind turbine will be or was located and shall be no more than 0,2 H from the centreline of the wind turbine where H is the wind turbine hub height. It is recommended that the wind turbine and reference meteorological masts be of the same type and have the same boom geometry so as to have similar mounting effects on the WME.

There are a number of factors that can affect site calibration. The most notable of these are terrain, meteorological mast location, and atmospheric conditions including wind shear, turbulence and stability. These factors can vary significantly from one location to another but are often correlated with each other.

The test wind turbine location should be selected to optimise valid data collection and provide a good correlation between the reference and wind turbine meteorological masts. The purpose of site calibration is to measure the change in the boundary layer as the wind follows the orography of the terrain, which is generally attached flow, whereas obstacles have more turbulent wakes associated with them, which are affected by sharp edges and vertical surfaces that may trigger flow separation. Additionally, certain terrain features such as cliffs or steep hills may also cause the flow to separate, resulting in a poor correlation. As a guide, the terrain type should be taken into consideration when selecting the test wind turbine and the reference meteorological mast location. The terrain types discussed here are informative, qualitative descriptions to aid selection of the test wind turbine and reference meteorological mast locations and to provide insight on what to expect when conducting measurements in these terrain types. Examples of these terrain types are illustrated in Figure C.2.

Type A:

Type A terrain is the least complex terrain type. A Type A site typically does not have significant changes in elevation relative to the hub height of the wind turbine or particularly steep slopes over long distances. Examples of Type A terrain include terrain that meets the requirements of Annex B, gentle rolling hills, and possibly wind turbines located on a ridge facing a plain.

When conducting site calibrations at Type A sites, the wind shear conditions at the reference meteorological mast may be different from the wind shear conditions at the wind turbine

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location. If this is the case, then the site calibration results will likely be dependent on wind shear and wind direction.

Type B:

Type B terrain is moderate to complex terrain. Type B terrain includes mountains, ridgelines, large hills, and hilly sites with moderate to steeply sloping terrain and significant changes in elevation relative to the hub height of the wind turbine. Typically the wind shear at Type B sites is low and relatively consistent, though at times negative wind shear may occur. Thus wind shear is not expected to be as significant a factor as for Type A sites. However, at Type B sites the site calibration results often depend on both wind speed and wind direction, especially if the difference in elevation between the reference meteorological mast and the test wind turbine is more than 10 m. Thus a linear regression correction is often appropriate for a Type B site.

The upflow/vertical wind speed component induced by the terrain at Type B sites can have a significant impact on the uncertainty, depending on the response of the anemometers to upflow. A vertical wind speed measurement may be used to assess the upflow angle, which can then be used in conjunction with the anemometer classification report to calculate an S-type anemometer operational characteristic with user-defined influence parameter ranges as defined in Clause I.3.

Type C:

Type C terrain includes the most extreme terrain from a measurement perspective. Type C sites typically have a steep terrain feature such as a mountain or canyon that may cause flow separation directly upwind of the test wind turbine and create a recirculation zone at the test wind turbine location. The scale of the flow separation is defined by the terrain feature and may disrupt the wind speed correlation between the test wind turbine and reference meteorological mast even if the terrain feature is located farther than $16L$ away from the test wind turbine. Type C terrain is typically so complex that the correlation between the winds at the reference meteorological mast and the test wind turbine may be poor. The flow corrections may differ significantly between adjacent wind direction bins. Caution shall be taken when selecting test wind turbines at Type C terrain locations because the data will typically have very high scatter and high uncertainty in the result.

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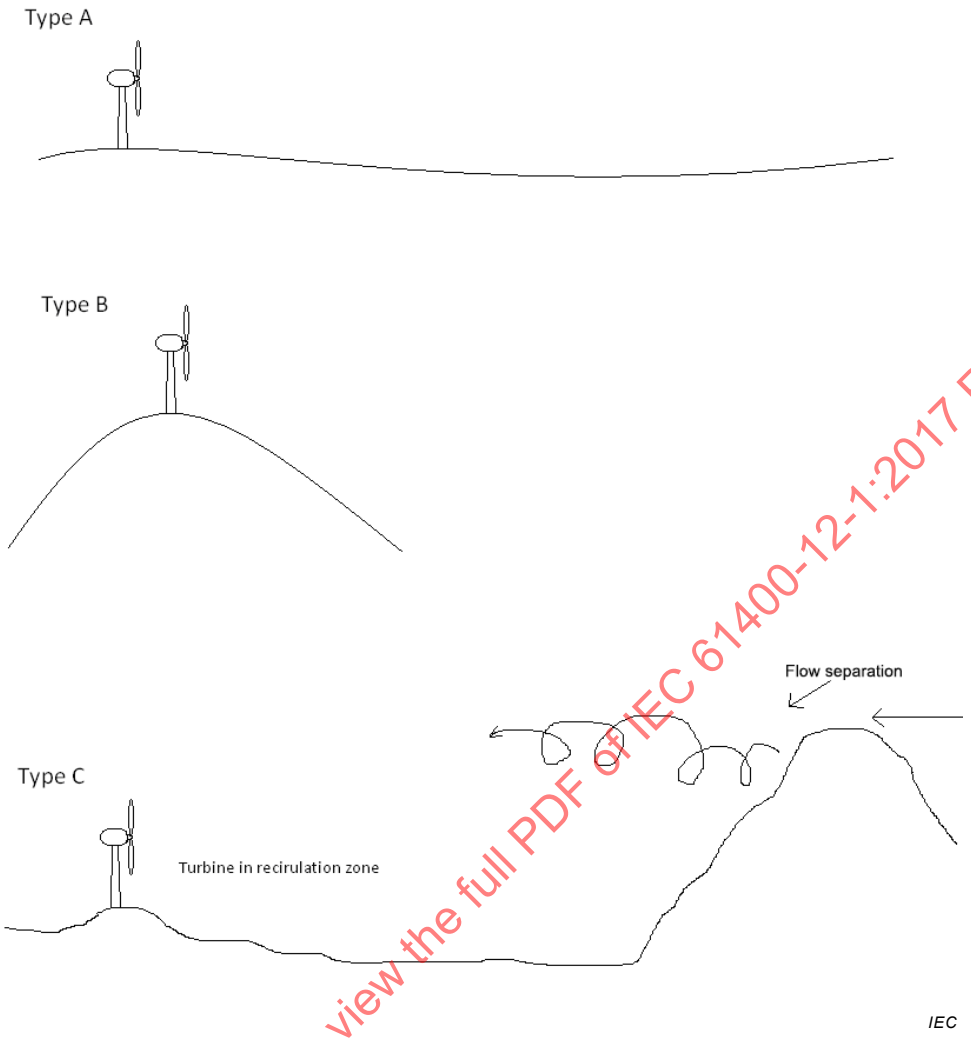

Figure C.2 – Terrain types

In order to improve the correlation, the reference meteorological mast should be located such that it has a similar elevation and wind conditions as those of the test wind turbine. For example, if the test wind turbine is located on a ridge, then the reference meteorological mast is recommended to be located on the ridge next to the wind turbine instead of at a lower elevation in front of the wind turbine.

C.3.2 Instrumentation

The test set-up requires as a minimum measurements of hub height wind speed, wind direction near hub height, and wind shear at both meteorological masts according to 7.2.8.

WME used in the site calibration shall meet the requirements of 7.2 and follow the guidelines for mounting of Annex G. The anemometers shall be of the same type with the same operating characteristics and shall be calibrated in the same wind tunnel. The anemometers shall be of the same type with the same operating characteristics for the power curve measurement as for site calibration.

Depending on the site characteristics, additional measurements are recommended so as to provide more information about the site conditions and thus are not normative. These measurements may also be used to improve the overall quality of the site calibration and power curve measurement by identifying unusual atmospheric conditions that correlate with outliers or may be used to determine the right instrument classification and in conjunction with

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the relevant classification report quantify the site-specific anemometer operational characteristic standard uncertainty:

a) A vertical wind speed measurement (e.g. using a 3D ultrasonic anemometer) is recommended within 10 % of hub height or within 5 m of hub height for smaller wind turbines so as not to violate the mounting requirements of Annex G for top mounted sensors. This measurement may be used to determine the correct class for the instrument classification and in conjunction with the instrument classification report to quantify the uncertainty due to operational characteristics in accordance with Annex I.

b) A wind veer measurement is recommended with the lower wind direction measured within 10 m of the lower tip height wind speed measurement;

c) If icing conditions are expected during the site calibration campaign, a temperature sensor or other means for icing detection is recommended near hub height.

Furthermore, to avoid the introduction of bias in the wind direction measurement due to uncertainty of the wind direction sensor installation, the reference meteorological mast and its wind direction sensor(s) should not be removed between the site calibration and the power curve measurement. If the primary wind direction sensor is removed or replaced, an additional uncertainty component shall be included (see C.7.4). If the reference meteorological mast is removed and re-installed between the site calibration and the power curve measurement, the instruments shall be mounted in the same configuration and with the same boom angles during both periods so as to have similar mounting effects.

C.4 Data acquisition and ~~analysis~~ rejection criteria

Data shall be collected continuously at the same sampling rate as for the power performance test. Data sets shall be based on 10 min periods derived from contiguous measured data. The mean, standard deviation, minimum and maximum values for each 10 min period shall be derived and stored.

~~The data sets shall be sorted into wind direction bins. Each bin shall be no larger than 10°.~~ The wind direction bin ~~should be not less than the uncertainty of the wind direction sensor~~ size shall be 10°.

Data sets shall be rejected from the database under the following circumstances:

a) failure or degradation (e.g. due to icing) of test equipment;

b) wind direction outside the measurement sector(s) as defined in 6.3.3;

c) mean wind speed at wind turbine meteorological mast less than 4 m/s or greater than 16 m/s;

d) any other special atmospheric conditions that ~~will also be used as rejection criteria during the power performance test~~ are found to influence the site calibration result and chosen to be rejection criteria;

e) special atmospheric conditions to be used as rejection criteria during the power performance test that are found to influence the site calibration.

~~As a minimum the site calibration data set shall consist of 24 h of data for each non-excluded wind direction bin. Of these each bin shall have at least 6 h of data where winds are above 8 m/s and at least 6 h of data where winds are below 8 m/s. Beyond these minimum requirements, the test should be monitored to indicate the convergence of data[28].~~

_____

~~[28] The most illustrative graph for this purpose plots normalized running averages against the number of hours per bin. Each running average is normalized by the final average obtained as of the date of analysis. For many sites, the running averages can be seen to converge to the final average within 1 % after 8 h to 16 h of data have been obtained. Further reduction to 0,5 % can be obtained by continuing the test until 24 h or more of data per bin are obtained. If one or more of the running averages shift away from the normalized value of one~~

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~~From the site calibration database, the averages of the flow correction factors due to terrain α_j, (ratio of wind speed at the wind turbine location divided by the wind speed at the meteorological mast) for each sector shall be made.~~

Any special atmospheric condition filtered during the site calibration shall also be filtered during the power curve test.

~~C.5 Selection of final measurement sector~~

~~It is often the case that the insufficient data are obtained to define the flow correction factors across the measurement sector used for site assessment per Annex A. In addition, the correction factors may change abruptly between wind direction bins. It is recommended that wind directions from the measurement sectors be eliminated when flow correction factors change by more than 0,02 between neighbouring sectors.~~

~~In some cases, the site calibration test may indicate that an obstruction has no discernable effect on the measured flow correction factors. In such cases, the measurement sector may be increased beyond the requirements stated in Annex A. The increase in measurement sector must account for the potential for the wake from an obstruction to affect the test turbine's rotor even if it does not affect an anemometer at the hub.~~

C.5 ~~Uncertainty~~ Analysis

~~Measurement uncertainty of flow correction factors shall be determined according to Annex D. An example is shown in Annex E, where the combined uncertainty is calculated for each wind direction bin.~~

The site calibration measures the relationship of wind speeds at two specific points in space. Orography represents a static influence on this relationship (the terrain is not moving over time) however wind shear adds a dynamic element to this relationship, as the wind speed gradient with height may vary significantly, or it may not if the site only sees a fairly steady shear over a limited range.

The first step in the site calibration process is therefore to assess the shear conditions at the site. The calculations and plots in C.5.1 are performed first to make this assessment, then based on the outcome either C.5.2 or C.5.3 is followed to complete the calculation of the flow corrections. Once the flow corrections have been calculated according to either C.5.2 or C.5.3, the procedure then continues with the additional calculations in C.5.4 which are inputs to the uncertainty calculations in Clause C.6 and the quality checks in Clause C.7.

C.5.1 Assessment of site shear conditions

C.5.1.1 Shear calculations and characterisation plots

For each 10 min data point, the following calculations shall be made:

a) the wind speed ratio, which is the hub height wind speed at the turbine location divided by the hub height wind speed at the reference meteorological mast;

b) the shear exponent at both met masts shall be calculated using the power law (see 3.31);

c) the time of day using a 24 hour clock shall be determined from the timestamp and any offset to the site local time. Any adjustment to the local clocks for more daylight hours in

~~after appearing to stabilize, the data set should be analyzed further to ensure that no problems have occurred with the anemometers or wind vane.~~

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summer vs. winter (i.e. Daylight Savings Time, summer time) shall be noted if it is applied to the data logger timestamps.

The analysis method shall depend on whether or not wind shear is determined to be a significant factor at the site. High shear, or more specifically a wide range of shear values, is typically due to a diurnal cycle of stable atmosphere at night and unstable atmosphere during the day. To illustrate the shear conditions at the site and to assist with the shear evaluation, the following scatter plots shall be generated for both the turbine location and reference met mast data from the filtered database:

1) scatter plot of wind shear exponent vs. time of day;
2) scatter plot of wind shear exponent vs. wind direction;
3) scatter plot of wind shear exponent vs. wind speed;
4) scatter plot of wind speed vs. time of day.

Please note that time of day should be used with care. What really lies behind this are the correlation to local sun-rise and sun-set times as these often strongly influence atmospheric stability. Especially for longer data sets and higher latitudes, the correlation between sun-rise, sun-set and time of day becomes quite poor.

For a site where these effects occur, typically the shear exponents observed during the day time will be low as the sun heats the ground causing turbulence and mixing of the layers and at night the shear will be high. Thus there may be a wide range of shear exponents and a noticeable change in the shear exponents from day time to night time for these sites.

C.5.1.2 Assess significance of shear

Regardless of atmospheric stability, shear shall be considered to be a significant factor if more than 25 % of the data points have a shear exponent greater than 0,25.

Shear shall be confirmed to be a significant parameter if the wind speed correlation improves following binning by direction and shear according to Method 1 in C.5.2; otherwise the site calibration may be evaluated following Method 2 – linear regression method described in C.5.3.

Dividing the measurement sector to allow for different methodologies for different sectors is permitted. This may be useful if, for example, the terrain from part of the measurement sector is Type A and from another direction it is Type B.

The goal is to ensure that the site calibration is not biased by unusual shear conditions; either the site calibration method accounts for the impact of shear or unusual conditions are filtered out. The site calibration results using either method C.5.2 or C.5.3 may be assessed using the method in C.5.4, where the site calibration corrections are applied to the permanent mast wind speed and this is then compared to the turbine location wind speed. Comparing the site calibration residuals against wind shear or other atmospheric stability metrics will show if the selected method accurately corrects the permanent location wind speed for all conditions or if additional steps are necessary to improve quality and reduce uncertainty. Specifically:

a) the self-consistency parameter (Equation (C.3) in C.5.4) bin-averaged against wind speed should be between 0,98 and 1,02 in the range of 4 m/s to 16 m/s within each sector;
b) a linear regression of $V_{\text{Turb_predicted}}$ (Equation (C.1)) vs. $V_{\text{Turb_measured}}$ should have an R^2 value > 0,95 within each sector.

C.5.1.3 Establish correlation of shear between locations

If shear is determined to be significant at the site and where there is a requirement to filter on shear at the turbine location, then it shall be established that the shear at the turbine location can be predicted from the shear measured at the reference met mast. The simplest method to achieve this is to plot the shear at the turbine location vs. the shear at the reference mast and

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calculate an Ordinary Least Squares linear regression. This shall be done using the filtered database. Note that this regression may be used during the power curve measurement to predict shear at the turbine location.

If the shear at the turbine location and the shear at the reference mast are not correlated for all cases, then steps shall be taken so that the data is correlated for all cases. For example, non-correlation may occur where there is a significant difference in elevation between the reference mast and test turbine location in conjunction with high shear, which is often correlated with time of day. In these cases, the suggested method to achieve correlated results is to filter the data based on time of day to remove the high shear night time data, although other methods to remove non-correlating data are permitted. The time of day filter may be established using the shear exponent vs. time of day plots. Reducing the measurement sector such that only directions with similar flow conditions are considered, filtering or breaking the site calibration up by seasons, or other methods to achieve a fully correlated data set may be used. The plots of wind shear exponent vs. wind direction may be useful in determining which sectors to use.

Any additional filter applied to the site calibration results shall also be applied to the power curve measurement. If a time of day filter is used, the filter may be adjusted seasonally to reflect longer days during the summer and shorter days during the winter. Only data from the reference mast should be used for any additional filters because it will not be possible to filter on the turbine location data during the power curve measurement.

Shear, turbulence, and wind speed are often correlated. The plots of wind shear exponent vs. wind direction, wind shear exponent vs. wind speed, and wind speed vs. time of day may be used to assess the potential impact of these filters on the power curve data in terms of reduced data at certain wind speeds. For example, if applying a time of day filter will result in the loss of most of the data at high wind speeds, then this filter may not be practical. In the extreme case a solution could be to have multiple site calibrations, each valid for a specific range of atmospheric conditions.

C.5.2 Method 1: Bins of wind direction and wind shear

To determine if the site calibration correction factors are influenced by the shear on the site, the data shall be sorted into bins of wind direction and shear. The size of the wind direction bins shall be 10° and shall not be less than the uncertainty of the wind direction sensor. At the edges of the measurement sector, the data shall be filtered to the extents of the measurement sector. For example, where the measurement sector ends at 43°, the site calibration at the edge of the sector will be evaluated from 35° to 43° only. It is required that the choice of direction bin centre definition (e.g. either bins centred on integer multiples of 10° or bins beginning on integer multiples of 10°) shall be carried through consistently from the site calibration to the power curve test. The wind shear bins shall be in increments of 0,05 shear exponent centred on integer multiples of 0,05.

The wind speed ratios within each wind direction and wind shear bin shall be averaged.

The completion criteria for the wind direction and wind shear bins is as follows:

a) For each wind direction bin, the number of data points across all wind shear bins within that wind direction bin shall total at least 144 (24 hours of data). Incomplete wind shear bins may be included in this total. Furthermore, each wind direction bin shall contain at least 6 hours above and 6 hours below 8 m/s.

b) Each wind shear bin within a complete wind direction bin shall contain at least 3 data points.

c) Wind shear bins in incomplete wind direction sectors that contain at least 6 hours of data may also be considered complete.

If after the matrix has been completed it is found that the site calibration corrections do not change with increasing wind shear, then the wind shear bins may be eliminated and the data

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evaluated only on a wind direction bin basis according to C.5.3. The level of change shall be evaluated against the statistical uncertainty of the site calibration.

If the variation between wind shear bins causes a higher variability in site calibration factors than twice the statistical uncertainty of the site calibration in one or more wind direction bins, the wind shear bins shall be included in the analysis alongside the wind direction bins.

If the variation between wind shear bins causes a lower variability in site calibration factors than twice the statistical uncertainty of the site calibration in one or more wind direction bins, the wind shear bins may be eliminated and the data evaluated only on a wind direction basis per C.5.3.

During the power curve measurement, the data shall be sorted into wind direction bins. For each 10 min data point, the wind shear exponent at the reference mast shall be calculated. The correction applied to the hub height wind speed shall be the wind speed ratio interpolated to the measured wind shear value from the wind shear bin average values and the measured wind shear exponent for that wind direction bin. Extrapolation is permitted for wind shear exponents falling within the last complete wind shear bins; for example if the last complete site calibration wind shear bin is the 0,6 wind shear bin, extrapolation is permitted for measured wind shear exponent values between 0,600 and 0,625 (where 0,625 is the upper edge of the 0,6 wind shear bin with a bin width of 0,05 and a range of 0,575 to 0,625). Interpolation between two complete wind shear bins across an incomplete wind shear bin is permitted. Interpolation between wind direction bins is not permitted.

C.5.3 Method 2: Linear regression method where shear is not a significant influence

The data sets shall be sorted into wind direction bins. The size of the wind direction bins shall be 10°. It is required that the choice of direction bin centre definition (e.g. either bins centred on integer multiples of 10° or bins beginning on integer multiples of 10°) shall be carried through consistently from the site calibration to the power curve test. At the edges of the measurement sector, the data shall be filtered to the extents of the measurement sector. For example, where the measurement sector ends at 43°, the site calibration at the edge of the sector will be evaluated from 35° to 43° only.

For each wind direction bin, an ordinary least squares linear regression shall be made with the turbine location wind speed as the dependent variable and the reference wind speed as the independent variable. Therefore, there will be one slope and one intercept for each wind direction bin.

Each wind direction bin shall have at least 24 h of data in total and shall have at least 6 h of data where winds are above 8 m/s and at least 6 h of data where winds are below 8 m/s. There should be a wide distribution of wind speeds within the bin to get a good correlation (see C.7.2), and it is therefore recommended that data with wind speeds at least up to 11 m/s be present. Note that outliers are highly weighted by the ordinary least squares regression method. Any outliers that appear to have a significant impact on the regression should be investigated and documented.

To illustrate the correlation between the reference and turbine location wind speed, the following plots shall be generated for each complete wind direction bin within the measurement sector:

> Turbine mast wind speed vs. reference mast wind speed, including an indication of the linear regression and correlation coefficients (commonly known as the R^2 value);

On a single axis, plot the following. See Figure C.11 in Clause C.9 for an example:

a) wind speed ratio vs. reference wind speed;

b) bin averages of the wind speed ratios in 0,5 m/s wind speed bins;

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c) a curve $y = m+b/x$ where m is the slope of the linear regression, b is the intercept and x is the reference wind speed, and y is the predicted turbine location wind speed normalized to the reference mast wind speed, i.e. y = the wind speed ratio;

d) a horizontal line indicating the average of all wind speed ratios within the wind direction bin.

C.5.4 Additional calculations

The site calibration flow corrections shall be applied to the reference meteorological mast data to calculate the predicted wind turbine location wind speed for each data point. This shall be done using the filtered database.

$$V_{\text{Turb_predicted}} = F(WD, \alpha) \times V_{\text{PM}} \quad \text{(C.1)}$$

where

$V_{\text{Turb_predicted}}$ is the predicted wind turbine location wind speed;

$F(WD,\alpha)$ is the site calibration flow correction determined in C.5.2;

V_{PM} is the reference meteorological mast wind speed;

WD is the wind direction bin;

α is the wind shear exponent, if applicable.

A site calibration residual shall be calculated as follows for each 10 min data point as the difference between the predicted wind turbine location wind speed and the measured wind turbine meteorological mast wind speed.

$$residual = V_{\text{Turb_predicted}} - V_{\text{Turb_measured}} \quad \text{(C.2)}$$

A self-consistency parameter shall be calculated as follows for each 10 min data point: divide the predicted wind turbine location wind speed by the actual wind turbine meteorological mast wind speed.

$$self_consistency_paramenter = \frac{V_{\text{Turb_predicted}}}{V_{\text{Turb_measured}}} \quad \text{(C.3)}$$

The residuals and the self-consistency parameter are used to assess the variation and any biases in the results. The mean of the residuals and self-consistency parameter reflect the mean bias, where mean values of 0 and 1,0 translate to zero bias, respectively. The standard deviation of these parameters is indicative of the variation around the mean bias, and is used for the calculation of the statistical uncertainty of the site calibration.

In addition to the statistical uncertainty calculations, which are based on the variation about an assumed mean bias of zero, these parameters are used for calculation of additional uncertainty to be added in certain scenarios listed in Clause C.7, which are based on assessments of the estimated mean bias introduced by the scenario which are reflected in shifts in the mean of these parameters away from 0 and 1,0, respectively.

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C.6 ~~Report requirements~~ Site calibration uncertainty

~~The reporting requirements of site calibration are described in Clause 9.~~

C.6.1 Site calibration category A uncertainty

C.6.1.1 Site calibration k-fold analysis

The site calibration trains a model to predict the wind speed at the turbine location based on the wind speed at the met mast location. To avoid the risk of under-estimating the category A uncertainty due to over-fitting the model to the data, the category A uncertainty shall be calculated using k-fold cross validation with k = 10. Note that in the wind industry, k has different meanings, however the use of the term 'k' here is consistent with its use in statistical learning, as the method applied is known as *k-fold cross validation*.

The final filtered data set shall be divided into k equally sized folds (partitions) based on timestamp.

For each fold (k = 1 through 10):

a) the site calibration corrections shall be calculated according to Clause C.5 using only data from the other 9 folds;

b) the site calibration corrections shall be used to calculate the predicted wind speed at the turbine location using the reference mast wind speeds measured during fold k;

c) the predicted turbine wind speeds in fold k shall be compared to the actual measured turbine wind speeds in fold k according to both the residual and self-consistency parameters defined in C.5.4;

d) the statistical uncertainty for fold k shall be determined per C.6.1.2.

The total category A uncertainty is the square root of the sum of the squares of the uncertainty calculated for each fold divided by the square root of k.

$$s_{\mathrm{sc}} = \sqrt{\frac{\sum_{i=1}^{k} s_{\mathrm{sc},i}^{2}}{k}} \tag{C.4}$$

A value of k=10 is chosen so that there is a higher probability that there will be sufficient information in the remaining sets to cover the range of wind speeds present in the data set being evaluated, however other values of k are allowed so long as $k \geq 2$.

The folds are divided by timestamp rather than randomly chosen since it is expected that the variations in relationship in wind speeds between the two locations may be correlated with meteorological events which are correlated with time, and so folds that are time based are more likely to better capture variation between the conditions during the site calibration and the power curve measurement time periods.

C.6.1.2 Site calibration statistical uncertainty for each fold

For each fold in the k-fold cross validation, the deviation between the site calibration corrected wind speed at the wind turbine location and the wind speed measured at the wind turbine meteorological mast is calculated for each 10 min period, and the standard deviation of the wind speed deviation over all 10 min periods is calculated as follows:

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$$d_{\text{std},k} = \sqrt{\frac{\sum_{j=1}^{N}\left(d_{j,k} - \bar{d}_k\right)^2}{N_k - 1}} \tag{C.5}$$

where

$d_{j,k}$ is the residual in the j-th 10 min period of fold k, see Equation (C.2);

$\bar{d}_k$ is the mean value of the residuals in fold k;

N_k is the number of data sets in fold k;

$d_{\text{std},k}$ is the standard deviation of site calibration residuals in fold k.

Only data that has been included in the assessment of the site calibration shall be included in the calculation of the standard deviation.

The statistical, category A, standard uncertainty of fold k is:

$$s_{\text{sc},k} = d_{\text{std},k} \cdot \frac{\sqrt{N_k - 1}}{\sqrt{f \cdot N_k}} \tag{C.6}$$

where

f is number of degrees of freedom of the site calibration.

The number f is the number of 10 min periods included in the site calibration minus the total number of parameters of the site calibration algorithm. In the case where the site calibration flow corrections are in the form of bin-averaged wind speed ratios, the number of parameters of the site calibration algorithm per wind direction sub-sector equals the number of wind shear bins. f is then N_k minus the number of wind direction sub sectors (normally number of 10° wide sectors). In the case where the site calibration flow corrections are in the form of linear regressions (slopes and offsets), the number of parameters of the site calibration algorithm is 2 per wind direction sub sector. f is then N_k minus twice the number of wind direction bins. In the case where the site calibration flow corrections are in the form of bin-averaged wind speed ratios per wind direction and wind shear bin, f is N_k minus the sum of the number of all wind shear bins in all wind direction sub-sectors.

C.6.2 Site calibration category B uncertainty

The following components of uncertainty should be considered to be independent of each other in evaluating the combined category B standard uncertainty.

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

$u_{\text{VT,class},i}$: Anemometer operational characteristics – the wind turbine meteorological mast anemometer operational standard uncertainty shall be taken into account in the site calibration uncertainty calculation. The correlation of the operational characteristics during the site calibration shall be studied to determine to what extent the turbine and reference anemometer operational characteristic uncertainties are to be taken into account. Depending on the differences in the environmental conditions during the power curve measurement

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compared to during the site calibration, an increase in operational characteristics uncertainty may be required. During the site calibration the turbine anemometer operational uncertainty should be fully accounted for.

$u_{VT,mnt,i}$: Mounting effects – the wind turbine meteorological mast anemometer as well as the reference meteorological mast anemometer mounting standard uncertainty shall be taken into account in the site calibration uncertainty evaluation.

$u_{dVT,i}$: Standard uncertainty in wind speed due to the data acquisition system shall be estimated per Annex D and E.

C.6.3 Combined uncertainty

The Category A and B components of uncertainty should be considered as independent of each other for the purpose of evaluating the combined uncertainty of the site calibration.

Narrowing the measurement sector with the goal of reducing uncertainty by eliminating higher uncertainty wind direction bins is permitted.

C.7 Quality checks and additional uncertainties

C.7.1 Convergence check

A convergence check shall be carried out using the self-consistency parameter from Equation (C.3) for each wind direction bin. The most illustrative graph for this purpose plots cumulative average of the self-consistency parameter against the number of hours per wind direction bin. The cumulative averages should be seen to converge to within 0,5 % of the final average within the larger of 16 h of data or 25 % of the total number of data points in that bin. If this criteria is not met, steps such as additional filtering may be applied to try to explain and correct the non-convergence. If these steps do not result in convergence, the self-consistency check according to Clause C.8 may be performed during the power curve measurement to assess if the non-convergence is an issue. If criteria for the self-consistency check during the power curve test is not met, then the bin shall be excluded from the measurement sector.

The k-fold cross validation method used to calculate the statistical uncertainty for the site calibration should reflect a higher test uncertainty for any non-convergence, so no uncertainty penalty is applied for this check.

C.7.2 Correlation check for linear regression (see C.5.3)

For each wind direction bin, the level of correlation shall be assessed based on the correlation coefficient of the regression, commonly known as the r value. This assessment shall be included in the report.

C.7.3 Change in correction between adjacent wind direction bins

It is recommended that wind direction bins from the measurement sectors be eliminated when flow corrections change by more than 2 % between neighbouring bins. This shall be evaluated by applying the self-consistency parameter method from C.5.4 as follows:

a) evaluate the data and calculate the site calibration flow corrections;

b) shift the site calibration flow corrections by one direction sector so that the flow corrections or regressions are applied to the adjacent wind direction bin. For example, if the flow correction applied to the 290° bin is $1{,}024x$ + 0,1, then apply this correction instead to the 280° bin;

c) using the adjusted site calibration flow corrections from the previous step and the site calibration data, calculate the predicted wind turbine location wind speed for each 10 min period and then calculate the self-consistency parameter with Equation (C.3);

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d) average the self-consistency parameters for each wind direction bin. If the average is less than 0,98 or greater than 1,02, then those wind direction bins should be eliminated. If those wind direction bins are not eliminated, then the uncertainty in those bins shall be increased by the value of 1 minus the average self-consistency parameter multiplied by 100 % and divided by 2 and the square root of 3. If a sector has this applied from both adjacent sectors, then the increase in uncertainty is the average of the two.

This method shall be applied by both adding and subtracting to the wind direction bin, for example applying the 290° bin results to both the 280° and 300° bins. The uncertainty adjustment for bins not on the edge shall be the average impact of moving one adjacent bin in each direction.

$$u_{VT,\mathrm{coc},i,j} = \frac{1}{2} \cdot \left(\frac{\left|1 - \mathrm{sccp}_{j,j-1}\right|}{2\sqrt{3}} + \frac{\left|1 - \mathrm{sccp}_{j,j+1}\right|}{2\sqrt{3}} \right) \tag{C.7}$$

where

$u_{VT,\mathrm{coc},i,j}$ is the standard uncertainty due to change in correction in wind direction bin j;

$\mathrm{sccp}_{j,j-1}$ is the site calibration consistency parameter for wind direction bin j using the site calibration corrections in bin $j-1$;

$\mathrm{sccp}_{j,j+1}$ is the site calibration consistency parameter for wind direction bin j using the site calibration corrections in bin $j+1$.

For sub sectors at the edges of the measurement sector, the uncertainty shall be assessed only by applying the correction from the respective neighbouring sub sector.

C.7.4 Removal of the wind direction sensor between site calibration and power performance test

If the wind direction sensor is removed between site calibration and the power performance test, 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. This uncertainty component shall be calculated for each wind direction bin as follows:

a) For each wind direction bin, apply the method in C.7.3 except that the uncertainty will also be applied where the average of the self-consistency parameters is between 0,98 and 1,02.

b) Determine the relative uncertainty in the wind direction measurements.

c) Multiply the result of bullet a) by the ratio of the relative uncertainty in the wind vane measurements to the total wind direction bin size.

For example, the wind vane fails and is replaced by a similar model between site calibration and power curve measurement. The uncertainty in the wind vane alignments is determined to be 3° and the bin size is 10°. Multiply the change in correction between adjacent bins from C.7.3 by $\frac{3}{10}$. This uncertainty is applied in addition to any uncertainty applied due to C.7.3.

$$u_{VT,\mathrm{rmv},i,j} = u_{VT,\mathrm{coc},i,j} \cdot \left(\frac{u_{w,i}}{\mathrm{BinSize}_j} \right) \tag{C.8}$$

where

$u_{w,i}$ is the wind direction uncertainty calculated according to Clause E.12;

BinSize is the bin size of wind direction bin j, e.g. 10°.

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Please note that $u_{w,i}$ may be evaluated on a relative basis, i.e. uncertainty components that are fully correlated between the site calibration and power curve measurement may be neglected. For example, if the met mast remains in place and only the sensor is replaced on the same boom and mount with an identical make and model, $u_{WVbo,i}$ *and* $u_{WVoe,i}$ may be neglected.

C.7.5 Site calibration and power performance measurements in different seasons

Seasonal changes in wind conditions and changes in surface roughness due to vegetation, precipitation (snow and ice) and freezing of bodies of water may cause a seasonal dependency in the site calibration flow corrections. It is therefore recommended that the site calibration and power performance measurements be conducted in the same part of the year, for example both occurring in summer. To assess the possible impact of this the following steps shall be taken:

The average wind conditions at the reference meteorological mast during the site calibration (wind shear, turbulence, upflow) shall be compared to the average wind conditions at the same meteorological mast during the power performance measurement for the wind directions within the measurement sector. An additional uncertainty shall be calculated for seasonal effects if any of these conditions for a wind direction bin differs by more than the following amounts:

a) 0,05 for wind shear exponent;

b) 3 % for turbulence intensity;

c) if upflow is measured, a limit of ± 2° change in vertical upflow is recommended.

The additional uncertainty for seasonal effects shall be calculated as one third of the magnitude of the site calibration flow correction.

C.8 Verification of results

~~If a site calibration is undertaken, the site calibration itself, derived from measurements with two masts, can be checked by using data measured directly at the turbine during the power curve measurements. Below rated power, the wind speed incident to the wind turbine can be derived from the momentary time averaged mean value of the electrical power by use of the measured power curve. The ratio of the wind speed estimated from the electrical power and the wind speed measured at the meteorological mast can be bin averaged according to the wind direction. Ideally these wind speed factors should be identical to the wind speed correction factor established from the site calibration before the erection of the wind turbine.~~

An example of a method to verify the results from a power performance measurement with or without site calibration is to use the measured electrical power data to derive a wind speed representative for the wind turbine for each 10 min period included in the power curve measurement. This wind speed is compared to the wind speed measured by the anemometer or RSD. Ideally this ratio should not vary as a function of the wind direction. Wind direction bins where the ratio varies strongly should be investigated and possibly excluded. If the power curve is a function of the rotor equivalent wind speed, the rotor equivalent wind speed should be applied for the self-consistency check.

a) The reverse power curve is defined as the wind speed bin-averaged as a function of the power output for the data sets that have been used for the power curve evaluation. For actively controlled wind turbines, the air density normalised wind speed is used for the evaluation of the reverse power curve. For non-actively controlled wind turbines, the air density normalised power output is applied for the evaluation of the reverse power curve. If a site calibration has been performed, the site calibrated and, if applicable, air density normalised wind speed should be used for the bin analysis. The results used should include power data where the maximum power does not reach the measured nominal rated power and for which the normalized wind speed is above 4 m/s.

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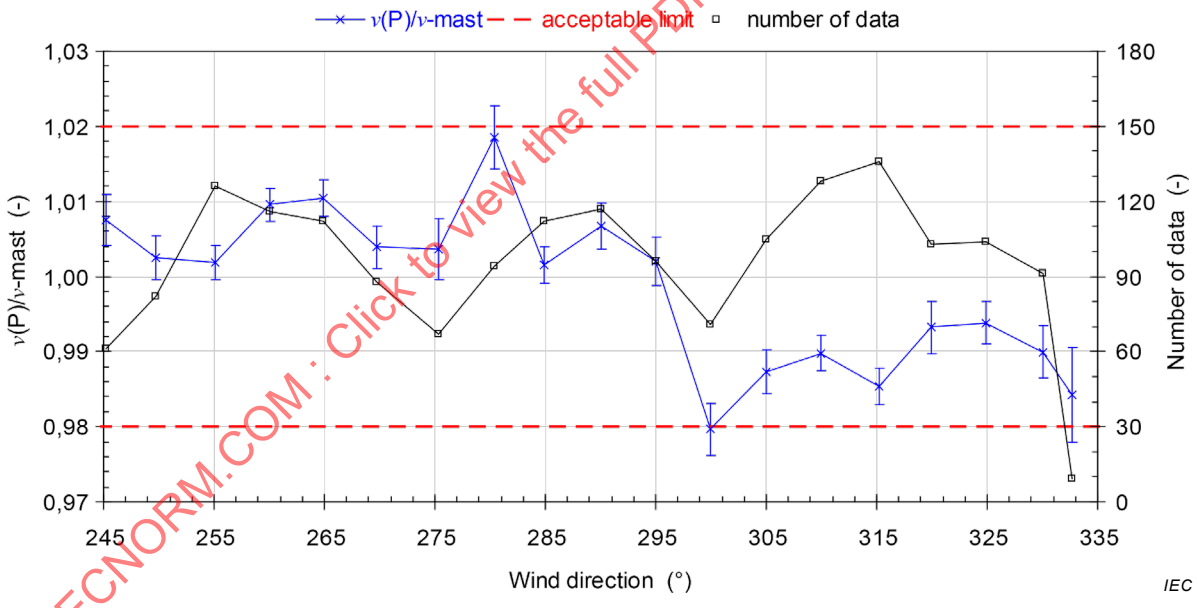
b) The reverse power curve (RPC) is applied in order to evaluate the wind speed representative of the wind turbine rotor from the measurement of the active power for each 10 min interval in which the test wind turbine is operational. For this, the wind speed is interpolated linearly between the bins of the RPC according to the measured active power. The result is the wind speed representative of the wind turbine rotor. For actively controlled wind turbines, the result is the air density normalised ambient wind speed representative of the wind turbine rotor. For non-actively controlled wind turbines, the air density normalised power output should be used for the evaluation of the ambient wind speed.

c) The ratio of the two wind speeds (derived/measured) should be bin-averaged as function of the wind direction in 5° sectors.

d) The derived and measured wind speeds are expected to be in good agreement for the measurement sector and hence the ratio should be near unity. Deviations from unity may occur due to site effects, imperfections of the site calibration procedure, or influences of environmental variables on the power curve. Sectors where the wind speed determined via the meteorological mast is not representative for the test wind turbine can clearly be identified as variations of the bin-averaged ratio. Larger deviations should be analysed further. These sectors should be excluded from the final power curve test if site effects are identified as the reason.

e) The power curve should be re-evaluated for the remaining sector. The self-consistency check may be repeated with the re-calculated RPC. If necessary, the measurement sector should be adjusted in accordance with the results of the repeated test.

An example of a result of a verification test is shown in Figure C.3.



The error bars indicate the category A standard uncertainty of the bin averaged ratios of v_P and v_{mast}. The acceptable range is for ratios of 0,98 to 1,02 for L < 3 rotor diameters and 0,97 to 1,03 for L between 3 and 4 rotor diameters.

Figure C.3 – Example of the results of a verification test

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C.9 Site calibration examples

C.9.1 Example A

Site description:

A power curve measurement is to be undertaken on a ridgeline site (Type B Terrain). The ridgeline is perpendicular to the principle wind direction, facing a plain and the ridge is approximately 40 m to 60 m higher than the plane. The wind turbines have a hub height of 80 m and are located in a single row along the top of the ridge.

The terrain type is between a type A and type B terrain. The relatively flat terrain up-wind of the ridge means that high wind shear may be a concern due to atmospheric stability; however the terrain local to the wind turbines is closer to a type B site where high upflow angles may also be a concern. The test wind turbine and meteorological mast location are therefore chosen to best minimize the possible upflow angle (lower local terrain slope) and to minimize the difference in elevation between the two locations (which will maximise correlation of wind speed flow corrections with different wind shear profiles) as much as possible given the wind turbine layout and terrain constraints.

Site calibration setup:

The reference meteorological mast is located on the ridge, next to the test wind turbine but at a slightly lower elevation that is about 10 m lower than the wind turbine elevation.

In addition to top mounted hub height cup anemometers in a side-by-side configuration, wind shear measurements are included in the form of anemometers located at 43 m elevation on both meteorological masts. A 3D ultrasonic anemometer is mounted on each meteorological mast to assess the operational characteristics of the hub height anemometers to quantify the uncertainty at the given terrain complexity.

Site calibration evaluation:

Data are collected for several months. The collected data are filtered based on the measurement sector, the wind speeds from 4 m/s to 16 m/s as recorded at the reference meteorological mast, sensor malfunction, and anemometer icing.

For each 10 min period, the following calculations are made according to C.5.1:

a) the ratio of the hub height wind speed at the wind turbine location to the hub height wind speed at the reference meteorological mast;
b) the wind shear exponents at each meteorological mast are calculated from the power law using the wind speed measurements at 80 m and 43 m;
c) a lag representing the time of day on a 24 h clock is calculated from the timestamp;
d) upflow angle is calculated from the vertical and horizontal wind speeds from the ultrasonic anemometers at each meteorological mast.

Step 1: Check the significance of wind shear at the site according to C.5.1.2:

For the filtered data, the wind shear exponent at each meteorological mast is plotted against time of day.

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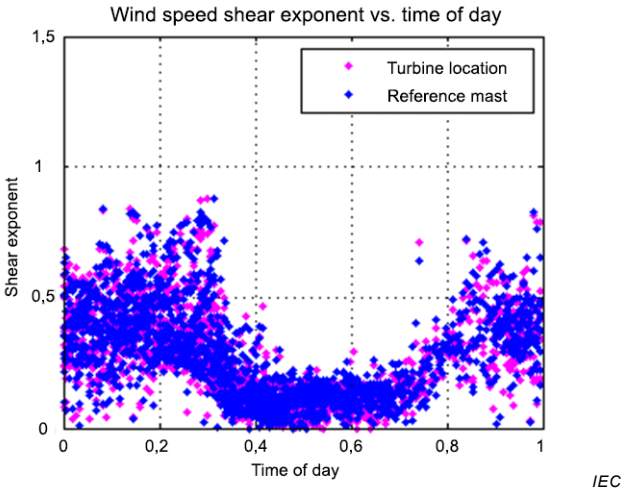

Figure C.4 – Wind shear exponent vs. time of day, example A

From Figure C.4 it is observed that wind shear is high at night and low during the day. This is typical of a site experiencing a diurnal cycle of atmospheric stability. At night, the atmosphere forms thermal layers (stable atmosphere). These layers suppress turbulence and result in variably high wind shear. During the day, the sun heats up the ground, introducing turbulent mixing which results in a more uniform wind speed profile (low wind shear) and higher turbulence.

It also appears that similar values of wind shear are occurring at both the wind turbine and reference meteorological mast locations.

Step 2: Verify correlation of wind shear at wind turbine and reference meteorological mast locations – Example A

To verify that the wind shear exponent values are correlated between the wind turbine and reference meteorological mast locations, a plot of the wind shear exponents at the wind turbine location vs. the wind shear exponents at the reference meteorological mast is made (see Figure C.5):

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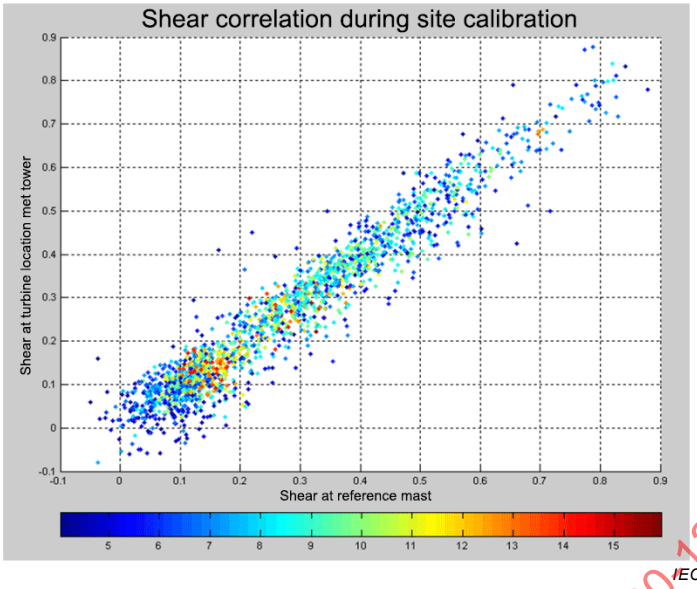

Figure C.5 – Wind shear exponents at wind turbine location vs. reference meteorological mast, example A where the colour axis = wind speed (m/s)

The wind shear exponents at the reference meteorological mast are a reasonably good indicator of the wind shear exponents at the wind turbine location.

Step 3: Calculate results according to C.5.1.3

The following calculations are made for each 10-minute data set based on measurements at the reference mast:

- wind shear bins centred on integer multiples of 0,05 values of wind shear exponent (–0,025 to 0,025, 0,025 to 0,075, 0,075 to 0,125, etc.).

It is now possible to make a matrix of wind shear exponent and wind direction. For each point in this matrix, the following calculations are made:

- the correction for each point in the matrix is calculated as the average of the wind speed ratios in that matrix bin;
- a count of all valid data points within that matrix bin.

Table C.1 and Table C.2 show the site calibration flow corrections and bin count, respectively. Figure C.6 is a graphical illustration of these results.

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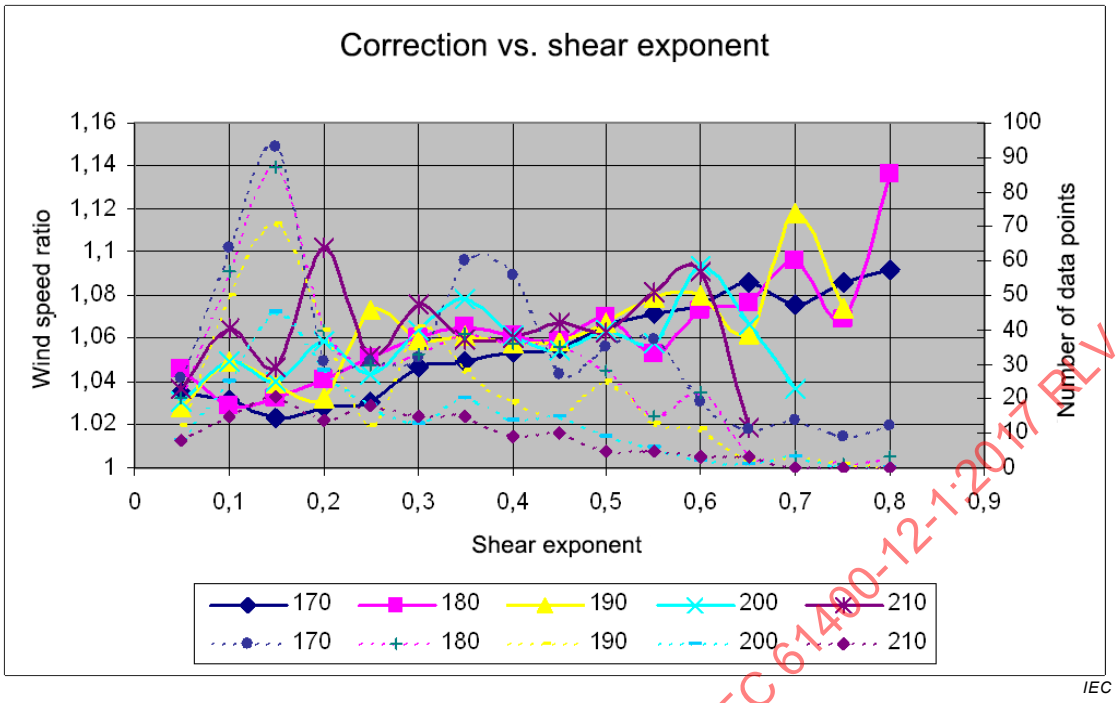

Figure C.6 – Wind speed ratios and number of data points vs. wind shear exponent and wind direction bin – wind speed ratios (full lines), number of data points (dotted lines)

Step 4: Quality checks and additional uncertainties

Anemometer operational characteristic uncertainty:

The upflow angle was recorded, which allows for the estimation of anemometer operational characteristic uncertainty at the site conditions according to C.3.2. The maximum upflow angle for all data points in all wind direction bins was 3° at the reference meteorological mast and 1° at the wind turbine location mast. All other parameters fell within the range of the Class A anemometer operational characteristics. Therefore, the Class A anemometer operational characteristic uncertainty may be used for both locations. The class is 1,4A.

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Table C.1 – Site calibration flow corrections (wind speed ratio)

	Wind direction bin				
Wind shear bin	**170**	**180**	**190**	**200**	**210**
0,05	1,035	1,046	1,028	1,031	1,037
0,10	1,031	1,029	1,05	1,05	1,064
0,15	1,023	1,033	1,039	1,04	1,047
0,20	1,028	1,041	1,032	1,059	1,102
0,25	1,031	1,051	1,073	1,044	1,052
0,30	1,047	1,06	1,06	1,064	1,076
0,35	1,049	1,066	1,062	1,078	1,06
0,40	1,054	1,061	1,058	1,061	1,06
0,45	1,055	1,058	1,059	1,055	1,067
0,50	1,066	1,07	1,067	1,064	1,063
0,55	1,072	1,053	1,079	1,058	1,081
0,60	1,076	1,074	1,08	INC	1,091
0,65	1,086	1,076	INC	INC	1,019
0,70	1,076	1,096	1,118	INC	INC
0,75	1,086	INC	INC	INC	INC
0,80	1,092	1,136	INC	INC	INC

Table C.2 – Site calibration data count

	Wind direction bin				
Wind shear bin	**170**	**180**	**190**	**200**	**210**
0,05	26	20	12	8	8
0,10	64	57	50	25	15
0,15	93	87	71	45	21
0,20	31	40	40	28	14
0,25	31	30	12	18	18
0,30	32	33	41	13	15
0,35	60	39	28	20	15
0,40	56	36	19	14	9
0,45	27	35	15	15	10
0,50	35	28	25	9	5
0,55	37	15	13	6	5
0,60	19	22	11	2	3
0,65	11	3	2	1	3
0,70	14	3	3	3	0
0,75	9	1	1	0	0
0,80	12	3	0	0	0

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Convergence check:

The convergence check found that the data converged to within 0,5 % of the final value (or within 0,995 and 1,005 in Figure C.7 for the 190° bin using over 50 h of data in the bin meeting the requirement, the larger of 16 h or 25 % of the total number of data points for all bins.

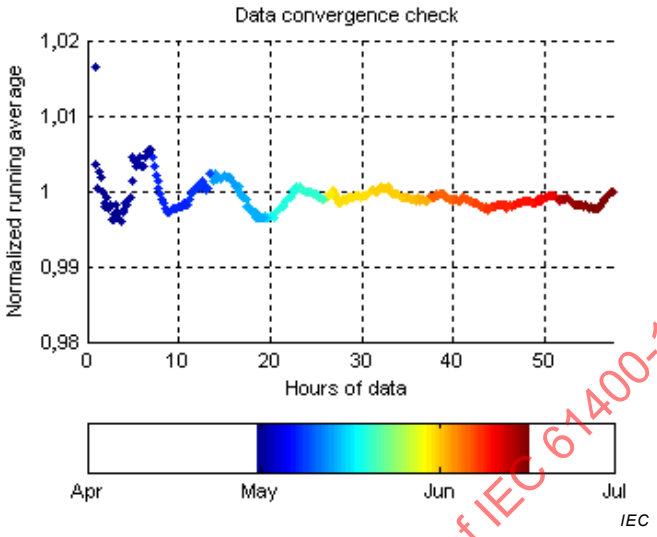

Figure C.7 – Data convergence check for 190° bin

Change in correction between bins:

The magnitude of the change in flow corrections was within 0,02 between all adjacent bins.

Wind vane adjustment:

No wind vane adjustment was made between measurements, so no additional uncertainty is required.

Seasonal uncertainty:

The power curve measurement fell during the same seasonal period and a comparison found that none of the changes in conditions exceeded the limits of C.7.5 so no additional uncertainty is needed to account for seasonal effects.

C.9.2 Example B

Site description:

The site is identical to the site in example A (Type B terrain) except that the local terrain to the wind turbine is slightly steeper.

Site calibration setup:

Unlike example A, it was not possible to locate the reference meteorological mast on the ridge. The reference meteorological mast is located at the base of the ridge (on the plain) 3 rotor diameters upwind of the test wind turbine that is on the top of the ridge. The difference in elevation between the test wind turbine and the reference meteorological mast is 45 m.

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Step 1: Check the significance of wind shear at the site

For the filtered data, the wind shear exponent at each meteorological mast is plotted against time of day (see Figure C.8).

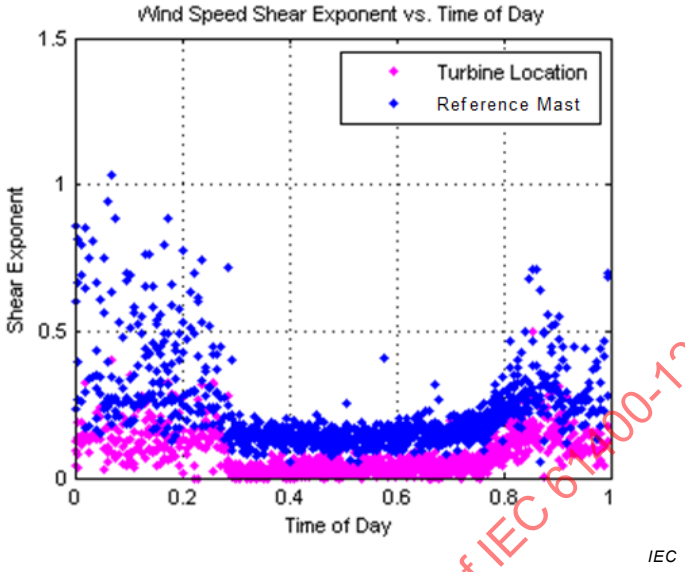

Figure C.8 – Wind shear exponent vs. time of day, example B

Similar to example A, the wind shear at night is higher than during the day, indicating a diurnal cycle of atmospheric stability. However, the wind shear at the wind turbine location appears to be significantly different than the wind shear at the reference meteorological mast. This will be problematic due to the change in elevation between the two locations, it is reasonable to assume that the relationship between the hub height wind speeds will be influenced by changes in the wind shear profile.

Step 2: Verify correlation of wind shear at wind turbine and reference meteorological mast locations – Example B

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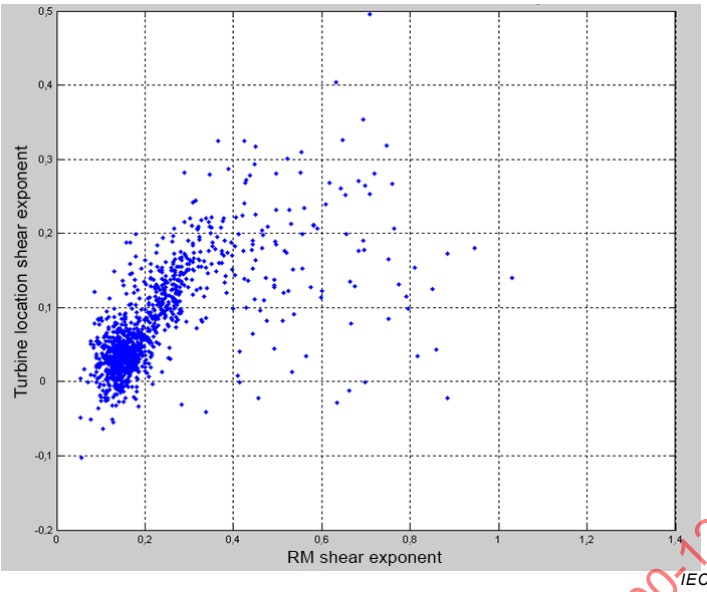
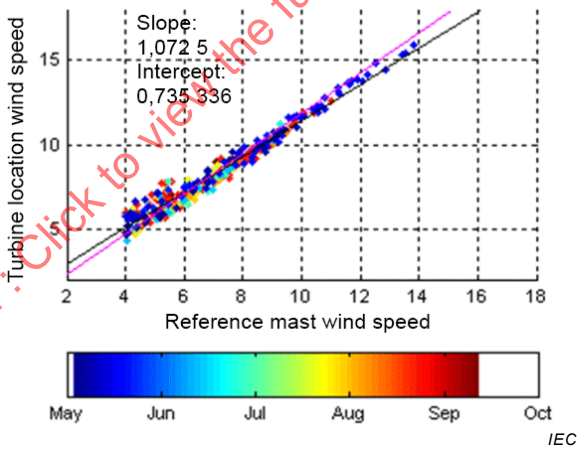


Figure C.9 – Wind shear exponents at wind turbine location vs. reference meteorological mast, example B

There is no correlation for wind shear values greater than 0,25. This suggests that the correlation of site calibration flow corrections will be inconsistent during stable atmospheric conditions. To illustrate/verify that this is the case, the plots specified in C.5.3 may be used (see Figure C.10):



The red line is the linear regression forced through origin (zero intercept), the black line is the two parameter linear regression (non-zero intercept).

Figure C.10 – Linear regression of wind turbine location vs. reference meteorological mast hub height wind speeds for 330° bin

The linear regression shows that there is a significant intercept in the linear regression. There is also high scatter at the lower wind speeds.

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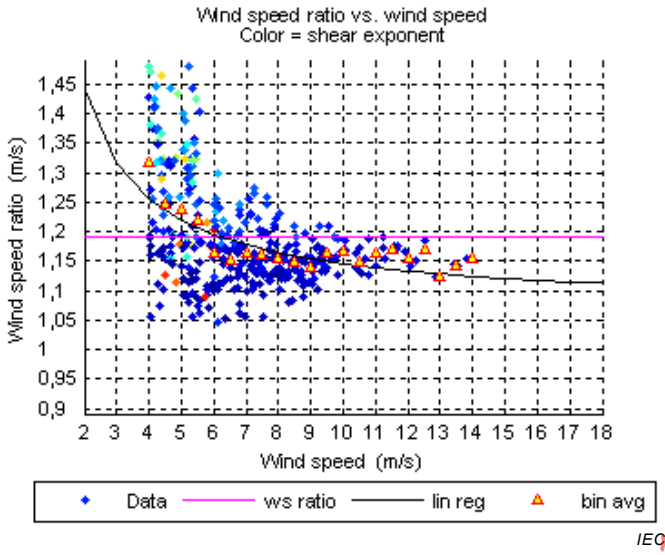

Figure C.11 – Wind speed ratios vs. wind speed for the 330° bin

The plot of wind speed ratio vs. wind speed (see Figure C.11) shows the high dependency of the flow correction on wind speed due to the high intercept. Also note that the overall magnitude of the flow correction is quite high, 19 % on average.

For illustrative purposes, a plot of the wind speed ratios vs. wind shear for the different wind bins is shown in Figure C.12.

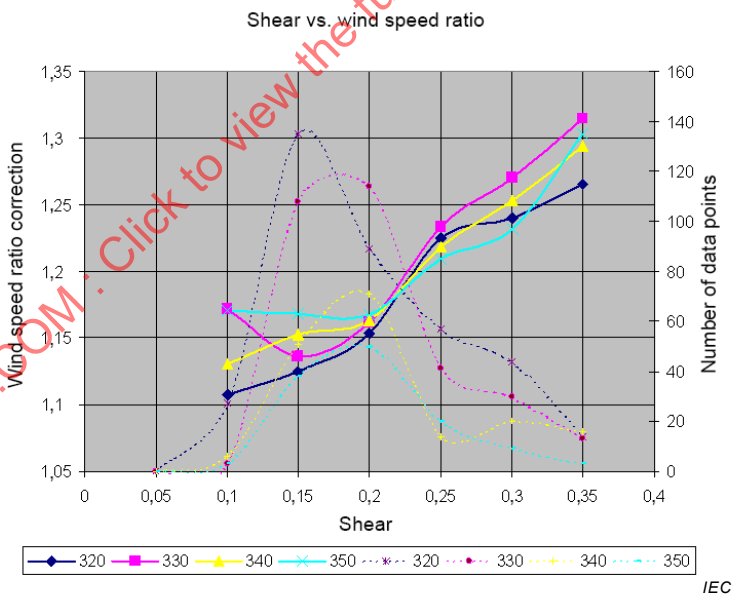

Figure C.12 – Wind speed ratios vs. wind shear for the 330° bin

These plots are useful illustrations of the impact to the site calibration due to the conditions at this site and the test setup. Figure C.12 shows that the correction changes by more than 5 % between 0,20 and 0,25, and Figure C.9 shows that the wind shear at the reference meteorological mast is not a good predictor of the wind shear at the wind turbine location for values greater than 0,25. Corrections using the wind direction-wind shear matrix method may not be reliable. Wind shear has been shown to have a significant influence and wind shear at the two locations is not well correlated so therefore additional filtering is necessary to try to improve the correlation.

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Step 2B: Attempt to remove non-correlating wind shear data

Low wind shear values appear to be correlated between the two locations. Low wind shear values occur during the day time (periods of atmospheric instability), therefore from the plots, a time-of-day filter is applied to select all daytime data between 07:00 and 19:00.

Plots according to C.5.2 are shown for the newly filtered data set (see Figure C.13, Figure C.14 and Figure C.15).

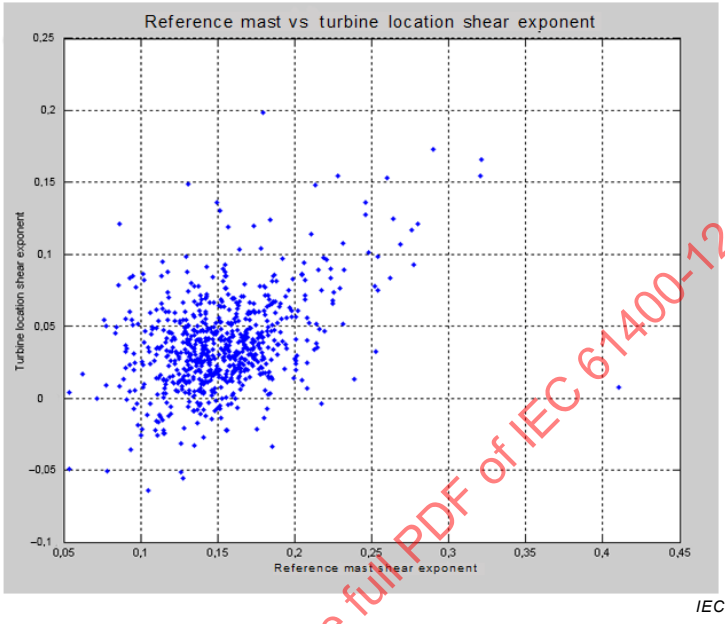

Figure C.13 – Wind shear exponents at wind turbine location vs. reference meteorological mast post-filtering

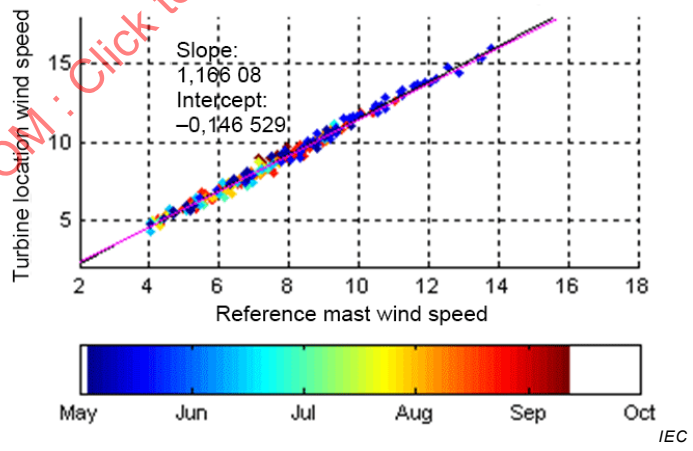

Figure C.14 – Linear regression of wind turbine location vs. reference meteorological mast hub height wind speeds for 330° bin, post-filtering

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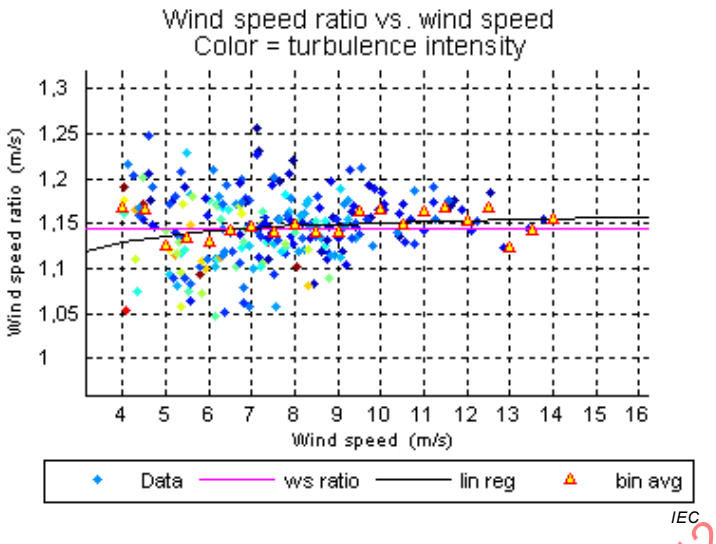

Figure C.15 – Wind speed ratios vs. wind speed for the 330° bin, post-filtering

Step 3: Calculate results

The previous step removed all of the data with high atmospheric stability leaving only day-time data with atmospheric instability. The wind shear values include a small range of wind shear exponents (0,10 to 0,20). This removes the dependence of the site calibration flow corrections on wind shear and so the linear regression method may be used instead of the wind direction – wind shear bin matrix.

For each wind direction bin, a linear regression of the wind speed at the wind turbine location vs. the wind speed at the reference meteorological mast is calculated along with the r^2 value of the regression. The count of total valid data points in each wind direction bin is also recorded.

Step 4: Additional uncertainties

Anemometer operational uncertainty:

No vertical wind speed measurement was included so the Class B operational characteristic uncertainty shall be used. The anemometer operational characteristic classification is 5,4B.

Convergence check (see Figure C.16**):**

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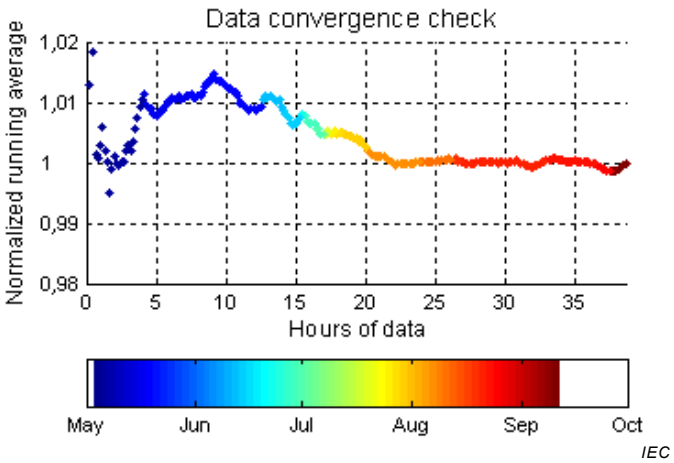

Figure C.16 – Data convergence check for 330° bin

Correlation check for linear regression:

As per C.7.2 (see Table C.3).

Table C.3 – r^2 values for each wind direction bin

Bin centre	r^2 value	Absolute value of residual mean (m/s)	Residual standard deviation (m/s)
320	0,978	0,00	0,33
330	0,988	0,00	0,26
340	0,979	0,00	0,26
350	0,981	0,00	0,23

Change in correction between bins:

As per C.7.3 (see Table C.4).

Table C.4 – Additional uncertainty due to change in bins

Bin centre	Magnitude of change between bins (left)	Magnitude of change between bins (right)	Additional standard uncertainty (%)
320	1,019	-	0 % (within limit)
330	1,009	0,981	0 % (within limit)
340	1,013	0,988	0 % (within limit)
350	-	0,992	0 % (within limit)

Wind vane adjustment:

The wind vane was left in place so no additional uncertainty is required per C.7.4.

Seasonal uncertainty:

The site calibration was conducted in the winter while the power curve measurement was conducted spanning multiple seasons, including the summer. Note that the time of day filter needed to be adjusted due to the change in sunrise and sunset. A comparison of the wind

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shear exponent values (see Figure C.17) found a change greater than 0,05 (0,15 vs. 0,22), which is greater than the limits of C.7.5 so additional uncertainty due to the measurements being in different seasons is required per C.7.5.

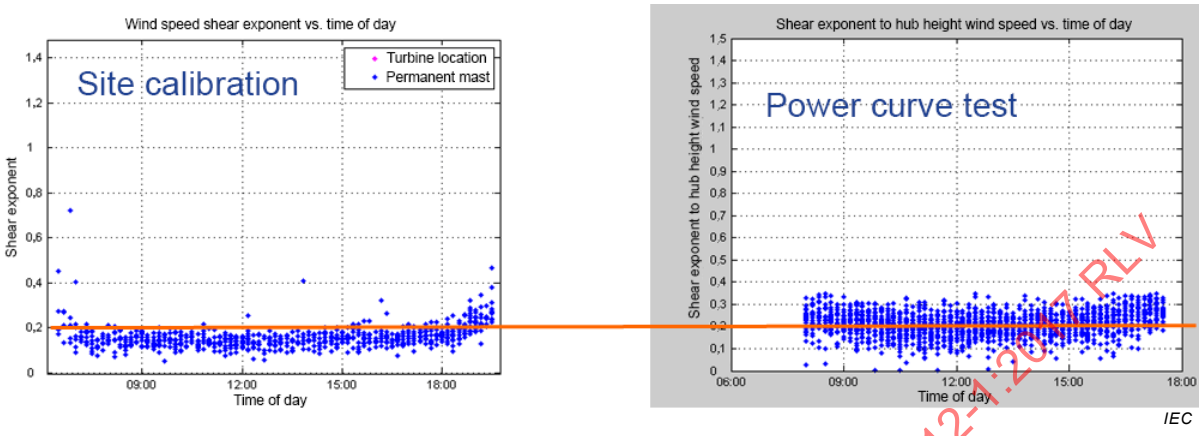

Figure C.17 – Site calibration wind shear vs. power curve test wind shear

The seasonal correction component is one-third of the magnitude of the total correction. This may be calculated for each data point as:

$$U = 1/3 \times \text{abs}(V_{\text{Turb_predicted}} - V_{\text{RM_measured}}) \quad \text{(C.9)}$$

where

U is the standard uncertainty in one data point;

$V_{\text{Turb_predicted-}i}$ is the wind turbine predicted wind speed applying site calibration flow correction;

$V_{\text{RM_measured-}i}$ is the measured wind speed from the reference meteorological mast used to predict the wind at the wind turbine.

The uncertainties during the power performance test may then be bin averaged against reference meteorological mast wind speed and direction to calculate the total uncertainty.

C.9.3 Example C

Site description:

The site is in very complex terrain. The site is a mountain top site within a mountain range. The site is a ridgeline site perpendicular to the principle wind direction, with terrain dropping off steeply in front of and behind the ridge. The wind is very mono-directional with nearly all winds coming from a 30° sector. There is another ridge line 3 km directly up-wind a few hundred meters taller than the ridgeline on which the site is located. The site is therefore considered to be type C terrain as it may be located in a recirculation zone from the upwind ridge.

Site calibration setup:

The meteorological mast is located 2,5 rotor diameters from the test wind turbine on the same ridge and at a very similar elevation (within 5 m). Wind shear was measured using anemometers mounted lower on the meteorological masts. A vertical wind speed measurement was not included.

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Step 1: Check the significance of wind shear at the site

Wind shear exponent values are low and sometimes negative. All wind shear values are between –0,05 and 0,20 and with no obvious correlation to time of day or other measured conditions. Turbulence is high. This indicates neutral to unstable atmosphere and wind shear is not therefore considered to be a significant factor for the site calibration, so the linear regression method may be used.

Step 2:

Skipped as wind shear has already been determined to be low. There is no stable atmosphere at this site.

Step 3: Calculate results

For each wind direction bin a linear regression of the wind speed at the wind turbine location vs. the wind speed at the reference meteorological mast is calculated along with the r^2 value of the regression. The count of total valid data points in each wind direction bin is also recorded. The data scatter is very high and the magnitude of the change in flow correction between bins was also very high.

Step 4: Quality checks and uncertainty

The data confirms that the site is in a recirculation zone of the up-wind ridge. The data scatter is very high and the results do not converge, indicating that despite the reference meteorological mast and test wind turbine being located side by side on the ridge at similar elevation with similar local terrain, the correlation in wind speed between the two locations is very poor. This will have negative consequences on the accuracy and uncertainty of a power curve measured at this location.

Anemometer operational uncertainty:

No vertical wind speed measurement was included so the Class B operational characteristic uncertainty shall be used. The anemometer operational characteristic classification is 5,4B.

Convergence check:

The data fails the convergence check for all wind direction bins. The data does not converge to within 0,5 % of the final value until 75 % of the data collected has been included. A sample check for one of the wind direction bins is shown in Figure C.18 below.

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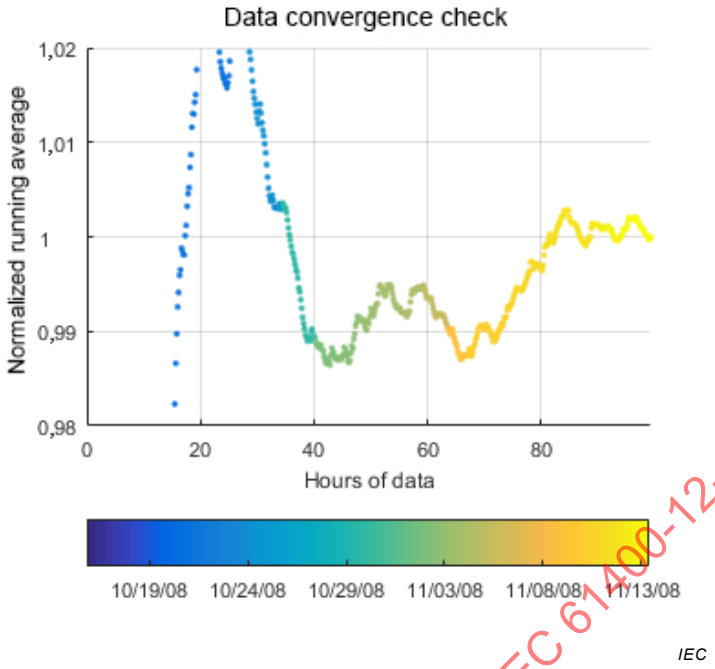

Figure C.18 – Convergence check for 270° bin

Change in magnitude of correction between bins:

All adjacent bins had changes in magnitude on the order of 10 %. The additional uncertainty is calculated as follows.

Table C.5 – Additional uncertainty due to change in bins

Bin centre	Magnitude of change between bins (left)	Magnitude of change between bins (right)	Additional standard uncertainty (%)
260	1,137	1,176	4,52 %
270	1,093	0,912	2,61 %
280	1,023	0,946	1,11 %

Wind vane adjustment:

No wind vane adjustment was made, so no additional uncertainty is required.

Seasonal uncertainty adjustment:

The site calibration and power performance test were conducted in different seasons (fall and summer), however the wind shear and turbulence values did not change by more than the allowable limits between seasons. A vertical wind speed was not recorded to assess the upflow angle, however given that the site is in a recirculation zone, a wide range of upflow angles are expected and there is no reason to expect seasonal dependence. The site was located in a hot climate with minimal vegetation, so no appreciable change in the surface roughness is expected.

No additional uncertainty for seasonal changes is necessary.

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Annex D
(normative)

Evaluation of uncertainty in measurement

Annex D addresses the requirements for the determination of uncertainty in measurement. The theoretical basis for determining the uncertainty using the method of bins, with a worked example of estimating uncertainties, can be found in Annex E.

The measured power curve shall be supplemented with an estimate of the uncertainty of the measurement. The estimate shall be based on the ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995).

Following the ISO/IEC Guide 98-3, there are two ~~types~~ categories of uncertainties: category A, the magnitude of which can be deduced from measurements, and category B, which are estimated by other means. In both categories, uncertainties are expressed as standard deviations and are denoted standard uncertainties.

a) The measurands

The measurands are the power curve, determined by the measured and normalized bin values of electric power and wind speed (see 9.1 and 9.2), and the estimated annual energy production (see 9.3). Uncertainties in the measurements are converted to uncertainty in the measurand by means of sensitivity factors.

b) Uncertainty components

Table D.1 provides a minimum list of uncertainty parameters that shall be included in the uncertainty analysis.

Table D.1 – List of uncertainty components

Measured parameter	Uncertainty component	Uncertainty category
Electric power	Current transformers	B
	Voltage transformers	B
	Power transducer or power measurement device	B
	Data acquisition system (see ~~note~~ below)	B
	Variability of electric power	A
Wind speed (cup and sonic anemometer)	Anemometer calibration	B
	~~Operational characteristics~~	~~B~~
	~~Mounting effects~~	~~B~~
	~~Flow distortion due to terrain~~	~~B~~
	Classification	B
	Mast flow distortion	B
	Boom flow distortion	B
	Lightning finial	B
	Data acquisition system (see ~~note~~ below)	B
	Post calibration / in-situ test	B
Wind speed (remote sensing device)	Verification test for RSD	B
	In-situ test	B
	RSD classification	B
	Mounting effects	B
	Flow variation across probe volume at same	

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Measured parameter	Uncertainty component	Uncertainty category
	height	B
	Monitoring test	B
Rotor equivalent wind speed	Wind shear measurement	B
	Wind veer measurement	B
Wind direction (vane or sonic)	Calibration	B
	North mark	B
	Boom orientation	B
	Operation (influence of mast)	B
	Magnetic declination angle	B
	Data acquisition system (see below)	B
Wind direction (remote sensing device)	Verification test	B
	Classification	B
	Monitoring test	B
	Flow variation across probe volume at same height	B
		B
	Alignment	B
	Magnetic declination angle	B
	Data acquisition system (see below)	
Air temperature	Temperature sensor	B
	Radiation shielding	B
	Mounting effects	B
	Data acquisition system (see ~~note~~ below)	B
Air pressure	Pressure sensor	B
	Mounting effects	B
	Data acquisition system (see ~~note~~ below)	B
Relative humidity	Humidity sensor	B
	Mounting effects	B
	Data acquisition system (see below)	B
Data acquisition system	Signal transmission	B
	System accuracy	B
	Signal conditioning	B
Terrain (no site calibration)	Flow distortion due to terrain	B
Terrain (with site calibration)	Anemometer calibration before test	B
	Post calibration/In-situ calibration	B
	Anemometer classification	B
	Mounting effects	B
	Standard mounting	B
	Alternative mounting	B
	Side mounted	B
	Lightning finial	B
	Data acquisition system (see below)	B
	Change of correction (adjacent wind direction bins)	B
		B
	Removal of wind direction sensor between site calibration and power curve measurement	B

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Measured parameter	Uncertainty component	Uncertainty category
	Seasonal variation	A
	Statistical variability in site calibration	
Method	Air density correction	B
	Wind conditions – missing shear information	B
	Wind conditions – missing veer information	B
	Wind conditions – missing upflow information	B
	Wind conditions – missing turbulence information	B
	Seasonal effects	B
	Turbulence normalisation (or lack of turbulence normalisation)	B
	Cold climate measurements	B

It should be noted that the implicit assumption of the hub height wind speed power curve method of this standard is that the 10 min mean power yield from a wind turbine is fully explained by the simultaneous 10 min mean wind speed measured at hub height and the air density.

This is not the case. Other flow variables affect power yield and thus identical wind turbines will yield different power at different sites even if the hub height wind speed and air density are the same. These other variables include turbulence fluctuations of wind speed (in three directions), the inclination of the flow vector relative to horizontal, scale of turbulence and wind shear of mean wind speed over the rotor. Presently, analytical tools offer little help in identification of the impact of some of these variables and experimental methods encounter equally serious difficulties.

The result is that the power curve will vary from one site to the next~~, but since the other influential variables are not measured and taken into account, the variation in the power curve~~ which will appear as uncertainty.

This ~~apparent~~ uncertainty stems from differences in observed power yield under different topographical and climatic conditions, i.e. when comparing an AEP measured in homogeneous terrain with an AEP measured at a non-homogeneous wind farm site.

Quantification of this apparent uncertainty is difficult. Depending on site conditions and climate, the uncertainty may amount to several percent. In general terms, the uncertainty may be expected to increase with increasing complexity of topography and with increasing frequency of non-neutral atmospheric conditions.

However, this issue of the standard presents methods to account for at least some of these influential variables (for example wind shear and turbulence). The uncertainty in these correction methods shall also be assessed. It is therefore implicit that where these variables are considered significant and a correction is not made then the uncertainty should be increased to account for the lack of a correction.

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Annex E
(informative)

Theoretical basis for determining the uncertainty of measurement using the method of bins

E.1 General

In Annex E, all the uncertainty statements made throughout the standard have been combined and added to in order to make a consistent uncertainty evaluation of a power curve measurement, covering both the power curve and the calculated AEP.

In order to achieve a clear structure to introduce this rather complex topic, this annex has been structured as shown below. The main structure is based on a separate section for each category of uncertainty components; as wind speed has many uncertainty components these have been given their own clauses, as seen below:

Clause E.2 A general mathematical outline and a table with an overview of all uncertainty components and their default magnitudes.

Clause E.3 Category A uncertainties

Clause E.4 Category B uncertainties – Introduction and data acquisition

Clause E.5 Category B – Power output

Clause E.6 Category B – Wind speed – Introduction and sensors

Clause E.7 Category B – Wind speed – RSD

Clause E.8 Category B – Wind speed – REWS

Clause E.9 Category B – Wind speed – Terrain

Clause E.10 Category B – Air density

Clause E.11 Category B – Method

Clause E.12 Category B – Wind direction

Clause E.13 Combining uncertainties.

In this annex, a calculation method is given for aggregating uncertainties, as well as relevant tables for correlation factors and a (non-exhaustive) numerical example.

For all the category B uncertainties, a description is given as to what that uncertainty component covers, the symbol used for each component, references to other annexes where the component is discussed and a discussion of the default magnitude.

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E.2 Combining uncertainties

E.2.1 General

In its most general form, the combined standard uncertainty of the power in bin i, $u_{c,i}$ can be expressed by:

$$u_{c,i}^2 = \sum_{k=1}^{M} \sum_{l=1}^{M} c_{k,i} u_{k,i} c_{l,i} u_{l,i} \rho_{k,l,i,i} \quad \text{(E.1)}$$

where

$c_{k,i}$ is sensitivity factor of component k in bin i;

$u_{k,i}$ is the standard uncertainty of component k in bin i;

M is the number of uncertainty components in each bin;

$\rho_{k,l,i,j}$ is the correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j (in the expression the components k and l are both in bin i).

The uncertainty component is the individual input quantity to the uncertainty of each measured parameter. The combined standard uncertainty in the estimated annual energy production, u_{AEP}, can in its most general form be expressed by:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{M} \sum_{l=1}^{M} f_i \, c_{k,i} \, u_{k,i} \, f_j \, c_{l,j} \, u_{l,j} \, \rho_{k,l,i,j} \quad \text{(E.2)}$$

where

f_i is the relative occurrence of wind speed ~~between V_{i-1} and V_i: $F(V_i) - F(V_{i-1})$~~ within bin i;

~~$F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;~~

N is the number of bins;

N_h is the number of hours in one year ≈ 8 760.

It is seldom possible to deduce explicitly all the values of the correlation coefficients $\rho_{k,l,i,j}$ and normally significant simplifications are necessary. To allow the above expressions of combined uncertainties to be simplified to a practical level, the following assumptions may be made:

a) uncertainty components are either fully correlated ($\rho_{k,l,i,j}$ = 1, implying linear summation to obtain the combined standard uncertainty) or independent ($\rho_{k,l,i,j}$ = 0, implying quadratic summation, i.e. the combined standard uncertainty is the square root of summed squares of the uncertainty components);

~~b) all category A uncertainty components are mutually independent and category A and B uncertainty components are independent (they are either from the same bin or they are from different bins), while category B uncertainty components are mutually fully correlated (e.g. uncertainty in power transducer in different bins).~~

b) category A uncertainties are uncorrelated across wind speed bins, while category B uncertainties are fully correlated across wind speed bins;

c) only relevant for site calibration uncertainties: category A uncertainties are uncorrelated across wind direction bins, while category B uncertainties are fully correlated across wind direction bins.

The correlation of the same type of uncertainty across different wind measurement heights when calculating the uncertainty of the rotor equivalent wind speed or a wind shear/veer normalised wind speed shall be assessed individually for each component and each case. Each uncertainty may first be accumulated across the measurement heights for a certain bin of the rotor equivalent or wind shear/veer normalised wind speed. Afterwards the uncertainty components of the rotor equivalent wind speed or the wind shear/veer normalised wind speed can be treated as described in bullet points a) and b).

Using these assumptions, the combined uncertainty of the power within a bin, $u_{c,i}$, can be expressed by

$$u_{c,i}^2 = \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + \sum_{k=1}^{M_B} c_{k,i}^2 \, u_{k,i}^2 = s_i^2 + u_i^2 \quad \text{(E.3)}$$

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where

M_A is the number of category A uncertainty components;

M_B is the number of category B uncertainty components;

$s_{k,i}$ is the category A standard uncertainty of component k in bin i;

s_i is the combined category A uncertainties in bin i;

u_i is the combined category B uncertainties in bin i.

It should be noted that $u_{c,i}^2$ is not independent of bin size due to the dependency of $s_{P,i}$ on the number of data sets in the bin (see Equation (E.10)).

The assumptions imply that the combined standard uncertainty in energy production, u_{AEP}, is:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} \left(\sum_{i=1}^{N} f_i \, c_{k,i} \, u_{k,i}\right)^2 \quad \text{(E.4)}$$

The significance of the second term in this equation is that each individual category B uncertainty component progresses through to the corresponding AEP uncertainty, applying the assumption of full correlation across bins for the individual components. Finally, the cross-bin combined uncertainty components are added quadratically into a resulting AEP uncertainty.

Furthermore, certain components of category A uncertainty cannot necessarily be conveniently derived or estimated on a bin-wise basis. For example the site calibration method category A components which may have been derived by a sensitivity analysis on the AEP calculation. In that case, these components should be added quadratically into the resulting AEP uncertainty. Refer to Equation (E.8) for an example of this.

In practice, it may not be convenient to sum category B uncertainty components across the bins before they are individually combined. An approximation, allowing the category B uncertainty components to be combined within bins before they are combined across bins (i.e. s_i and u_i can be used), leads to the more convenient expression:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \left(\sum_{i=1}^{N} f_i \sqrt{\sum_{k=1}^{M_B} c_{k,i}^2 \, u_{k,i}^2}\right)^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \, s_i^2 + N_h^2 \left(\sum_{i=1}^{N} f_i u_i\right)^2 \quad \text{(E.5)}$$

The u_{AEP}, obtained by this expression is always equal to or larger than that obtained using Equation (E.4).

E.2.2 Expanded uncertainty

The combined standard uncertainties of the power curve and the AEP may additionally be expressed by expanded uncertainties. Referring to the ISO/IEC Guide 98-3 and assuming normal distributions, intervals having levels of confidence shown in Table E.1 can be found by multiplying these combined standard uncertainties by a coverage factor also shown in the table.

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Table E.1 – Expanded uncertainties

Level of confidence %	Coverage factor
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

E.2.3 ~~Example~~ Basis for the uncertainty assessment

The calculation methodology goes through an estimate of the category A and B uncertainties for each bin of a measured power curve. The uncertainty of the power curve is derived, and finally the uncertainty of the annual energy production (AEP) is estimated. Please note that a fully worked out example has not been included, due to the differences in calculations for the various measurement approaches. Where possible a worked-out example for part of the calculation has been included to show how the equations and estimates of default values for uncertainty components have been applied.

The calculation methodology follows the ISO guide and the assumptions made above. Using the combination of the category B uncertainty components according to Equation (E.5), all uncertainty components within each bin can be combined first to express the combined category B uncertainty of each measured parameter, as for example for the wind speed:

$$u_{V,i}^2 = u_{V1,i}^2 + u_{V2,i}^2 + \ldots \tag{E.6}$$

where uncertainty components refer to the uncertainty components in Table E.2, using symbols and indices as in the table.

Secondly, the standard uncertainties of the measurands can be expressed by the uncertainties of the measurement parameters in bin i:

$$u_{c,i}^2 = s_{P,i}^2 + c_{V,i}^2 s_{SC,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2 + c_{V,i}^2 u_{M,i}^2 \tag{E.7}$$

where

$s_{P,i}$ is the category A standard uncertainty of power in bin i;

$s_{SC,i}$ is the category A standard uncertainty of site calibration in bin i;

$u_{P,i}$ is the category B standard uncertainty of power in bin i;

$u_{V,i}$ is the category B standard uncertainty of wind speed in bin i;

$u_{T,i}$ is the category B standard uncertainty of temperature in bin i;

$u_{B,i}$ is the category B standard uncertainty of pressure in bin i;

$u_{RH,i}$ is the category B standard uncertainty of relative humidity in bin i;

$u_{M,i}$ is the category B standard uncertainty of the method in bin i;

$c_{V,i}$ is the sensitivity factor for wind speed in bin i;

$c_{T,i}$ is the sensitivity factor for temperature in bin i;

$c_{B,i}$ is the sensitivity factor for pressure in bin i;

$c_{RH,i}$ is the sensitivity factor for relative humidity in bin i.

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This also gives

$$u_{AEP}^2 = N_h^2\left(\sum_{i=1}^{N} f_i^2 (s_{P,i}^2 + c_{V,i}^2 s_{SC,i}^2) + \left(\sum_{i=1}^{N} f_i \sqrt{u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2 + c_{V,i}^2 u_{M,i}^2}\right)^2\right) \quad \text{(E.8)}$$

In the above equation, the uncertainties due to the data acquisition system are part of the uncertainty of each measurement parameter ~~and flow distortion due to terrain is included in the uncertainty of wind speed~~. ~~The uncertainty related to climatic variations, s_W, is evaluated separately.~~

~~The example only considers the uncertainty components, which shall be included in the uncertainty analysis according to Table D.1.~~ The measured power curve, shown in Figure 6 and Table 4, is used in the uncertainty calculation in this annex. ~~The power curve is extrapolated with a constant power, which is the power in the last bin, to the cut-out wind speed of 25 m/s.~~ The results of the uncertainty analysis in the example are also shown in Figure 6, Table 4 and Table 5. All sensitivity factors are listed in Table E.10, and category B uncertainties are listed in Table E.11.

Table E.2 – List of category A and B uncertainties

Category B: Instruments	Note	~~Standard~~	Uncertainty	Sensitivity	Magnitude
Power output			$u_{P,i}$	$c_{P,i} = 1$	
Current transformers *	a		~~$u_{P1,I}$~~ $u_{P,CT,i}$		0,75 %
Voltage transformers *	a	~~IEC 60044-1~~ ~~IEC 60044-2~~	~~$u_{P2,V}$~~ $u_{P,VT,i}$		0,5 %
Power transducer or *	a	~~IEC 60688~~	~~$u_{P3,I}$~~ $u_{P,PT,i}$		0,5 %
Power measurement device*	~~c~~				
DAQ (see E.4.2)	d		$u_{dP,i}$		0,1 % to 0,2 %
Wind speed			$u_{V,i}$		
~~Anemometer *~~	~~b~~		~~$u_{V1,i}$~~		
~~Operational characteristics *~~	~~cd~~		~~$u_{V2,i}$~~		
Wind speed measurement			$u_{VHW,i}$		
Wind speed (cup or sonic)			$u_{VS,i}$		
Calibration	b		$u_{VS,precal,i}$	For the *AEP* uncertainty (and for the last bin of the power curve uncertainty) use: $c_{V,i} \approx \frac{P_i - P_{i-1}}{V_i - V_{i-1}}$ For the power curve uncertainty, use: $c_{V,i} \approx \frac{1}{2}\cdot\left(\frac{(P_{i+1}-P_i)}{(V_{i+1}-V_i)} + \frac{(P_i-P_{i-1})}{(V_i-V_{i-1})}\right)$	From calibration
Post calibration / In-situ	b		$u_{VS,postcal,i}$		0,2 m/s
Classification	c		$u_{VS,class,i}$		1,0 %
Mounting effects *	~~c~~		~~$u_{V3,i}$~~		
Single top-mounted	d		$u_{VS,mnt,i}$		0,5 %
Side-by-side mounted	d		(same)		1,0 %
Side-mounted	d		(same)		1,5 %
Lightning finial	d		$u_{VS,lgt,i}$		0,1 % to 0,2 %
DAQ (see E.4.2)	d		$u_{dVS,i}$		0,1 % to 0,2 %
Wind speed (RSD)			$u_{VR,i}$	$c_{V,i}$ (see above)	
Calibration	bc		$u_{VR,ver,i}$		2 % to 3 %
In-situ check	c		$u_{VR,isc,i}$		See E.7.3
Classification	c		$u_{VR,class,i}$		1,0 % to 1,5 %
Mounting	c		$u_{VR,mnt,i}$		0,1 %
Flow variation in different probe volumes at same	d		$u_{VR,flow,i}$		2 % to 3 % see

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Category B: Instruments	Note	~~Standard~~	Uncertainty	Sensitivity	Magnitude
height					E.7.6
Monitoring test	c		$u_{VR,mon,i}$		0,5 %
Rotor equivalent wind speed			$u_{REWS,\ i}$	$c_{V,i}$ (see above)	
Wind shear	c		$u_{REWS,shear,\ i}$		See E.8.2
Wind veer	c		$u_{REWS,veer,\ i}$		See E.8.3
Wind speed – Terrain effects			$u_{VT,i}$	$c_{V,i}$ (see above)	
Without site calibration					
Flow distortion due to terrain	d		$u_{VT,i}$	$c_{V,i}$ (see above)	2 % or 3 % (offshore 1 % or 2 %)
With site calibration					
Anemometer calibration	b		$u_{VT,precal,i}$		From calibration
Post calibration / In-situ	b		$u_{VT,postcal,i}$		0,2 m/s
Anemometer classification	c		$u_{VT,class}$		1,0 %
Mounting effects					
Single top-mounted	d		$u_{VT,mnt,i}$		0,5 %
Side-by-side mounted	d		(same)		1,0 %
Side-mounted	d		(same)		1,5 %
Lightning finial	d		$u_{VT,lgt,i}$		0,1 % to 0,2 %
DAQ (see E.4.2)	d		$u_{dVT,i}$		0,1 % to 0,2 %
Change of correction (adjacent wind **direction** bins)	c		$u_{VT,coc,i}$		See E.9.8
Removal of wind direction sensor between site calibration and power curve measurement	c		$u_{VT,rmv,i}$		See E.9.9
Seasonal variation	c		$u_{VT,sv,i}$		See E.9.10
Air density			$u_{AD,i}$	$c_{T,i} \approx \frac{P_i}{288{,}15\,\mathrm{K}}$ $c_{B,i} \approx \frac{P_i}{1013\,\mathrm{hPa}}$	
Temperature			$u_{T,i}$	$c_{T,i}$ (see E.10.2)	
Temperature sensor *	ab		~~$u_{T1,i}$~~ $u_{T,cal,i}$		0,4 K to 0,6 K
Radiation shielding *	cd		~~$u_{T2,i}$~~ $u_{T,shield,i}$		1,5 K to 2,5 K
Mounting effects *	cd		~~$u_{T3,i}$~~ $u_{T,mnt,i}$		0,25 K to 0,4 K
DAQ (see E.4.2)	c		$u_{dT,i}$		0,1 % to 0,2 %
Air pressure		~~ISO 2533~~	$u_{B,i}$	$c_{B,i}$ (see E.10.7)	
Pressure sensor *	ab		~~$u_{B1,i}$~~ $u_{B,cal,i}$		2 hPa to 4 hPa
Mounting effects *	~~c~~ a		~~$u_{B2,i}$~~ $u_{B,mnt,i}$		10 % of correction
DAQ (see E.4.2)	c		$u_{dB,i}$		0,1 % to 0,2 %
Relative Humidity			$u_{RH,i}$	$c_{RH,i}$ (see E.10.11)	
Humidity sensor	ab		$u_{RH,cal,i}$		1 % to 2 %

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Category B: Instruments	Note	~~Standard~~	Uncertainty	Sensitivity	Magnitude
					(RH)
Mounting effects	cd		$u_{RH,mnt,i}$		0,1 % to 0,2 %
DAQ (see E.4.2)	c		$u_{dRH,i}$		0,1 % to 0,2 %
Method	cd		$u_{AD,method,i}$	$c_{AD,method,I} = c_{V.,i}$ (for actively regulated turbines)	0,2 % to 0,3 % on wind speed
Air density normalisation				$c_{AD,method,I} = c_{V.,i} = I$ (for stall regulated turbines)	
~~**Data acquisition system**~~			~~$u_{d,i}$~~	~~Sensitivity factor is derived from actual uncertainty parameter~~	
~~Signal transmission *~~	~~b~~		~~$u_{d1,i}$~~		
~~System accuracy *~~	~~cd~~		~~$u_{d2,i}$~~		
~~Signal conditioning*~~			~~$u_{d3,i}$~~		
Method			$u_{M,\ i}$	$c_{V,I}$ (see above)	
Wind conditions	d		$u_{M,wc,\ i}$		See E.11.2.1 bullet a) or b).
Wind conditions – wind shear	d		$u_{M,shear,\ i}$		See E.11.2.2
Wind conditions – wind veer	d		$u_{M,veer,\ i}$		See E.11.2.3
Wind conditions – upflow	d		$u_{M,upflow,\ i}$		See E.11.2.4
Wind conditions – turbulence	d		$u_{M,ti,\ i}$		0,3 % to 0,5 % (only for RSD with lower met mast) See E.11.2.5
Seasonal effects	d		$u_{M,sfx,\ i}$		0,7 % See E.11.3
Turbulence normalisation	d		$u_{M,tinorm,\ i}$		See E.11.4
Cold climate	d		$u_{M,cc,\ i}$		0,5 % to 1 %
Wind direction					
Wind direction vane / sonic			$u_{WV,\ i}$	None (see E.12.2.1)	
Calibration	b		$u_{WV,cal,\ i}$		See E.12.2.1
North mark	c		$u_{WV,nm,\ i}$		See E.12.2.2
Boom orientation	d		$u_{WV,bo,\ i}$		See E.12.2.3
Operation (influence of mast)	c		$u_{WV,oe,\ i}$		See E.12.2.4
Magnetic declination angle	c		$u_{WV,mda,\ i}$		See E.12.2.5
DAQ (see E.4.2)	c		$u_{dWV,\ i}$		See E.12.2.6

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Wind direction (RSD)			$u_{WR,\,i}$	None (see E.12.3)	
Verification	ab		$u_{WR,ver,\,i}$		See E.12.3.1
Classification	c		$u_{WR,class,\,i}$		See L.4.4
Monitoring test	c		$u_{WR,mon,\,i}$		See E.12.3.2
Flow variation in different probe volumes at same height	c		$u_{WR,fv,\,i}$		See E.12.3.3
Alignment	d		$u_{WR,align,\,i}$		See E.12.3.4
Magnetic declination angle	c		$u_{WR,mda,\,i}$		See E.12.3.5
DAQ (see E.4.2)	c		$u_{dWR,\,i}$		See E.12.3.6
~~**Category B: Terrain**~~					
~~**Flow distortion due to terrain***~~	~~bc~~		~~$u_{V4,i}$~~	~~$c_{V,i}$ (see above)~~	
~~**Category B: Method**~~					
~~**Method**~~ ~~Air density correction~~					
Category A: Statistical	~~cd~~		~~$u_{m,i}$~~ ~~$u_{m1,i}$~~	~~$c_{T,i}$ and $c_{B,i}$~~	
Electric power *	e		$s_{P,I}$	$c_{P,i}$ = 1	
~~Climatic variations~~	~~e~~		~~s_w~~	~~---~~	
Site calibration	e		s_{sc}	$c_{V,i}$ (see above)	
~~* parameter required for the uncertainty analysis~~					

NOTE Identification of uncertainties:
a = reference to standard;
b = calibration;
c = other "objective" method";
d = "guesstimate";
e = statistics.

The ranges for the uncertainty components given in Table E.2 should be considered. Where available, actual values from specific measurements should be used. It should be noted that uncertainty components should not be estimated with a value of zero, as per guidance in the GUM, unless the specific uncertainty components are not relevant for the specific test methodology applied (see Clause E.14).

Also, it is important to note that the wind direction uncertainty does not influence directly the uncertainty of the power curve or the AEP (unless a wind veer normalisation is applied). However, the wind direction uncertainty is included here as it is important to understand how accurate the measurement sector filtering is being implemented as well as how accurate the site calibration factors are applied to data from the right sectors. As the wind direction uncertainty shall be reported, this table gives the minimum uncertainty components that shall be considered for the wind direction uncertainty. An estimate of the magnitude of these components is not given, but these should be included in a reported power curve.

Note that some calibration reports report an uncertainty for a coverage factor of two instead of one. In order to combine uncertainties correctly, the uncertainties should be converted to a coverage factor consistent with all uncertainty inputs (by default, use a coverage factor of 1).

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E.3 Category A uncertainties

E.3.1 General

~~The only category A uncertainty that needs to be considered is the uncertainty of the measured and normalized electric power data in each bin.~~

Category A uncertainties in measured and normalised electric power and due to climatic variations and the site calibration (if conducted) need to be considered.

E.3.2 Category A uncertainty in electric power

The standard deviation of the distribution of normalized power data in each bin is calculated by the equation:

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1} \sum_{j=1}^{N_i} \left(P_i - P_{n,i,j}\right)^2} \quad \text{(E.9)}$$

where

$\sigma_{P,I}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10 min data sets in bin i;

P_i is the normalized and averaged power output in bin i;

$P_{n,i,j}$ is the normalized power output of data set j in bin i.

The standard uncertainty of the normalized and averaged power in the bin is estimated by the equation:

$$s_i = s_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \quad \text{(E.10)}$$

where

$s_{P,i}$ is the category A standard uncertainty of power in bin i;

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10 min data sets in bin i.

E.3.3 Category A uncertainties in ~~climatic variations~~ the site calibration

~~The power performance test may have been carried out under special atmospheric conditions that affect the test result systematically, such as very stable (large vertical shear and low turbulence) or unstable (little shear and high turbulence) atmospheric stratification or frequent and/or large changes in wind direction. The order of magnitude of this climatic uncertainty, s_w, can be tested by~~

~~a) subdividing the data record into segments, each long enough to have small (statistical) uncertainty on power;~~

~~b) estimate annual energy production for each of the derived power curves, and~~

~~c) calculate the standard deviation of the annual energy production estimates.~~

The residuals between the site calibration corrected and measured wind speed at the wind turbine meteorological mast are used to define the category A uncertainty of the site calibration, s_{sc}. Refer to C.6.1 for the method of derivation.

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E.4 Category B uncertainties: Introduction and data acquisition system

E.4.1 Category B uncertainties: Introduction

The category B uncertainties are assumed to be related to the instruments, the data acquisition system,the terrain surrounding the power performance test site, the wind conditions and the uncertainty related to the applied method. If the uncertainties are expressed as uncertainty limits, or have implicit, non-unity coverage factors, the standard uncertainty ~~must~~ shall be estimated or they ~~must~~ shall be properly converted into standard uncertainties.

~~NOTE~~ Consider an uncertainty expressed as an uncertainty limit ± U. If a rectangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{3}} \tag{E.11}$$

If a triangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{6}} \tag{E.12}$$

E.4.2 Category B uncertainties: data acquisition system

The uncertainties related to the data acquisition have been included under the treatment for the specific signals. The uncertainty of the electrical power includes a component for data acquisition and the same for wind speed and the other measured signals.

We assume in this annex the data acquisition system to have a standard uncertainty $u_{\mathrm{d},i}$ of 0,1 % of the full range of each measurement channel. However, for the reporting of a specific power performance test the data acquisition uncertainty shall be estimated for the specific test setup, including at least the contributions to the data acquisition uncertainty mentioned in E.4.2.

There may be uncertainties from transmission, signal conditioning, analogue to digital conversion, and data processing in the data acquisition system. The uncertainties may be different for each measurement channel. The standard uncertainty of the data acquisition system for the full range of a certain measurement channel, $u_{\mathrm{d},i}$, can be expressed as:

~~$$u_{\mathrm{d},i} = \sqrt{u_{\mathrm{d1},i}^2 + u_{\mathrm{d2},i}^2 + u_{\mathrm{d3},i}^2}$$~~

$$u_{\mathrm{d},i} = \sqrt{u_{\mathrm{d,ST},i}^2 + u_{\mathrm{d,SA},i}^2 + u_{\mathrm{d,SC},i}^2} \tag{E.13}$$

where

~~$u_{\mathrm{d1},i}$ is the uncertainty in signal transmission and signal conditioning in bin i;~~

~~$u_{\mathrm{d2},i}$ is the uncertainty in digitization in bin i, for example from quantization resolution;~~

~~$u_{\mathrm{d3},i}$ is the uncertainty in other parts of the integrated data acquisition system (software, storage system) in bin i.~~

$u_{\mathrm{d,ST},i}$ is the uncertainty due to signal transmission in bin i;

$u_{\mathrm{d,SA},i}$ is the uncertainty due to system accuracy in bin i;

$u_{\mathrm{d,SC},i}$ is the uncertainty due to signal conditioning in bin i.

Although the assumption of a standard uncertainty of 0,1 % of the full range of the measurement channel is reasonable in many cases, specific hardware and conditions can

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cause this to be much higher. In order to ensure that the uncertainty of the data acquisition system is indeed negligible compared to the uncertainty of the sensors (which as a guidance should be interpreted as a factor 10 in magnitude when comparing standard uncertainties) an assessment of the actual uncertainty of the data acquisition system used shall be done.

E.5 Category B uncertainties ~~in electric power~~: Power output

E.5.1 General

The category B uncertainties regarding the power output are based on four different uncertainty components which are introduced here.

The symbol for this uncertainty component is $u_{P,i}$.

The uncertainty of the power ~~sensor~~ measurement has uncertainty contributions from the current and voltage transformers and from the power transducer (or other power measurement device). Uncertainties of these subcomponents are normally stated by their classification.

Finally the uncertainty related to the data acquisition of the power signal shall be added.

~~The standard uncertainty of the electric power for each bin, ($u_{P,i}$), is calculated by combining the standard uncertainties from the power transducer, the current and voltage transformers and the data acquisition system:~~

$$u_{P,i} = \sqrt{u_{P1,i}^2 + u_{P2,i}^2 + u_{P3,i}^2 + u_{dP,i}^2} \quad \text{(E.14)}$$

~~where~~

~~$u_{P1,i}$ is the uncertainty in current transformers in bin i;~~

~~$u_{P2,i}$ is the uncertainty in voltage transformers in bin i;~~

~~$u_{P3,i}$ is the uncertainty in the power transducer in bin i;~~

~~$u_{dP,i}$ is the uncertainty in the data acquisition system for the power channel in bin i.~~

E.5.2 Category B uncertainties: Power output – Current transformers

This uncertainty component covers the uncertainty due to the current transformer as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{P,CT,i}$.

In this annex, the current ~~and voltage~~ transformers and the power transducer are all assumed to be of class 0,5 which is the minimum acceptable class for a power curve measurement as required by this standard.

The current transformers of class 0.5 (nominal loads of the current transformers are here designed to match the nominal power, ~~1 000~~ 2 000 kW, and not ~~200~~ 125 % of nominal power). They have uncertainty limits, referring to IEC ~~60044-1~~ 61689-2, of ±0,5 % of the current at 100 % load. At 20 % and 5 % loads, though, the uncertainty limits are increased to ±0,75 % and ±1,5 % of the current, respectively. For power performance measurements on wind turbines, the most important energy production is produced at a reduced power. Thus, we anticipate the uncertainty limits of ±0,75 % of the current at 20 % load to be a good average.

The uncertainty distribution for a current transformer is assumed to be rectangular. If current transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.

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It is assumed that the uncertainties of the three current transformers are caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each current transformer contributes by one-third to the power measurement, it follows that the uncertainty of all current transformers is proportional to the power as follows:

$$u_{\mathrm{P,CT},i} = \frac{0{,}75\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}43\ \% \cdot P_i\ [\mathrm{kW}] \qquad \text{(E.14)}$$

E.5.3 Category B uncertainties: Power output – Voltage transformers

This uncertainty component covers the uncertainty due to the voltage transformer as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{\mathrm{P,VT},i}$.

In this annex, the voltage transformers and the power transducer are all assumed to be of class 0.5, which is the minimum acceptable class for a power curve measurement as required by this standard.

The voltage transformers of class 0,5, have uncertainty limits, referring to IEC ~~60044-2~~ 61869-3, of ±0,5 % of the voltage at all loads. The uncertainty distribution is assumed to be rectangular.

Voltage transformers are not used in all measurements and the value for this uncertainty components may be set to zero when not used.

If the voltage transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.

The grid voltage is normally rather constant and independent of the wind turbine power. The uncertainties of the three voltage transformers are as for the current transformers assumed to be caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each voltage transformer contributes by one-third to the power measurement, it follows that the uncertainty of all voltage transformers is proportional to the power as follows:

$$u_{\mathrm{P,VT},i} = \frac{0{,}5\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}29\ \% \cdot P_i\ [\mathrm{kW}] \qquad \text{(E.15)}$$

E.5.4 Category B uncertainties: Power Output – Power transducer or other power measurement device

~~If current and voltage transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.~~

This uncertainty component covers the uncertainty due to the power transducer (or other power measurement device) as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{\mathrm{P,PT},i}$.

The power transducer of class 0,5, referring to IEC 60688, with a nominal power of ~~2 000~~ 2 500 kW (~~200~~ 125 % of the nominal power, ~~1 000~~ 2 000 kW, of the wind turbine) has an uncertainty limit of ~~10~~ 12,5 kW. The uncertainty distribution is assumed to be rectangular.

The uncertainty of the power transducer is thus:

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$$u_{P3,i} = \frac{10\ \text{kW}}{\sqrt{3}} = 5{,}8\ \text{kW} \quad \text{(E.17)}$$

$$u_{P,PT,i} = \frac{12{,}5\ \text{kW}}{\sqrt{3}} = 7{,}2\ \text{kW} \quad \text{(E.16)}$$

E.5.5 Category B uncertainties: Power output – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the power signal.

The symbol for this uncertainty component is $u_{dP,i}$.

The magnitude of this component has an assumed default value of 0,1 % to 0,2 % of the full range of the data acquisition system.

Considering the electric power range of the measurement channel for a 2 MW turbine to be ~~2~~ ~~500~~ 3 000 kW and an uncertainty of the data acquisition system of 0,1 % of this range~~, the standard uncertainty from the electric power sensor for each bin is~~ gives a resulting uncertainty of 3 kW.

$$u_{P,i} = \sqrt{(0{,}43\ \% \cdot P_i\,[\text{kW}])^2 + (0{,}29\ \% \cdot P_i\,[\text{kW}])^2 + (5{,}8\ \text{kW})^2 + (0{,}1\ \% \cdot 2\,500\ \text{kW})^2} = \sqrt{(0{,}52\ \% \cdot P_i\,[\text{kW}])^2 + (6{,}3\ \text{kW})^2} \quad \text{(E.18)}$$

E.6 Category B uncertainties: Wind speed – Introduction and sensors

~~The uncertainty of the wind speed measurement is a combination of several uncertainty components. Usually, the most important ones are flow distortion due to the terrain, operational characteristics of the cup anemometer, the mounting effects on the anemometer, and the uncertainty of the anemometer calibration. If the terrain complies with the terrain requirements of Annex B, the flow distortion due to the terrain is determined as 2 % or 3 %, dependent on the distance of the meteorological mast from the wind turbine. If an experimental site calibration is undertaken according to Annex C, the standard uncertainty derived from the site calibration shall be used. The flow distortion due to mounting effects (see Annex G) might be considerable unless the anemometer is mounted on a tube on top of the mast. The uncertainty of the anemometer calibration(see Annex F) and the uncertainty due to operational characteristics (see Annex I) might be dominating in the measurement.~~

~~The category B uncertainty from wind speed in bin i, $u_{V,i}$, can be expressed as:~~

$$u_{V,i} = \sqrt{u_{V1,i}^2 + u_{V2,i}^2 + u_{V3,i}^2 + u_{V4,i}^2 + u_{dV,i}^2} \quad \text{(E.19)}$$

~~where~~

~~$u_{V1,i}$ is the uncertainty of the anemometer calibration in bin i;~~

~~$u_{V2,i}$ is the uncertainty due to operational characteristics of the anemometer in bin i;~~

~~$u_{V3,i}$ is the uncertainty of flow distortion due to mounting effects in bin i;~~

~~$u_{V4,i}$ is the uncertainty of flow distortion due to the terrain in bin i;~~

~~$u_{dV,i}$ is the uncertainty in the data acquisition system for the wind speed in bin i.~~

~~The sensitivity factor is determined as the local slope of the measured power curve:~~

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$$c_{V,i} = \left| \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right| \qquad \text{(E.20)}$$

The standard uncertainty of the anemometer calibration is estimated to be 0,1 m/s. Uncertainty due to operational characteristics of the anemometer is derived from the classification (Annex I) which is estimated to be a class 1,2A. Assuming a rectangular uncertainty distribution, the class corresponds to a standard uncertainty of 0,034 m/s + 0,0034 V_i. The standard uncertainty of the flow distortion due to mounting effects is estimated to be 1 % of the wind speed. Considering a wind speed range of 30 m/s of the measurement channel and an uncertainty of the data acquisition system of 0,1 % of this range, the standard uncertainty from data acquisition is 0,03 m/s. In this example, it is assumed that site calibration is not undertaken, and the flow distortion due to the terrain is estimated to be 3 % of the wind speed. The uncertainty of each wind speed bin is:

$$u_{V,i} = \sqrt{\begin{array}{l}(0{,}1\,\text{m/s})^2 + (0{,}034\,\text{m/s} + 0{,}0034 \cdot V_i[\text{m/s}])^2 + \\ (0{,}01 \cdot V_i[\text{m/s}])^2 + (0{,}03 \cdot V_i[\text{m/s}])^2 + (0{,}001 \cdot 30\,\text{m/s})^2\end{array}} \qquad \text{(E.21)}$$

$$= \sqrt{(0{,}104\,\text{m/s})^2 + (0{,}032 \cdot V_i[\text{m/s}])^2 + (0{,}034\,\text{m/s} + 0{,}0034 \cdot V_i[\text{m/s}])^2}$$

In the case where a site calibration has been undertaken, the uncertainty from the site calibration shall be included as the uncertainty of the flow distortion due to the terrain $u_{V4,i}$, instead of the fixed value (2 % or 3 %). The category A uncertainty of the flow correction factors of each wind direction bin is determined from the distribution of the measured flow correction factors (ratio of wind speed at wind turbine and wind speed at meteorological mast). The standard deviation of the distribution in each bin is $s_{\alpha,j}$, and the category A uncertainty is the standard deviation of the mean value $s_{\alpha,j} / \sqrt{N_j}$, where N_j is the number of wind speed ratios in wind direction bin j. Calibration uncertainty is the same as for the power curve measurement. Operational uncertainties of the two cup anemometers in site calibration may be considered correlated if the cup anemometers are of the same type and may therefore be neglected. The site calibration uncertainty (ratio of wind speeds for each wind direction bin j can be expressed as:

$$u_{\alpha,i,j} = \sqrt{2u_{V1,i}^2 / V_i^2 + 2u_{dV,i}^2 / V_i^2 + s_{\alpha,j}^2 / N_j} \qquad \text{(E.22)}$$

where

$u_{\alpha,i,j}$ is the uncertainty of site calibration in wind speed bin i and wind direction bin j;

$u_{V1,i}$ is the uncertainty of anemometer calibration in bin i;

$u_{dV,i}$ is the uncertainty in data acquisition system for the wind speed in bin i;

$s_{\alpha,j}$ is the standard deviation of wind speed ratios in wind direction bin j;

N_j is the number of wind speed ratios in wind direction bin j.

The site calibration uncertainty is dependent on the wind speed. It is recommended to present the uncertainty of site calibration for a specific wind speed, for example 10m/s. In Clause 6, it is specified that the uncertainty shall be calculated for three wind speeds.

When the site calibration uncertainty is included in the wind speed uncertainty, the site calibration uncertainty is multiplied with the sensitivity factor, which is equal to the wind speed of each bin:

$$u_{V4,i,j} = \sqrt{2u_{V1,i}^2 + 2u_{dV,i}^2 + s_{\alpha,j}^2 V_i^2 / N_j} \qquad \text{(E.23)}$$

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~~The uncertainty of each wind speed bin of the power curve shall be weighted with the number of data in that wind speed bin for each wind direction bin of the site calibration:~~

$$u_{V4,i} = \frac{\sum_j u_{V4,i,j} N_{i,j}}{\sum_j N_{i,j}} \quad \text{(E.24)}$$

~~where $N_{i,j}$ is number of power curve data sets for wind speed bin i and wind direction bin j.~~

E.6.1 Category B uncertainties: Wind speed – Introduction

The wind speed uncertainty consists of three components, each of which again consists of multiple subcomponents. These three components are:

a) the uncertainty related to use of sensing hardware (cups, sonic and remote sensing devices (RSD);
b) the uncertainty related to the flow distortion due to the terrain;
c) the uncertainty related to the methods applied.

The symbol for this uncertainty component is $u_{V,i}$.

These uncertainty components as well as the sub-components will be introduced in the next subclauses.

The sensitivity factor, $c_{V,i}$, is defined in Table E.2.

E.6.2 Category B uncertainties: Wind speed – Hardware

The wind speed uncertainty related to hardware consists of three components, each of which again consists of multiple subcomponents. These three components are:

a) The uncertainty related to use of sensors placed in a meteorological mast (cup anemometers and sonic anemometers);
b) The uncertainty related to a remote sensing device (RSD);
c) The uncertainty related to a rotor equivalent wind speed (REWS);

The symbol for this uncertainty component is $u_{VHW,I}$.

E.6.3 Category B uncertainties: Wind speed – Meteorological mast mounted sensors

E.6.3.1 General

This uncertainty component covers the uncertainty related to the use of cup anemometers and sonic anemometers in meteorological masts (either top mounted or side mounted).

The symbol for this uncertainty component is $u_{VS,i}$. (V stands for wind speed and S stands for sensors).

This uncertainty component has six sub components:

a) uncertainty related to the calibration of the sensor before start of the power performance test;
b) uncertainty related to the calibration of the sensor during or after the power performance test;

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c) the uncertainty related to the operational characteristics as determined by the classification of the sensor;

d) the uncertainty related to the mounting of the sensor;

e) the uncertainty related to the mounting of the lightning finial;

f) the uncertainty related to the data acquisition of the signal from the sensor.

E.6.3.2 Category B uncertainties: Wind speed – Met mast sensors – Pre-calibration

This uncertainty component covers the uncertainty related to calibration of the sensor before the test. This includes the variability of repeated tests for one test facility as well as the variability of repeated tests between various facilities.

The symbol for this uncertainty component is $u_{V\mathrm{S,precal},i}$.

This uncertainty is also discussed in Annex F of this standard.

For a specific power performance test, the values as indicated on the calibration for the sensors employed shall be used for the uncertainty calculation.

E.6.3.3 Category B uncertainties: Wind speed – Met mast sensors – Post-calibration

This uncertainty component covers the uncertainty related to the in-situ calibration and/or the post-calibration of the sensor during and/or after the test.

The symbol for this uncertainty component is $u_{V\mathrm{S,postcal},i}$.

This uncertainty is also discussed in 7.2.2 and Annex K of this standard.

If both an in-situ calibration has been done during the power performance test as well as a post-calibration has been done after the power performance test, the magnitude for this uncertainty component shall be taken from the post-calibration.

If a post calibration is done, the magnitude of this uncertainty component shall be the maximum difference between the precalibration and post-calibration in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

Please note that due to the inherent uncertainty of the calibration the expectation will be that small differences will occur between the pre-calibration and post-calibration. The best estimate of the calibration value for a specific sensor will be the average of the calibrations done; in the limit of a very large amount of calibrations the average will converge towards the centre of the distribution.

As only the pre-calibration is used to determine the wind speed from the sensor, the maximum difference can therefore be used as an added uncertainty contribution.

If only an in-situ calibration is done according to Annex K, the magnitude of this uncertainty component shall be the maximum value of δ in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

E.6.3.4 Category B uncertainties: Wind speed – Met mast sensors – Classification

This uncertainty component covers the uncertainty related to the operational characteristics of the sensor as determined by the classification of the sensor.

The symbol for this uncertainty component is $u_{V\mathrm{S,class},i}$.

This uncertainty is also discussed in Annex I of this standard.

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The magnitude of this uncertainty shall be taken from the classification report. Care shall be taken that the terrain type the sensor is used in matches the terrain type of the classification of the sensor (Class A, B or S).

A reference to the classification report shall be included in the power performance report.

The measured range of the influence parameters used for the classification as per Annex I shall be reported for the same data set used for the power performance report. If upflow is not measured, compliance with the accuracy class shall be argued from the local terrain slopes for the experienced wind directions by fitting a plane to the terrain within a distance of 5 times the measurement height relative to the position of the WME according to IEC 61400-1:2005, 11.9.

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

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

E.6.3.5 Category B uncertainties: Wind speed – Met mast sensors – Mounting

This uncertainty component covers the uncertainty related to the mounting of the sensor.

The symbol for this uncertainty component is $u_{V\mathrm{S,mnt},i}$.

This uncertainty is also discussed in 7.2.4 and 9.1.2 as well as Annex G of this standard.

This uncertainty component has three default values corresponding to the three mounting arrangements allowed by Annex G (single top-mounted anemometer, side-by-side top-mounted anemometer or side-mounted anemometer).

For a single top-mounted anemometer, the default magnitude for this uncertainty component is 0,5 % of the measured wind speed.

For a side-by-side top-mounted anemometer, the default magnitude for this uncertainty component is 1,0 %.

For a side-mounted anemometer, the default magnitude for this uncertainty component is one the following:

- for not-flow-corrected signals the default magnitude for this uncertainty component is 1,5 % of the measured signal;
- for a flow-corrected signal according to 7.2.4 and 9.1.2 (mast flow distortion correction) the default magnitude for this uncertainty component is the root-sum-square of half the mean correction applied to the wind speed signal and 0,5 % of the measured signal. Wake effects shall be excluded for the correction to be applied.

The same correction principle can also be applied to two top-mounted anemometers in a goal-post configuration, with the same default magnitude for the flow-corrected signal.

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E.6.3.6 Category B uncertainties: Wind speed – Met mast sensors – Lightning finial

This uncertainty component covers the uncertainty related to a possible top-mounted lightning finial and its influence on a top-mounted anemometer when the requirements in Clause G.5 for the mounting of the lightning finial cannot be met.

The symbol for this uncertainty component is $u_{V\mathrm{S,lgt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the wind speed signal.

E.6.3.7 Category B uncertainties: Wind speed – Met mast sensors – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the wind speed signal.

The symbol for this uncertainty component is $u_{\mathrm{d}V\mathrm{S},i}$.

This uncertainty is also discussed in E.4.2 of this standard.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the measured wind speed signal.

Considering a wind speed range of 30 m/s of the measurement channel and an uncertainty of the data acquisition system of 0,1 % of this range, the standard uncertainty from data acquisition is 0,03 m/s.

E.7 Category B uncertainties: Wind speed – RSD

E.7.1 General

This uncertainty component covers the uncertainty related to the use of remote sensing devices for wind speed measurements (LIDAR and SODAR).

The symbol for this uncertainty component is $u_{V\mathrm{R},i}$ (V stands for wind speed and R stands for remote sensing device).

This uncertainty component has six sub components:

a) uncertainty related to the verification of the device;

b) uncertainty related to the in-situ check of the device;

c) the uncertainty related to the operational characteristics of the device as determined by the classification of the device;

d) the uncertainty related to the mounting of the device;

e) the uncertainty related to flow variation in different probe volumes at the same height;

f) the uncertainty related to the monitoring test.

E.7.2 Category B uncertainties: Wind speed – RSD – Calibration

This uncertainty component covers the uncertainty related to the calibration of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,ver},i}$.

This uncertainty is also discussed in Annex L.

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Prior to the measurement a calibration according to Annex L shall be undertaken and its uncertainties evaluated ($u_{VR,vrf,i}$) (for details refer to L.4.3). If the uncertainties for the exact measurement height are not available, the uncertainties are recommended to be interpolated. The default magnitude for this uncertainty component is 1,0 % to 3,0 % of the measured wind speed.

E.7.3 Category B uncertainties: Wind speed – RSD – in-situ check

This uncertainty component covers the uncertainty related to the verification of the remote sensing device, only applied for an RSD with a lower than hub height met-mast.

The symbol for this uncertainty component is $u_{VR,isc,i}$ ("isc" stands for in-situ check).

This uncertainty is also discussed in Annex L of this standard.

The in-situ test shall be evaluated as described in Annex K, where the RSD is the main measurement and the anemometer on the monitoring mast is the control anemometer with the same uncertainty limits.

E.7.4 Category B uncertainties: Wind speed – RSD – Classification

This uncertainty component covers the uncertainty related to the classification of the remote sensing device.

The symbol for this uncertainty component is $u_{VR,class,i}$.

This uncertainty is also discussed in Annex L of this standard.

The uncertainty due to the operational characteristics are coming from the classification report of the RSD which is providing slopes and ranges of environmental variables. There are three ways of calculating the uncertainty due to these variables:

1. The environmental variable is measured during the measurement:

(according to Equation (L.6) of Annex L)

$$u_{VR,class,i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \left| \bar{x}_{PC,j,i} - \bar{x}_{ver,j,i} \right| \right)^2} \qquad \text{(E.17)}$$

where

v_i is the wind speed measured at height i;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of results from a minimum of 3 classification tests;

$\bar{x}_{PC,j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the power curve test;

$\bar{x}_{ver,j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the performance verification test of the remote sensing device.

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2. The environmental variable is NOT measured during the measurement:

$$u_{VR,\mathrm{class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \frac{\max\left(\left| x_{\mathrm{min},j,i} - \bar{x}_{\mathrm{ver},j,i} \right|, \left| x_{\mathrm{max},j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)}{\sqrt{3}} \right)^2} \quad \text{(E.18)}$$

where

v_i is the wind speed measured at height i;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of results from a minimum of 3 classification tests;

$x_{\mathrm{min},j,i}$ is the expected lower range limit of not measured environmental variable j in wind speed bin i;

$x_{\mathrm{max},j,i}$ is the expected upper range limit of not measured environmental variable j in wind speed bin i;

$\bar{x}_{\mathrm{ver},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the performance verification test of the remote sensing device.

3. If a fixed range is expected:

$$u_{VR,\mathrm{class},i} = v_i \frac{\text{accuracy class}}{\sqrt{3}} \quad \text{(E.19)}$$

NOTE This equation is inaccurate because the variations of the environmental variable are already included in the uncertainties of cat. A of the power curve.

According to L.4.4, $u_{VR,\mathrm{class}}$ becomes equal to zero if the verification test includes the same data as the power curve test.

For more details, see L.4.4 of Annex L.

The default magnitude for this uncertainty component is 1,0 % to 1,5 % of the measured wind speed.

E.7.5 Category B uncertainties: Wind speed – RSD – Mounting

This uncertainty component covers the uncertainty related to the mounting of the remote sensing device.

The symbol for this uncertainty component is $u_{VR,\mathrm{mnt},i}$.

This uncertainty is also discussed in Annex L of this standard.

The uncertainty of the remote sensing device due to non-ideal levelling of the device shall be estimated. The uncertainty is highly dependent on the type of instrument being used.

The default magnitude for this uncertainty component is 0,1 % of the measured wind speed.

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E.7.6 Category B uncertainties: Wind speed – RSD – Flow variation

This uncertainty component covers the uncertainty related to the flow variation across the measurement volume of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,flow},i}$.

This uncertainty is also discussed in Annex L of this standard.

The user should consult with the remote sensing device manufacturer for the best method for evaluating the uncertainty for their specific device at the test site.

The following procedure is recommended for a standard use (according to Albers *et al.*, reference [12][29]):

$$u_{V\mathrm{R,flow},i} = \frac{(\tan(\alpha_2) - \tan(\alpha_1)) \cdot v_i}{2 \cdot \tan(\Phi)} \tag{E.20}$$

α_1 is the upflow angle into the probe volume;

α_2 is the upflow angle out of the probe volume;

Φ is the opening angle of the RSD from the vertical.

As a first estimation for the upflow angles into and out of the probe volume, 1° and –1° respectively, may be used.

This default first estimate results in an uncertainty component of 2 % to 3 % of the measured wind speed (depending on the RSD opening angle), as per L.4.5. Alternatively the method referenced in E.6.3.4 based on terrain slope may be used.

E.7.7 Category B uncertainties: Wind speed – RSD – Monitoring test

This uncertainty component covers the uncertainty related to the result of the monitoring of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,mon},i}$.

This uncertainty is also discussed in Annex L.

Three scenarios are possible and shall be treated as follows:

1. No additional uncertainty needs to be added if the following criterion is met:

$$\sqrt{u^2_{V\mathrm{Rvrf},mh,i} + u^2_{V\mathrm{Rcls},mh,i}} > \left| v_{\mathrm{RSD},mh,i} - v_{\mathrm{MM},i} \right| \tag{E.21}$$

$u_{V\mathrm{Rvrf},mh,i}$ is the uncertainty of the RSD verification at control mast height in bin i;

$u_{V\mathrm{Rcls},mh,i}$ is the uncertainty due to operational characteristics of the RSD at control mast height in bin i;

$v_{\mathrm{RSD},mh,i}$ is the wind speed of the RSD at control mast height in bin i;

29 Figures in square brackets refer to the bibliography.

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$v_{\mathrm{MM},i}$ is the wind speed of the control mast in bin i

2. If Equation (E.21) is not met and the measurement height of the RSD and the control met mast are equal, the following uncertainty shall be added:

$$u_{V\mathrm{Rmon},i} = \left| v_{\mathrm{RSD},mh,i} - v_{\mathrm{MM},i} \right| - \sqrt{u^2_{V\mathrm{Rvrf},mh,i} + u^2_{V\mathrm{Rcls},mh,i}} \quad \text{(E.22)}$$

3. If Equation (E.21) is not met and the measurement heights of the RSD and the control met mast are not the same, $u_{V\mathrm{Rmon},i}$ shall be calculated as follows:

$$u_{\mathrm{added_systematic},j,i} = u_{\mathrm{added_systematic},1,i} \frac{u_{\mathrm{systematic},j,i}}{u_{\mathrm{systematic},1,i}} \quad \text{(E.23)}$$

where

$u_{\mathrm{added_systematic},j,i}$ is added category B standard uncertainty at measurement height j (not covered by the meteorological mast);

$u_{\mathrm{added_systematic},1,i}$ is added category B uncertainty at the height of the top of the meteorological mast;

$u_{\mathrm{systematic},j,i}$ is cumulated other category B uncertainties of the remote sensing device at height j;

$u_{\mathrm{systematic},1,i}$ is cumulated other category B uncertainties of the remote sensing device at the height of the top of the meteorological mast.

The default magnitude for this uncertainty component is 0,5 % of the measured wind speed.

E.8 Category B uncertainties: Wind speed – REWS

E.8.1 General

A number of uncertainty components are not related to the wind speed measurement (at least not when applied to a hub height wind speed) but to the use and definition of the rotor equivalent wind speed (REWS). The uncertainty components related to REWS will be covered in this subclause.

The rotor equivalent wind speed according to Equation (5) in 9.1.3.2 includes wind speed measurements at different heights above ground. In order to make uncertainty calculations of the rotor equivalent wind speed feasible, Equations (E.3) and (E.4) are needed. Equation (E.3) and (E.4) are approximations of (E.1) and (E.2) respectively for the case that the category B uncertainty components are independent between different category B uncertainty sources. This approximation is highly violated if uncertainties of wind speed measurements at different height levels are considered as separate category B uncertainties, because the uncertainty components of wind speed measurements at different height levels are well correlated. Thus, Equations (E.3) and (E.4) cannot be applied directly.

In order to overcome this problem, Equations (E.3) and (E.4) shall be applied with such category B components of the rotor equivalent wind speed which can be considered as independent from each other. Subclause E.8.2 provides advice how this can be implemented.

E.8.2 Category B uncertainties: Wind speed – REWS – Wind speed measurement over whole rotor

E.8.2.1 General

This uncertainty component covers the uncertainty of the REWS wind speed based on the multiple wind speed measurements the REWS is based on.

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The symbol for this uncertainty component is $u_{\mathrm{REWS,shear},i}$.

This uncertainty is also discussed in Annex P of this standard.

NOTE This uncertainty will be used instead of $u_{\mathrm{V},i}$ in conjunction with E.13.3.

What is very important for this uncertainty component is that the derivation and hence the magnitude is strongly dependent on the various measurement methods as introduced in 7.2. A configuration with a hub-height only meteorological mast will not lead to a REWS implementation, the other measurement configurations are considered in the subclauses below.

Please note that the same symbol is used in each subclause as these configurations are mutually exclusive and depending on the specific measurement setup only one of subclauses E.8.2.2 to E.8.2.4 applies.

E.8.2.2 REWS shear uncertainty – Meteorological mast significantly above hub height

In this configuration the REWS is based on signals from side-mounted cup anemometers or sonic anemometers from multiple measurement heights on a meteorological mast.

In this case Equation (5) in 9.1.3.2 applies and the REWS uncertainty components come from Clause E.6.

The default values come from the combination of the default values in Clause E.6.

The way to combine these components into a REWS uncertainty is explained in E.13.7.

E.8.2.3 REWS shear uncertainty – RSD + lower-than-hub-height meteorological mast

In this configuration, the REWS is based on signals from an RSD. The data from the meteorological mast is only used to validate the RSD data.

In this case, Equation (5) in 9.1.3.2 applies and the REWS uncertainty components come from Clause E.7.

The default values come from the combination of the default values in Clause E.7.

The way to combine these components into a REWS uncertainty is explained in E.13.7.

E.8.2.4 REWS shear uncertainty – hub height meteorological mast + RSD for shear

In this configuration, the REWS is based on a cup anemometer or sonic anemometer on a hub-height meteorological mast combined with shear data from an RSD.

In this case, Equation (11) in 9.1.3.4 applies and the REWS uncertainty components come from both Clause E.6 as well as Clause E.7.

In this case, we still have a further division: either the RSD signals are considered as absolute wind speed measurements or as relative wind speed measurements, as the treatment is different between these. This depends on the type of equipment used or the available sensitivity & verification test.

For an absolute wind speed the way to combine these components into a REWS uncertainty is explained in E.13.8.

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For a relative wind speed the way to combine these components into a REWS uncertainty is explained in E.13.9.

E.8.3 Category B uncertainties: Wind speed – REWS – Wind veer

This uncertainty component covers the uncertainty related to the influence of veer on the Rotor Equivalent Wind Speed.

The symbol for this uncertainty component is $u_{\mathrm{REWS,veer},i}$.

This uncertainty is also discussed in Annex Q of this standard.

The veer measurement is based on signals from side-mounted wind vanes or sonic anemometers from multiple measurement heights on a meteorological mast or on signals from an RSD.

The sub-components for this uncertainty component therefore come from E.12.2 or from E.12.3.

E.9 Category B uncertainties: Wind speed – Terrain

E.9.1 General

This uncertainty component covers the uncertainty related to the flow distortion of the wind speed between measurement point and wind turbine due to the local terrain.

The symbol for this uncertainty component is $u_{V\mathrm{T},i}$ (V stands for wind speed and T stands for Terrain).

This uncertainty is also discussed in 6.3.4 of this standard.

When the power performance test is done without a site calibration, the default magnitude of this uncertainty component is determined by the distance between the measurement device and the turbine under test. If this distance is between 2 and 3 rotor diameters ($2D$ ≤ distance ≤ $3D$), this default magnitude is 2 % of the measured wind speed for onshore flat terrain and 1 % for offshore. If this distance is between 3 and 4 rotor diameters ($3D$ < distance ≤ $4D$), this default magnitude is 3 % of the measured wind speed for onshore flat terrain and 2 % offshore.

When the power curve test is done with a site calibration, the default magnitude of this uncertainty component is determined by the site calibration measurement.

In this case, this uncertainty component related to the terrain has nine sub components:

a) uncertainty related to the calibration of the anemometers used for the site calibration;
b) uncertainty related to the operational characteristics of the anemometers used for the site calibration;
c) the uncertainty related to the mounting of the anemometers used for the site calibration;
d) the uncertainty related to the data acquisition of the signals from the anemometers used for the site calibration;
e) the uncertainty related to the lightning finial;
f) the uncertainty related to the convergence check (refer to C.7.1);
g) the uncertainty related to the correlation check (refer to C.7.2);
h) the uncertainty related to the change in correction between adjacent bins;

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i) the uncertainty related to the removal of the wind direction sensor between site calibration and power curve measurement;

j) the uncertainty related to seasonal variation.

E.9.2 Category B uncertainties: Wind speed – Terrain – Pre-calibration

This uncertainty component covers the uncertainty related to the calibration of the sensors before the site calibration test.

The symbol for this uncertainty component is $u_{VT,precal,i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

This uncertainty is virtually the same as $u_{VS,precal,i}$ with the difference that here it is applied to measured wind speeds on two masts.

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

E.9.3 Category B uncertainties: Wind speed – Terrain – Post-calibration

This uncertainty component covers the uncertainty related to the in-situ calibration and/or the post-calibration of the sensor during and/or after the site calibration.

The symbol for this uncertainty component is $u_{VT,postcal,i}$.

This uncertainty is also discussed in 7.2.2 and Annex K of this standard.

If both an in-situ calibration has been done during the power performance test as well as a post-calibration has been done after the power performance test, the magnitude for this uncertainty component shall be taken from the post-calibration.

If a post calibration is done, the magnitude of this uncertainty component shall be the maximum difference between the precalibration and post-calibration in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

Note that due to the inherent uncertainty of the calibration, the expectation will be that small differences will occur between the pre-calibration and post-calibration. The best estimate of the calibration value for a specific sensor will be the average of the calibrations done; in the limit of a very large amount of calibrations, the average will converge towards the centre of the distribution.

As only the pre-calibration is used to determine the wind speed from the sensor, the maximum difference can therefore be used as an added uncertainty contribution.

If only an in-situ calibration is done according to Annex K, the magnitude of this uncertainty component shall be the maximum value of δ in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

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E.9.4 Category B uncertainties: Wind speed – Terrain – Classification

This uncertainty component covers the uncertainty related to the classification of the sensors for the site calibration.

The symbol for this uncertainty component is $u_{V\mathrm{T,class},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

The magnitude of this uncertainty shall be taken from the classification report. Care shall be taken that the terrain type the sensor is used in matches the terrain type of the classification of the sensor (Class A, B or S).

A reference to the classification report shall be included in the site calibration report. If no such reference is included, the default magnitude for the uncertainty shall be a class 3,4A (for non-complex terrain) or a class 4,5B (for complex terrain).

The measured range of the influence parameters used for the classification as per Annex I shall be reported for the same data set used for the site calibration report. If upflow is not measured, compliance with the accuracy class shall be argued from the local terrain slopes for the experienced wind directions, assuming that the vertical angle of the wind is 2/3 of the average terrain slope within 5D of the turbine upwind of the turbine.

If the measured range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the site calibration is significantly different from the range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the power curve test, an additional uncertainty addition may be required. However, as long as both tests stay within the ranges defined for class A and B, this is considered to be sufficiently covered and no additional uncertainty needs to be taken into account.

E.9.5 Category B uncertainties: Wind speed – Terrain – Mounting

This uncertainty component covers the uncertainty related to the mounting of the sensors during the site calibration.

The symbol for this uncertainty component is $u_{V\mathrm{T,mnt},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

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The default magnitude for this uncertainty component is:

a) 0,5 % of the measured wind speed for a single top-mounted anemometer;

b) 1,0 % for a setup with side-by-side top-mounted anemometers;

c) for a side-mounted anemometer, the default magnitude for this uncertainty component is one of the following:

   1) for not-flow-corrected signals the default magnitude for this uncertainty component is 1,5 % of the measured signal;

   2) for a flow-corrected signal according to 7.2.4 and 9.1.2, the default magnitude for this uncertainty component is the root-sum-square of half the mean correction applied to the wind speed signal and 0,5 % of the measured signal. Wake effects shall be excluded for the correction to be applied. This is in lieu of the not-flow-corrected uncertainty and shall not be added to it.

The same correction principle can also be applied to two top-mounted anemometers in a goal-post configuration, with the same default magnitude for the flow-corrected signal.

E.9.6 Category B uncertainties: Wind speed – Terrain – Lightning finial

This uncertainty component covers the uncertainty related to a possible top-mounted lightning finial and its influence on a top-mounted anemometer when the requirements in Clause G.5 for the mounting of the lightning finial cannot be met.

The symbol for this uncertainty component is $u_{V\mathrm{T,lgt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the wind speed signal.

E.9.7 Category B uncertainties: Wind speed – Terrain – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signals of the wind speed sensors during the site calibration.

The symbol for this uncertainty component is $u_{\mathrm{d}V\mathrm{T},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the wind speed measurement channel.

E.9.8 Category B uncertainties: Wind speed – Terrain – Change in correction between adjacent bins

This uncertainty component covers the uncertainty related to the change in correction between adjacent bins.

The symbol for this uncertainty component is $u_{V\mathrm{T,coc},i}$ (COC stands for 'change in correction').

Refer to C.7.3 for details of the evaluation of this uncertainty.

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E.9.9 Category B uncertainties: Wind speed – Terrain – Removal of WD sensor

This uncertainty component covers the uncertainty related to removal of the wind direction sensor between the site calibration and the power performance test.

The symbol for this uncertainty component is $u_{V\mathrm{T,rmv},i}$.

Refer to C.7.4 for details of the evaluation of this uncertainty.

E.9.10 Category B uncertainties: Wind speed – Terrain – Seasonal variation

This uncertainty component covers the uncertainty related to seasonal variation between the site calibration and the power performance test.

The symbol for this uncertainty component is $u_{V\mathrm{T,sv},i}$ (SV stands for seasonal variation).

This uncertainty is also discussed in C.7.5 of this standard.

This uncertainty shall only be applied if any of these conditions for a wind direction bin differs between site calibration and power performance test by more than the following amounts:

a) 0,05 for wind shear exponent

b) 3 % for turbulence intensity,

c) if upflow is measured, a limit of ± 2° change in vertical upflow is recommended.

If one or more of these conditions is triggered, then the default magnitude for this uncertainty is one third of the magnitude of the site calibration flow correction.

E.10 Category B uncertainties: Air density

E.10.1 General

This uncertainty component covers the uncertainty related to the influence of air density on the power curve.

The symbol for this uncertainty component is $u_{\mathrm{AD},i}$.

The air density is derived from measurements of the air temperature, the humidity and the air pressure.

The ~~measurement of the air temperature might include the following uncertainty~~ air density uncertainty consists of four components:

- the uncertainty related to the use of a temperature sensor and the data acquisition;
- ~~uncertainty due to imperfect radiation shielding of the temperature sensor (bad shielding raises the temperature at the sensor);~~
- ~~uncertainty due to mounting effects (vertical air temperature profile variations from day to night influence the estimate of temperature if the temperature sensor is not at hub height).~~
- the uncertainty related to the use of a pressure sensor and the data acquisition;
- the uncertainty related to the use of a relative humidity (RH) sensors and the data acquisition, or the lack of such a sensor;
- the uncertainty due to the air density correction.

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These uncertainty components as well as the subcomponents will be introduced in Clause E.10.

~~The standard uncertainty in measured air temperature for each bin, $u_{T,i}$, can be expressed as:~~

$$u_{T,i} = \sqrt{u_{T1,i}^2 + u_{T2,i}^2 + u_{T3,i}^2 + u_{dT,i}^2} \quad \text{(E.25)}$$

~~where~~

~~$u_{T1,i}$ is the uncertainty of temperature sensor calibration in bin i;~~

~~$u_{T2,i}$ is the uncertainty due to imperfect radiation shielding of temperature sensor in bin i;~~

~~$u_{T3,i}$ is the uncertainty due to mounting effects of temperature sensor in bin i;~~

~~$u_{dT,i}$ are the uncertainties in the data acquisition system for the air temperature in bin i.~~

~~The sensitivity factor for the air temperature measurement is, for sea level conditions, estimated by~~

$$c_{T,i} \approx \frac{P_i}{288{,}15}\,[\text{kW/K}] \quad \text{(E.26)}$$

~~The measurement of the air pressure sensor might include first a correction factor to correct the air pressure to hub height if the sensor is not positioned at hub height. An uncertainty due to the correction might be considered, and the uncertainty (calibration) of the pressure sensor shall be included. The standard uncertainty in measured air pressure for each bin, $u_{B,i}$, is:~~

$$u_{B,i} = \sqrt{u_{B1,i}^2 + u_{B2,i}^2 + u_{dB,i}^2} \quad \text{(E.27)}$$

~~where~~

~~$u_{B1,i}$ is the uncertainty of air pressure sensor calibration in bin i;~~

~~$u_{B2,i}$ is the uncertainty due to mounting effects of air pressure sensor in bin i;~~

~~$u_{dB,i}$ are the uncertainties in data acquisition system for the air pressure in bin i.~~

~~The sensitivity factor for the air pressure measurement is, for sea level conditions, estimated by~~

$$c_{B,i} \approx \frac{P_i}{1013}\,[\text{kW/hPa}] \quad \text{(E.28)}$$

~~The uncertainty due to the relative humidity might be significant if the average air temperature is high. At sea level and at an air temperature of 20 °C, the air density varies 1,2 % between 0 % and 100 % relative humidity. It varies 2,0 % and 4,0 % at 30 °C and 40 °C, respectively. Thus, at high temperatures it is recommended that the relative humidity be measured and corrected for. The influence of the relative humidity is not taken into account in this example.~~

~~The standard uncertainty of the temperature sensor is assumed to be 0,5 °C. The shielding of the temperature sensor is assumed to produce a standard uncertainty of 2 °C. The standard uncertainty due to mounting effects of the temperature sensor is dependent on the vertical distance from the hub height. With the temperature sensor mounted within 10 m of hub height a standard uncertainty of 1/3 °C is assumed. Considering a temperature range of 40 °C of the measurement channel and an uncertainty of the data acquisition system of 0,1 % of this range, the expression for the standard uncertainty of the air temperature in each bin is:~~

$$u_{T,i} = \sqrt{(0{,}5\ \text{K})^2 + (2{,}0\ \text{K})^2 + (0{,}3\ \text{K})^2 + (0{,}1\,\% \cdot 40\ \text{K})^2} = 2{,}1\,\text{K} \quad \text{(E.29)}$$

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~~The pressure sensor is estimated to have a standard uncertainty of 3,0 hPa. It is assumed that the pressure is corrected to the hub height according to ISO 2533 (which, for a standard atmosphere and a height difference of 28 m between the sensor and the hub, is 3,4 hPa). The uncertainty due to deployment is estimated to be 10 % of the correction, which is 0,34 hPa. Considering a pressure range of 100 hPa of the measurement channel and an uncertainty of the data acquisition system of 0,1 % of this range, the expression for the standard uncertainty of the air pressure is:~~

$$u_{B,i} = \sqrt{(3{,}0\ \text{hPa})^2 + (0{,}34\ \text{hPa})^2 + (0{,}1\,\% \cdot 100\ \text{hPa})^2} = 3{,}0\ \text{hPa} \qquad \text{(E.30)}$$

E.10.2 Category B uncertainties: Air density – Temperature introduction

This uncertainty component covers the uncertainty related to the measurement of the temperature.

The symbol for this uncertainty component is $u_{T,i}$.

This uncertainty component has four sub-components:

a) uncertainty related to the calibration of the temperature sensor;
b) uncertainty related to the radiation shielding of the temperature sensor;
c) uncertainty related to the mounting of the temperature sensor;
d) uncertainty related to the data acquisition of the signal from the temperature sensor.

The equations for the sensitivity factors for temperature are:

Sensitivity for temperature for a measurement on wind turbine with active power control:

$$c_{T,i} = -\frac{c_{V,i} v_i}{3\rho_i}\left(\frac{\rho_i}{T_i} + \frac{\phi_i}{T_i}\left(\frac{1}{R_0} - \frac{1}{R_\text{w}}\right) 0{,}0000205 \cdot \exp(0{,}0631846 T_i)\right) \qquad \text{(E.24)}$$

where

$c_{T,i}$ is the sensitivity factor for temperature in bin i;
$c_{v,i}$ is the sensitivity factor for wind speed in bin i;
v_i is the average wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
Φ_i is the average relative humidity (range 0 % to 100 %) in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK];
R_w is the gas constant of water vapour 461,5 [J/kgK].

Sensitivity for temperature for a measurement on a stall regulated wind turbine:

$$c_{T,i} = \frac{P_i}{\rho_i}\left(\frac{\rho_i}{T_i} + \frac{\phi_i}{T_i}\left(\frac{1}{R_0} - \frac{1}{R\text{w}}\right) \cdot 0{,}0000205 \cdot 0{,}0631846 \cdot \exp(0{,}0631846 \cdot T_i)\right) \qquad \text{(E.25)}$$

where

$c_{T,i}$ is the sensitivity factor for temperature in bin i;
P_i is the sensitivity factor for wind speed in bin i;
ρ_i is the is the average air density in bin i;

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T_i is the average temperature in bin i;

Φ_i is the average relative humidity (range 0 % to 100 %) in bin i;

R_0 is the gas constant of dry air 287,05 [J/kgK];

R_w is the gas constant of water vapour 461,5 [J/kgK].

E.10.3 Category B uncertainties: Air density – Temperature – Calibration

This uncertainty component covers the uncertainty related to calibration of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{cal},i}$.

The default magnitude for this uncertainty component is 0,4 °C to 0,6 °C.

E.10.4 Category B uncertainties: Air density – Temperature – Radiation shielding

This uncertainty component covers the uncertainty related to the radiation shielding of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{shield},i}$.

The default magnitude for this uncertainty component is 1,5 °C to 2,5 °C.

E.10.5 Category B uncertainties: Air density – Temperature – Mounting

This uncertainty component covers the uncertainty related to the mounting of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{mnt},i}$.

The default magnitude for this uncertainty component is 0,25 °C to 0,4 °C.

E.10.6 Category B uncertainties: Air density – Temperature – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the temperature sensor.

The symbol for this uncertainty component is $u_{\mathrm{d}T,i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the measurement channel. With an assumed temperature range of 40 °C this comes to 0,04 °C.

E.10.7 Category B uncertainties: Air density – Pressure introduction

This uncertainty component covers the uncertainty related to the measurement of the pressure.

The symbol for this uncertainty component is $u_{B,i}$.

This uncertainty component has three sub-components:

a) uncertainty related to the calibration of the pressure sensor;

b) uncertainty related to the mounting of the pressure sensor;

c) uncertainty related to the data acquisition of the signal from the pressure sensor.

The equation for the sensitivity factors for pressure are:

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Sensitivity for pressure for a measurement on wind turbine with active power control:

$$c_{B,i} = \frac{c_{V,i} v_i}{3 \rho_i T_i R_0} \tag{E.26}$$

where

$c_{B,i}$ is the sensitivity factor for temperature in bin i;

$c_{v,i}$ is the sensitivity factor for wind speed in bin i;

v_i is the average wind speed in bin i;

ρ_i is the is the average air density in bin i;

T_i is the average temperature in bin i;

R_0 is the gas constant of dry air 287,05 [J/kgK].

Sensitivity for pressure for a measurement on a stall regulated wind turbine

$$c_{B,i} = -\frac{P_i}{\rho_i T_i R_0} \tag{E.27}$$

where

$c_{B,i}$ is the sensitivity factor for temperature in bin i;

P_i is the sensitivity factor for wind speed in bin i;

ρ_i is the is the average air density in bin i;

T_i is the average temperature in bin i;

R_0 is the gas constant of dry air 287,05 [J/kgK].

E.10.8 Category B uncertainties: Air density – Pressure – Calibration

This uncertainty component covers the uncertainty related to the calibration of the pressure sensor.

The symbol for this uncertainty component is $u_{B,\mathrm{cal},i}$.

The default magnitude for this uncertainty component is 2 hPa to 4 hPa.

E.10.9 Category B uncertainties: Air density – Pressure – Mounting

This uncertainty component covers the uncertainty related to the mounting of the pressure sensor.

The symbol for this uncertainty component is $u_{B,\mathrm{mnt},i}$.

The default magnitude for this uncertainty component is determined by the height difference for which the signal from the pressure sensor is corrected. Using ISO 2533 the pressure related to this height difference can be calculated. The default magnitude for the uncertainty related to this pressure correction is 10 % of the correction.

For a sensor installed at a height of 2 m and a hub height of 100 m, the difference is 98 m which gives a pressure difference of 11,7 hPa. The uncertainty would then be 1,17 hPa.

E.10.10 Category B uncertainties: Air density – Pressure – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the pressure sensor.

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The symbol for this uncertainty component is $u_{\mathrm{dB},i}$.

The default magnitude for this uncertainty component is 0,1 % of the full range of the measurement channel for pressure. Considering a pressure range of 100 hPa of the measurement channel this gives 0,1 hPa.

E.10.11 Category B uncertainties: Air density – Relative humidity introduction

This uncertainty component covers the uncertainty related to the measurement of the relative humidity.

The symbol for this uncertainty component is $u_{\mathrm{RH},i}$.

The relative humidity is not required to be measured. In that case, a default value of 50 % shall be assumed with an uncertainty of 100 % (from 0 % to 100 %).

In case the humidity is measured, this uncertainty component has three sub-components:

a) uncertainty related to the calibration of the humidity sensor;
b) uncertainty related to the mounting of the humidity sensor;
c) uncertainty related to the data acquisition of the signal from the humidity sensor;

The equations for the sensitivity factors for relative humidity are:

Sensitivity for relative humidity for a measurement on wind turbine with active power control:

$$c_{\mathrm{RH},i} = -\frac{c_{v,i} v_i}{3\rho_i T_i}\left(\frac{1}{R_0} - \frac{1}{R_w}\right)\cdot 0{,}0000205 \cdot \exp\left(0{,}0631846 \cdot T_i\right) \tag{E.28}$$

where

$c_{\mathrm{RH},i}$ is the sensitivity factor for temperature in bin i;
$c_{v,i}$ is the sensitivity factor for wind speed in bin i;
v_i is the average wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK];
R_w is the gas constant of water vapour 461,5 [J/kgK].

Sensitivity for relative humidity for a measurement on a stall regulated wind turbine

$$c_{\mathrm{RH},i} = \frac{P_i}{\rho_i T_i}\left(\frac{1}{R_0} - \frac{1}{R_w}\right)\cdot 0{,}0000205 \cdot \exp\left(0{,}0631846 \cdot T_i\right) \tag{E.29}$$

where

$c_{\mathrm{RH},i}$ is the sensitivity factor for temperature in bin i;
P_i is the sensitivity factor for wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK];
R_w is the gas constant of water vapour 461,5 [J/kgK].

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E.10.12 Category B uncertainties: Air density – Relative humidity – Calibration

This uncertainty component covers the uncertainty related to the calibration of the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{RH,cal},i}$.

The default magnitude for this uncertainty component is 1 % to 2 %.

E.10.13 Category B uncertainties: Air density – Relative humidity – Mounting

This uncertainty component covers the uncertainty related to the mounting of the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{RH,mnt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the measured value.

E.10.14 Category B uncertainties: Air Density – Relative humidity – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{dRH},i}$.

The default magnitude for this uncertainty component is 0,1 % of the full range of the measurement channel for relative humidity.

E.10.15 Category B uncertainties: Air density – Correction

This uncertainty component covers the uncertainty related to the air density correction.

The symbol for this uncertainty component is $u_{\mathrm{AD,method},i}$.

As part of the data analysis, a normalisation from measured air density to a reference air density is performed. This normalisation is related to an uncertainty component, in part because of the uncertainties in the measured temperature, pressure and relative humidity but also because one of the underlying assumptions upon which the normalisation formula is based is increasingly inaccurate the larger the air density difference is on which the air density normalisation is applied.

For a stall-regulated wind turbine with constant pitch and constant rotational speed, this uncertainty shall be evaluated by bin averaging the air density normalised power output and the measured power output against the wind speed at hub height. Half of the deviation of the normalised and measured power output per wind speed bin shall be considered as the standard uncertainty of the air density normalisation in that wind speed bin.

For a wind turbine with active power control, the uncertainty of the air density normalisation shall be evaluated by bin averaging the measured wind speed against the wind speed normalised for the air density. Half of the deviation of the normalised and measured wind speed shall be considered as the standard uncertainty of the air density normalisation in that wind speed bin.

In this example using a wind turbine with active power control, the wind speed deviations per wind speed bin are listed in Table E.9.

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E.11 Category B uncertainties: Method

E.11.1 General

The specific method used to measure or analyse a power curve can also contribute to the uncertainty of the result. As much as possible these have been included with the category B uncertainties they are related to. Therefore the uncertainty related to the air density correction is included under air density and the uncertainty related to the flow distortion correction is included under the wind speed sensors.

However, some of the uncertainties related to the method cannot easily be attributed to a specific component and these have been grouped under the header 'Method'.

The symbol for this uncertainty component is $u_{\mathrm{M},i}$.

E.11.2 Category B uncertainties: Method – Wind conditions

E.11.2.1 General

Although this uncertainty is not directly discussed elsewhere in this standard, it is strongly related to the definition of the power curve as given in Clause 5 of this standard.

As per the definition the power curve according to this standard is a climate specific power curve. The wind conditions in terms of wind shear, wind veer, turbulence and upflow have a direct influence upon the power performance of a wind turbine.

As an example, let's assume that a power curve is measured for a specific set of wind conditions, namely shear = 0,1; wind veer is 10°, turbulence is 10 % and upflow is +2°. The measured power curve would then be reported together with these values and no further uncertainty needs to be introduced.

However, mostly we will not experience constant values for these parameters during a power curve measurement and during the power curve measurement each of these parameters will reflect a range of values that the turbine has been subjected to. As part of this example, let's assume that shear ranges from 0 to 0,3, wind veer from 0° to 20°, turbulence from 3 % to 20 % and upflow from 0° to 5°. As the measurement progresses, we are in fact sampling from many different power curves. As we have no control over these input variables, the next power curve measurement at the same site (be it immediately after the first measurement or a year later to catch the same part of the annual season) will be somewhat different from the first power curve measured. This is the basic argument for adding an uncertainty component related to the wind conditions.

From this perspective, we have the following considerations:

a) If one or more of the four parameters that determine the wind conditions have not been measured, the power curve cannot be reported accurately. The uncertainty related to this can only be estimated by assuming possible values and ranges for the missing parameters and estimating the potential influence on the power performance of the turbine.

b) For the parameters that have been measured more information is available, but not necessarily all information sufficient to characterise the power performance in detail. For example:

   - A parameter measured on three points across the rotor may still not give a full picture for the areas that have not been measured.
   - The wind conditions (e.g. shear) are measured two to four rotor diameters away from the turbine and in most cases without further data to which extent the conditions at the measurement location reflects the conditions at the turbine location. Note that the uncertainty of the hub height wind speed correlation is considered in E.9.1.

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- A similar argument goes for the horizontal dimension of the rotor; the measurement to a large extent only characterises the changes of these parameters with height (if even that) but not the horizontal variability of the measured parameters.

In the light of these arguments a practical approach has been adopted. For nine or more measurement heights for one of these parameters, the assumption has been made that no further uncertainty needs to be added. For fewer measurement heights, an additional increase in uncertainty will be added.

This means that some of the above points are not addressed at all in the current uncertainty analysis; this will be incorporated in a future revision of this standard once sufficient details have been clarified to do so.

c) If one or more of these parameters have been measured, it may be possible to normalise the power curve using this information, as explained in Annex M, Annex P and Annex Q.

The uncertainties related to points a) and b) are covered in this subclause, whereas the uncertainty related to the normalisations is covered further down.

Many of the influences here will be expressed as an uncertainty on wind speed. The experience values that the default estimates are based on are often expressed in terms of AEP. As a practical approach, the choice has been made to express this as an uncertainty through wind speed.

E.11.2.2 Category B uncertainties: Method – Wind conditions – Shear

E.11.2.2.1 General

The symbol for this uncertainty component is $u_{\mathrm{M,shear},i}$.

The default magnitude for this uncertainty component can be found in the two subclauses below.

E.11.2.2.2 Half rotor wind shear measurement coverage

This uncertainty estimation applies to a power curve with a hub height wind speed definition and without Annex P normalization. As wind turbine power curves are influenced by wind shear, the uncertainty of the measured power curve due to wind shear shall be conservatively estimated and taken into account even if no wind shear measurement is performed. For this, a wind shear correction factor according to Equation (9) and (10) in 9.1.3.3 shall be calculated under the following assumptions:

a) Assuming 20 virtual wind speed measurements equally distributed over the rotor height range, resulting in 20 weighting factors.

b) Assuming one power law for the lower rotor half and another power law for the upper rotor half. Based on these power laws, the wind speed relative to hub height shall be calculated for each virtual measurement height. The wind shear exponent applied for the lower rotor half shall be determined from the measurements for each 10 minute data point. The wind shear exponent for the upper rotor half shall be assumed to be half the value used for the lower rotor half. In case of negative shear values, also half of these values shall be assumed for the upper rotor half.

The standard uncertainty of the measured power curve in terms of the wind speed due to not measuring the wind shear shall be assumed for the i -th wind speed bin as:

$$u_{\mathrm{M,shear},i} = \frac{1}{\sqrt{3}} \left| f_r - 1 \right| v_{\mathrm{h},i} \tag{E.30}$$

where

f_r is the wind shear correction factor as calculated in 9.1.3.3;

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$v_{h,i}$ is the wind speed at hub height in bin i.

Examples of estimated standard uncertainties of power curve measurements in terms of the wind speed due to the absence of wind shear measurements are shown in Table E.3. The respective uncertainty increases with the rotor diameter and decreases with the hub height.

Table E.3 – Example of standard uncertainties due to absence of a wind shear measurement

H	D	$u_{M,shear,i}$ / v_H
[m]	[m]	[%]
60	60	3,0
60	80	3,9
100	80	2,4
120	80	2,0
100	120	3,5
150	120	2,4
Wind shear exponents of 0,5 and 0 have been assumed for the lower and upper rotor half, respectively.		

E.11.2.2.3 Full rotor wind shear measurement coverage

This uncertainty estimation applies to:

a) a power curve with a rotor equivalent wind speed definition;

b) a hub height wind speed power curve to which the normalization in Annex P is applied.

The calculation of the rotor equivalent wind speed according to Equation (5) in 9.1.3.2 assumes a constant wind speed for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed. This uncertainty shall be estimated by fitting a power law through each pair of wind speed measurements of successive measurement heights (z_m). The wind speed according to this power law shall be calculated for at least 10 height levels equally distributed between each pair of measurement heights. The summation according to Equation (5) shall be repeated with all height levels covered by the power law assumption and measurement heights. The percentage deviation of the resulting rotor equivalent wind speed compared to the rotor equivalent wind speed using only the measured wind speeds shall be assumed as the (percentage) standard uncertainty of the wind speed due to the limited number of measurement heights.

The estimation of the standard uncertainty due to the limited number of measurement heights shall be performed on the basis of the bin averages of the wind speed measurements at the different height levels as function of the wind speed finally applied for the power curve evaluation.

NOTE The 10-min data sets are necessary for the calculation.

E.11.2.3 Category B uncertainties: Method – Wind conditions – Wind veer

E.11.2.3.1 General

This uncertainty component covers the uncertainty related to fewer than nine measurement heights for wind veer.

The symbol for this uncertainty component is $u_{M,veer,i}$.

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The default magnitude for this uncertainty component can be determined using the three subclauses below.

E.11.2.3.2 No veer measurement

A wind veer correction factor according to Equation (Q.1) shall be calculated under the following assumptions:

a) Assuming wind speeds to be equal to 1 at all measurement heights. Then Equation (Q.1) transforms to a wind veer correction factor.

b) Assuming 20 virtual wind direction measurements equally distributed over the rotor height range, resulting in 20 weighting factors.

c) Assuming homogenous wind veer over the entire rotor height range as large as can be reasonably expected for the test site. If no reasonable assumptions about extreme wind veer are possible for the test site, a wind veer of 40°/100 m shall be assumed.

The standard uncertainty of the measured power curve in terms of the wind speed due to not measuring the wind veer shall be assumed for the i -th wind speed bin as:

$$u_{\mathrm{M,veer},i} = \frac{1}{\sqrt{3}} |f_r - 1| v_{\mathrm{h},i} \tag{E.31}$$

where

f_r is the wind veer correction factor as calculated above;

$v_{\mathrm{h},i}$ is the wind speed at hub height in bin i.

Examples of power curve measurement estimated standard uncertainties in terms of the wind speed due to the absence of wind veer measurements are shown in Table E.4. The respective uncertainty increases with the rotor diameter.

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Table E.4 – Example of standard uncertainties due to absence of a wind veer measurement

D	$U_{M,veer}/\ v_h$
[m]	[%]
20	0,04
40	0,1
60	0,3
80	0,6
100	0,9
120	1,2
140	1,7
160	2,1
180	2,7
200	3,2
An extreme wind veer of 40°/100 m has been assumed for the calculations.	

E.11.2.3.3 Half rotor veer measurement

The calculation of the rotor equivalent wind speed according to Equation (Q.1) assumes a constant wind direction for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed.

The uncertainty related to a veer measurement across half a rotor shall be estimated using the same procedure as used for the veer across a full rotor (see E.11.2.3.4), with the change that the wind veer across the full rotor is 2,5 times that measured across the half rotor.

E.11.2.3.4 Full rotor veer measurement

The calculation of the rotor equivalent wind speed according to Equation (Q.1) assumes a constant wind direction for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed. This uncertainty shall be estimated by assuming a linear increase of the wind veer between each pair of wind speed measurements of successive measurement heights. The wind speed according to this assumption shall be calculated for at least 10 height levels equally distributed between each pair of measurement heights. The summation according to Equation (Q.1) shall be repeated with all height levels covered by the wind veer profile assumption and measurement heights and by assuming a constant wind speed for all heights. The percentage deviation of the resulting rotor equivalent wind speed to the rotor equivalent wind speed using only the measured wind directions, shall be assumed as (percentage) standard uncertainty of the wind speed due to the limited number of wind direction measurement heights.

The estimation of the uncertainty due to the limited number of wind direction measurement heights shall be performed on the basis of the bin averages of the wind direction measurements at the different height levels as function of the wind speed finally applied for the power curve evaluation.

NOTE The 10-min data sets are necessary for the calculation.

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E.11.2.4 Category B uncertainties: Method – Wind conditions – Upflow

This uncertainty component covers the uncertainty related to fewer than nine measurement heights for upflow. This uncertainty component shall be applied for sites that do not meet the requirements of Annex B.

The symbol for this uncertainty component is $u_{\mathrm{M,upflow},i}$.

The default magnitude for this uncertainty component can be found in Table E.5.

Table E.5 – Uncertainty contributions due to lack of upflow knowledge

Number of measurement heights	[% of wind speed]
0 (no upflow measurement)	0,3 to 0,5
1 (at hub height only)	0,15 to 0,25
2 (lower rotor area)	0,08 to 0,12
3	0,03 to 0,07
5	0,015 to 0,025
7	0,005 to 0,015

Please note that this is a very different uncertainty component for upflow than is considered in the classification of the wind speed sensor where also upflow is included. In that case we are looking at the inaccurate measurement of the horizontal wind speed due to the presence of a vertical wind speed component. Here we consider the influence of the upflow on the turbine's performance. Although we define a horizontal wind speed, the turbine's performance still varies when a vertical component is present.

E.11.2.5 Category B uncertainties: Method – Wind conditions – Turbulence intensity

This uncertainty component covers the uncertainty related to not having a measurement for hub height turbulence.

The symbol for this uncertainty component is $u_{\mathrm{M,ti},i}$.

For turbulence we do not consider other measurement heights as Clause 5 of this standard defined the power curve only for hub height turbulence. This is a required signal. The reason this is still included as an additional uncertainty components is that the measurement configuration with a lower-than-hub height meteorological mast only has a hub height turbulence measured by a remote sensing device. The turbulence as measured by a remote sensing device is significantly different from the turbulence as measured by a sonic or cup anemometer. Hence the additional uncertainty.

The default magnitude for this uncertainty component can be found in Table E.6.

Table E.6 – Uncertainty contributions due to lack of turbulence knowledge

Number of measurement heights	[% of wind speed]
0 (no accurate TI due to RSD)	0,3 % to 0,5 %

E.11.3 Category B uncertainties: Method – Seasonal effects

This uncertainty component covers the uncertainty related to the influence of seasonal effects on the power curve. Note that some seasonal variations contribute in the wind speed

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uncertainty as they influence the wind profile characteristics (shear, turbulence, etc.). These variations are treated separately.

Some other contributions, such as blade accretion from bugs and/or dirt on the blades (e.g. during a warm and dry period), increase the blade surface roughness and deteriorate the blade aerodynamic performance. Therefore, for the same kinetic energy in the wind, the turbine production will be lower when blades are dirty. These contributions are combined in the uncertainty component $u_{\mathrm{M,sfx},i}$.

Clearly, these contributions do not influence the wind profile characteristics and therefore, strictly speaking, are effects on the electrical power. However, with the purpose to quantify the contribution to the AEP variation, this uncertainty component is more conveniently expressed as uncertainty in the wind speed.

A default magnitude of 0,7 % on the wind speed is suggested, yet the magnitude of this component will vary with the site location and the year period of the performance test and where possible it should be estimated from experience or AEP variation data from the specific site.

E.11.4 Category B uncertainties: Method – Turbulence normalisation (or the lack thereof)

This uncertainty component covers the uncertainty related to the turbulence normalisation of the power curve

The symbol for this uncertainty component is $u_{\mathrm{M,tinorm},i}$.

This uncertainty is also discussed in Annex M and 9.1.6.

The turbulence normalisation given in Annex M is designed to handle effects of the 10 min data averaging on the evaluated power curve. There are further effects of the turbulence intensity on wind turbine power curves, which could, for instance, be due to direct impact of the turbulence intensity on the aerodynamics or due to the 3-dimensional character of turbulence. In the end, the turbulence intensity normalisation is a strongly simplified approach for characterising short term wind speed fluctuations. Thus, there is a remaining uncertainty of the evaluated power curve due to possible turbulence effects, even if the turbulence normalisation procedure is applied. The turbulence normalisation often removes about half of the observed effect of the turbulence intensity on measured wind turbine power curves. Thus, the following steps should be performed in order to calculate the uncertainty of the turbulence normalisation:

a) The final bin-averaged power curve shall be evaluated on the basis of the turbulence normalised power output and on the basis of the non-turbulence normalised power output.

b) the deviation of these two power curves shall be assumed to be the maximum uncertainty of the turbulence-normalised power curve per wind speed bin resulting from the turbulence normalisation. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the power curves divided by $\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties of the power performance measurement for the determination of the total standard uncertainty according to Annex D.

In the absence of turbulence normalisation, the uncertainty due to turbulence effects on the power curve should be calculated as described in Clause M.5.

E.11.5 Category B uncertainties: Method – Cold climate

This uncertainty component covers the uncertainty related to the influence of measurement in cold climate on the classification of the anemometers.

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The symbol for this uncertainty component is $u_{\mathrm{M,cc},i}$.

This uncertainty is also discussed in Annex O of this standard.

If an extended temperature range is required, the uncertainty component for the sensor classification shall be based on a class S classification report; this is covered by the uncertainty component $u_{\mathrm{VS,class},i}$.

Although ice detection is recommended, it cannot be avoided that snow and ice will accrete on the mounting structure and thus influence the measured wind speed. This aspect is covered by the uncertainty component as discussed here.

Please note that these considerations already should be considered for 'normal' class B measurements, as class B extends to –10 °C and most snow and ice occurs around 0 °C. If a measurement is exposed to more than a few days of snow and/or ice, this additional uncertainty component shall be applied. Otherwise this components can be set to zero.

The default magnitude of this uncertainty component is 0,5 % to 1 % on wind speed.

E.12 Category B uncertainties: Wind direction

E.12.1 General

There is an influence of the wind direction uncertainty on the power curve through the site calibration as well as a smaller effect. Based on the magnitude of the wind direction uncertainty compared to the site calibration bin size, some data will be incorrectly assigned to a bin. For a bin size of 10° and a wind direction uncertainty of 5°, roughly 39 % of the data in a bin has been wrongly assigned. Although this will tend to average out, it can have an effect for small measurement sectors and large differences between adjacent bins. A similar argument goes for the filtering on the power curve measurement sector, but to a lesser extent.

These uncertainties shall only apply if the wind direction sensor or its mounting is changed for sites on which a site calibration was performed.

This background is the main reason why the standard requires that the wind direction uncertainty is assessed to ensure that it stays below 5°.

The influence from the wind direction on the power curve and AEP is not quantifiably established and no sensitivity factors have been developed.

As the wind direction uncertainty shall be reported, Clause E.12 gives the minimum uncertainty components that shall be considered for the wind direction uncertainty. An estimate of the magnitude of these components is not given, but shall be included for a reported power curve.

E.12.2 Category B uncertainties: Wind direction – Vane or sonic

E.12.2.1 Category B uncertainties: Wind direction – Vane or sonic – Calibration

This uncertainty component covers the uncertainty related to the calibration of the wind direction sensor.

The symbol for this uncertainty component is $u_{\mathrm{WV,cal},i}$.

The resolution of the wind direction sensor is also included here and this value divided by $2\sqrt{3}$ shall be taken as a minimum value.

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No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.2 Category B uncertainties: Wind direction – Vane or sonic – North mark

This uncertainty component covers the uncertainty related to the accurate determination of the sensors north mark in relation to the boom on which the sensor is installed.

The symbol for this uncertainty component is $u_{\mathrm{WV,nm},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.3 Category B uncertainties: Wind direction – Vane or sonic – Boom orientation

This uncertainty component covers the uncertainty related to establishing the direction of the boom with regards to the North reference, i.e. magnetic or true.

The symbol for this uncertainty component is $u_{\mathrm{WV,bo},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.4 Category B uncertainties: Wind direction – Vane or sonic – Operational effects

This uncertainty component covers the uncertainty related to the influence of the mast on the free stream wind direction at the point of measurement.

The symbol for this uncertainty component is $u_{\mathrm{WV,oe},i}$.

As the wind will flow around the mast, the wind direction as measured by the sensor may not be the free flow wind direction. This effect is covered under this uncertainty component.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.5 Category B uncertainties: Wind direction – Vane or sonic – Magnetic declination angle

This uncertainty component covers the uncertainty related to the difference between magnetic north and true north.

The symbol for this uncertainty component is $u_{\mathrm{WV,mda},i}$ (MDA stands for magnetic declination angle).

The correction from magnetic north to true north is also related to an uncertainty.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.6 Category B uncertainties: Wind direction – Vane or sonic – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the wind direction sensor.

The symbol for this uncertainty component is $u_{\mathrm{dWV},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

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E.12.3 Category B uncertainties: Wind direction – RSD

E.12.3.1 Category B uncertainties: Wind direction – RSD – Verification

This uncertainty component covers the uncertainty related to the verification of the wind direction sensor.

The symbol for this uncertainty component is $u_{\mathrm{WR,ver},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.2 Category B uncertainties: Wind direction – RSD – Monitoring

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the wind direction monitoring by the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{WR,mon},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.3 Category B uncertainties: Wind direction – RSD – Flow variation

This uncertainty component covers the uncertainty related to the flow variation in different probe volumes.

The symbol for this uncertainty component is $u_{\mathrm{WR,fv},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.4 Category B uncertainties: Wind direction – RSD – Alignment

This uncertainty component covers the uncertainty related to accuracy of the alignment of the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{WR,align},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.5 Category B uncertainties: Wind direction – RSD – Magnetic declination angle

This uncertainty component covers the uncertainty related to the correction from magnetic north to true north.

The symbol for this uncertainty component is $u_{\mathrm{WR,mda},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.6 Category B uncertainties: Wind direction – RSD – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{dWR},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

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E.13 Combining uncertainties

E.13.1 General

In Clause E.13, the equations and further considerations to combine uncertainty components to an aggregate level will be presented and discussed. An example is the calculation of the site calibration uncertainty based on the uncertainty components of the site calibration uncertainty.

E.13.2 Combining Category B uncertainties in electric power ($u_{P,i}$)

The standard uncertainty of the electric power for each bin, $u_{P,i}$, is calculated by combining the standard uncertainties from the power transducer, the current and voltage transformers and the data acquisition system:

$$u_{P,i} = \sqrt{u_{P,CT,i}^2 + u_{P,VT,i}^2 + u_{P,PT,i}^2 + u_{dP,i}^2} \quad \text{(E.32)}$$

where

$u_{P,i}$ is the uncertainty on the power measurement;

$u_{P,CT,i}$ is the uncertainty related to the current transformers;

$u_{P,VT,i}$ is the uncertainty related to the voltage transformers;

$u_{P,PT,i}$ is the uncertainty related to the power transducers;

$u_{dP,i}$ is the uncertainty related to the data acquisition of the power signal.

Considering the default magnitudes for these uncertainty components as given in Clause E.5 the standard uncertainty from the electric power sensor for each bin is:

$$\begin{aligned} u_{P,i} &= \sqrt{(0{,}43\% \cdot P_i[\text{kW}])^2 + (0{,}29\% P_i[\text{kW}])^2 + (7{,}2\text{kW})^2 + (0{,}1\% \cdot 3\,000\,\text{kW})^2} \\ &= \sqrt{(0{,}53\% \cdot P_i[\text{kW}])^2 + (7{,}8\,\text{kW})^2} \end{aligned} \quad \text{(E.33)}$$

E.13.3 Combining uncertainties in the wind speed measurement ($u_{V,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed, $u_{V,i}$:

$$u_{V,i} = \sqrt{u_{VHW,i}^2 + u_{VT,i}^2 + u^2_{AD,method,i}} \quad \text{(E.34)}$$

where

$u_{VHW,i}$ is the uncertainty on the hardware used and is one of $u_{VS,i}$, $u_{VR,i}$ or $u_{REWS,I}$;

$u_{VT,i}$ is the uncertainty related to the flow distortion from the terrain;

$u_{AD,method,i}$ is the uncertainty related to the air density correction.

E.13.4 Combining uncertainties in the wind speed measurement from cup or sonic ($u_{VS,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from cup or sonic, $u_{VS,i}$:

$$u_{VS,i} = \sqrt{u_{VS,precal,i}^2 + u_{VS,postcal,i}^2 + u_{VS,class,i}^2 + u_{VS,mnt,i}^2 + u_{VS,lgt,i}^2 + u_{dVS,i}^2} \quad \text{(E.35)}$$

where

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$u_{VS,precal,i}$ is the uncertainty related to the calibration of the sensor before the start of the power performance test;

$u_{VS,postcal,i}$ is the uncertainty related to the calibration of the sensor during or after the power performance test;

$u_{VS,class,i}$ is the uncertainty related to the classification of the sensors;

$u_{VS,mnt,i}$ is the uncertainty related to the mounting of the sensors;

$u_{VS,lgt,i}$ is the uncertainty related to the flow distortion from lighting finial;

$u_{dVS,i}$ is the uncertainty related to the data acquisition of the wind speed signal.

E.13.5 Combining uncertainties in the wind speed measurement from RSD ($u_{VR,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from an RSD device, $u_{VR,i}$:

$$u_{VR,i} = \sqrt{u^2_{VR,ver,i} + u^2_{VR,isc,i} + u^2_{VR,class,i} + u^2_{VR,mnt,i} + u^2_{VR,flow,i} + u^2_{VR,mon,i}} \quad \text{(E.36)}$$

where

$u_{VR,ver,i}$ is the uncertainty due to the verification test;

$u_{VR,isc,i}$ is the uncertainty due to the in-situ test;

$u_{VR,class,i}$ is the uncertainty related to the classification of the RSD;

$u_{VR,mnt,i}$ is the uncertainty related to the mounting of the RSD;

$u_{VR,flow,i}$ is the uncertainty related to the flow variation across the measurement volume of the RSD;

$u_{VR,mon,i}$ is the uncertainty related to the monitoring of the RSD.

E.13.6 Combining uncertainties in the wind speed measurement from REWS $u_{REWS,i}$

The following uncertainty components are combined to calculate the category B uncertainty for a wind speed measurements expressed as a rotor equivalent wind speed, $u_{REWS,i}$:

$$u_{REWS,i} = \sqrt{u^2_{REWS,shear,i} + u^2_{REWS,veer,i}} \quad \text{(E.37)}$$

where

$u_{REWS,i}$ is the uncertainty of the rotor equivalent wind speed (REWS);

$u_{REWS,shear,i}$ is the uncertainty due to the influence on REWS from the shear measurement across the rotor;

$u_{REWS,veer,i}$ is the uncertainty due to the influence on REWS from the veer measurement across the rotor.

The value of $u_{REWS,shear,i}$ is taken from one of the following:

– $u_{veq,i}$ (from E.13.7),
– $u_{veq,final,i}$ (from E.13.8),
– or determined through $u_{fr,RSD,k,i}$ (from E.13.9).

The value of $u_{REWS,veer,i}$ is taken from $u_{veq,i}$ (from E.13.10).

The wind speed uncertainty components that are included in the REWS uncertainty are based on Equation (5) of 9.1.3.2 or Equation (11) of section 9.1.3.4. Equation (6) in 9.1.3.2 (which would also influence Equation (11)) implies that there is an uncertainty component related to establishing the correct measurement height. As this is considered to be insignificant for a meteorological mast measurement and is included in a LIDAR calibration as per Annex L, the only concern is with SODAR measurements especially for higher wind speeds when 'beam

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bending' may occur. In case this is experienced during a measurement this shall be included as a further uncertainty component.

E.13.7 Combining uncertainties in the wind speed measurement for REWS for either a meteorological mast significantly above hub height or an RSD with a lower-than-hub-height meteorological mast

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from an RSD device.

The rotor equivalent wind speed shall be considered as a single wind speed measurement. The total standard uncertainty of the rotor equivalent wind speed in the wind speed bin i can then be expressed by:

$$u^2_{v_{\mathrm{eq}},i} = \sum_{k=1}^{M}\sum_{l=1}^{M} u_{v_{\mathrm{eq}},k,i}\, u_{v_{\mathrm{eq}},l,i}\, \rho_{k,l,i} \tag{E.38}$$

where

M is the number of uncertainty components of v_{eq};

i is the wind speed bin referring to bin averaging of power curve;

$u_{v_{\mathrm{eq}},k,i}$ is the standard uncertainty sub-component k of v_{eq} in wind speed bin i;

$u_{v_{\mathrm{eq}},l,i}$ is the standard uncertainty sub-component l of v_{eq} in wind speed bin i;

$\rho_{k,l,i}$ is the correlation coefficient between the uncertainty component k height m and n in wind speed bin i.

Please note that the sensitivity factors are expressly not included here as they are included in the equation below.

The uncertainty components of v_{eq} in wind speed bin i shall be calculated from the uncertainty components of the wind speed measurements in single measurement heights by the method of error propagation:

$$u^2_{v_{\mathrm{eq}},k,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{m,i}\, u_{v_m,k,i}\, c_{n,i}\, u_{v_n,k,i}\, \rho_{m,n,k,i} \tag{E.39}$$

where

L is the number of measurement heights across the rotor;

$u_{v_m,k,i}$ is the standard uncertainty sub-component k of wind speed measurement at height m in wind speed bin i;

$u_{v_n,k,i}$ is the standard uncertainty sub-component k of wind speed measurement at height n in wind speed bin i;

$c_{m,i}$ is the sensitivity factor of v_{eq} on wind speed at height m in wind speed bin i;

$c_{n,i}$ is the sensitivity factor of v_{eq} on wind speed at height n in wind speed bin i;

$\rho_{m,n,k,i}$ is the correlation coefficient between the uncertainty component k height m and n in wind speed bin i.

The sensitivity factors $c_{m,i}$ and $c_{n,i}$ are gained from the definition of the rotor equivalent wind speed by error propagation as:

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$$c_{m,i} = \frac{\partial v_{\mathrm{eq},i}}{\partial v_{m,i}} = \frac{A_m}{A}\left(\frac{v_{m,i}}{v_{\mathrm{eq},i}}\right)^2 \tag{E.40}$$

where

A_m is the rotor segment attributed to wind speed measurement at height m according to Equation (6) in 9.1.3.2;

A is the rotor swept area;

$v_{m,i}$ is the wind speed at height m in wind speed bin i;

$v_{\mathrm{eq},i}$ is the equivalent wind speed in bin i.

For the application of Equation (E.40), the wind speed measured at the different measurement heights $v_{m,i}$ shall be bin averaged as function of the wind speed finally applied for the power curve evaluation (air density normalised and wind shear corrected wind speed).

Equation (E.39) in combination with Equation (E.40) simplifies if either full correlation or no correlation between the uncertainty components at different measurement heights is assumed. The correlation coefficients suggested in Table E.7 should be applied for the calculation of the uncertainties of v_{eq}. Lower correlation coefficients shall be used only if they are evident.

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Table E.7 – Suggested assumptions for correlations of measurement uncertainties between different measurement heights[30]

Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
Wind shear measurement by cup anemometers		
Wind tunnel calibration	1	Calibration in same wind tunnel is required; high correlation of uncertainties of calibrations of different cup anemometers
Cup anemometer classification	1	Anemometers at different heights measure under very similar climatic conditions
Cup anemometer mounting	1, 0	1, if boom mounted and same boom configuration; 0, if one anemometer top mounted and the other boom mounted
Data acquisition system	0	Different input channels applied
Site effects due to distance between the reference meteorological mast and the test wind turbine	1	As a first approximation, the site effects may be assumed to be identical for the rotor height range.
Uncertainty due to limited number of measurements over rotor height range	1	To a first approximation, this uncertainty is fully correlated between the measurement heights
Wind shear measurement by remote sensing device		
Verification test	1	Normally, very similar conditions of reference sensors at different heights present. Sensitivity of accuracy of remote sensing device on measurement height may be ignored.
Sensitivity analysis / classification	1	Classification performed under very similar conditions at different heights. Dependency of sensitivity of remote sensing device on environmental conditions on measurement height may be ignored.
Uncertainty resulting from control with meteorological mast	1	Same uncertainty assumed for all heights
Uncertainty due to flow variation in different probe volumes at same height	1	Normally, quite similar effect expected at different measurement heights. Sensitivity of error on measurement height may be ignored.
Mounting	1	Similar effect of system mounting in different measurement heights
Site effects due to distance between the measurement and the test wind turbine	1	As a first approximation, the site effects may be assumed to be identical for the rotor height range.
Uncertainty due to limited number of measurements over rotor height range	1	To a first approximation, this uncertainty is fully correlated between the measurement heights

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30 An additional uncertainty of the determination of the wind speed results from the air density normalisation. This component is produced after the rotor averaging of wind speeds and must be added for the final evaluation of wind speed uncertainties.

NOTE If one assumes that for all components the correlation coefficient is equal to 1 and all components for each height is the same, this procedure simplifies to the extent that the uncertainty calculation can be done as described in Clause E.6 using $v_{\mathrm{eq},i}$ instead of v_i. For fixed values (such as the calibration), this value can be used for $v_{\mathrm{eq}} v_{\mathrm{eq},i}$.

E.13.8 Combining uncertainties in the wind speed measurement for REWS for a hub height meteorological mast + RSD for shear using an absolute wind speed

The uncertainty of the wind speed measurement at hub height by means of a cup or sonic anemometer and the uncertainty of the wind shear measurement by the remote sensing device can be considered as being independent from each other. Error propagation on Equation (11) of 9.1.3.4 leads then to the following equation for the uncertainty of the final rotor equivalent wind speed:

$$u^2_{v_{\mathrm{eq}},\mathrm{final},i} = f^2_{r,X,i} u^2_{v_h,i} + v^2_{h,i} u^2_{f_{r,X},i} \tag{E.41}$$

where

$u_{v_{\mathrm{eq}},\mathrm{final},i}$ is the standard uncertainty of final rotor equivalent wind speed in bin i;

$f_{r,X,i}$ is the wind shear correction factor in wind speed bin i;

$v_{h,i}$ is the wind speed measured at hub height in bin i by cup or sonic anemometer

u_{v_h},i is the standard uncertainty of $v_{h,i}$ in wind speed bin i;

$u_{f_{r,X}},i$ is the standard uncertainty of $f_{r,X,i}$ in wind speed bin i.

The uncertainty of the wind shear correction factor is (error propagation on Equation (9) and (10) of 9.1.3.3):

$$u^2_{f_{r,X},i} = \frac{1}{v^2_{h,X,i}} u^2_{v_{\mathrm{eq},X},i} + \frac{v^2_{\mathrm{eq},X,i}}{v^4_{h,X,i}} u^2_{v_{h,X},i} - 2\frac{v_{\mathrm{eq},X,i}}{v^3_{h,X,i}} u_{v_{\mathrm{eq},X},i} u_{v_{h,X},i} \rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},i} \tag{E.42}$$

where

$v_{h,X,i}$ is the wind speed measured by remote sensing device in bin i;

$u_{v_{h,X}},i$ is the standard uncertainty of $v_{h,X,i}$;

$v_{\mathrm{eq},X,i}$ is the rotor equivalent wind speed as measured with the remote sensing device in bin i;

$u_{v_{\mathrm{eq},X}},i$ is the standard uncertainty of $v_{\mathrm{eq},X,i}$ in bin i;

$\rho_{u_{v_{\mathrm{eq}}},u_{v_{h,X}},i}$ is the correlation coefficient between uncertainty components $u_{v_{\mathrm{eq},X},i}$ and $u_{v_{h,X},i}$ in bin i.

Considering that $v_{\mathrm{eq},X,i}$ and $v_{h,X,i}$ both have the same types of uncertainty sub components as given in Table E.7 and assuming that these sub components are independent from each other, Equation (E.42) is equal to:

$$u^2_{f_{r,X},i} = \sum_{k=1}^{M} \frac{1}{v^2_{h.X.i}} u^2_{v_{\mathrm{eq},X},k,i} + \frac{v^2_{\mathrm{eq},X,i}}{v^4_{h,X,i}} u^2_{v_{h,X},k,i} - 2\frac{v_{\mathrm{eq},X,i}}{v^3_{h,X,i}} u_{v_{\mathrm{eq},X},k,i} u_{v_{h,X},k,i} \rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i} \tag{E.43}$$

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where

$u_{v_{\mathrm{eq},X},k,i}$ is the standard uncertainty component k of rotor equivalent wind speed as measured with the remote sensing device in bin i, to be analysed according to Equation (E.39);

$u_{v_{h,X},k,i}$ is the standard uncertainty component k of hub height wind speed as measured with the remote sensing device in bin i;

$\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}$ is the correlation coefficient between standard uncertainty components $u_{v_{\mathrm{eq},X},k,i}$ and $u_{v_{h,X},k,i}$ in bin i;

M is the number of uncertainty components of $v_{\mathrm{eq},X}$ and $v_{h,X}$.

For the application of Equation (E.43), $v_{h,X,i}$ and $v_{\mathrm{eq},X,i}$ are gained from bin averaging the rotor equivalent wind speed and the hub height wind speed measured by the remote sensing device as function of the wind speed finally applied for the power curve evaluation (air density and wind shear normalised wind speed). The correlation coefficients between the standard uncertainty components of the rotor equivalent wind speed and the hub height wind speed measured by the remote sensing device $\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}$ shall be estimated from the results of the verification test and sensitivity test/classification of the remote sensing device. In some cases, the assumption of correlation coefficients close to 1 can be justifiable.

Equation (E.43) in combination with Equation (E.41) and Equation (E.39) allows evaluating all standard uncertainty components of the final rotor equivalent wind speed. These sub components shall be implemented in Equations (E.3) and (E.4).

According to Equation (E.41), the total uncertainty of the final rotor equivalent wind speed is larger than the uncertainty of the wind speed measured at hub height by the cup or sonic anemometer (at least as soon as the wind shear correction factor exceeds 1). The uncertainty is increased due to the uncertainty of the wind shear correction factor. According to Equation (E.43), this additional uncertainty vanishes if the uncertainties of the rotor equivalent wind speed and the wind speed measured at hub height by the remote sensing device are fully correlated $(\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}=1)$ and if the rotor equivalent wind speed is equal to the wind speed at hub height measured by the remote sensing device.

NOTE Assuming all correlation coefficients are equal to 1 and $u_{v_{\mathrm{eq},X},k,i}$ is equal to $u_{v_{h,X},k,i}$ (see E.13.7) the equation for $u^2_{f_{r,X},i}$ simplifies as follows:

$$u_{f_{r,X},i} = \left(\frac{v_{h,X,i} - v_{\mathrm{eq},X,i}}{v^2_{h,X,i}}\right) \sqrt{\sum_{k=1}^{M} u^2_{v_{h,X},k,i}} \qquad \text{(E.44)}$$

where

$v_{h,X,i}$ is the wind speed measured by remote sensing device in bin i;

$u_{vh,X,k,i}$ is the standard uncertainty of component k of either $v_{h,X,i}$ or $v_{\mathrm{eq},X,i}$;

$v_{\mathrm{eq},X,i}$ is the rotor equivalent wind speed as measured with the remote sensing device in bin i.

E.13.9 Combining uncertainties in the wind speed measurement for REWS for a hub height meteorological mast and RSD for shear using a relative wind speed

A sensitivity analysis and verification test of the remote sensing device for wind shear measurements instead of for absolute wind speed measurements may be available. This

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means that the accuracy of the remote sensing device in terms of wind shear measurements is verified by the verification test, and that the sensitivity of the wind shear measurement on environmental variables is tested for the classification of the remote sensing device. If such a sensitivity analysis and verification test of the remote sensing device is present, it is useful for the evaluation of uncertainties to introduce a relative wind speed measurement as performed by the remote sensing device:

$$v_{r,\mathrm{RSD},m} = \frac{v_{m,\mathrm{RSD}}}{v_{h,\mathrm{RSD}}} \tag{E.45}$$

where

$v_{r,\mathrm{RSD},m}$ is the relative wind speed measured by remote sensing device at m -th height relative to hub height wind speed measured by remote sensing device;

$v_{h,\mathrm{RSD}}$ is the wind speed measured by remote sensing device at hub height;

$v_{m,\mathrm{RSD}}$ is the wind speed measured by remote sensing device at m-th height.

The wind shear correction factor as defined in Equation (9) in 9.1.3.3 can then be rewritten as

$$f_{r,\mathrm{RSD}} = \left(\sum_{m=1}^{L} \frac{A_m}{A} v_{r,\mathrm{RSD},m}^3 \right)^{\frac{1}{3}} \tag{E.46}$$

where

A_m is the rotor segment attributed to wind speed measurement at m-th height according to Equation (5) in 9.1.3.2;

A is the rotor swept area;

L is the number of measurement heights in the height area of the rotor.

Equation (E.41) can then be applied for assessing the uncertainty of the final rotor equivalent wind speed with the uncertainty components of the wind shear correction factor in wind speed bin i gained from:

$$u^2_{f_{r,\mathrm{RSD}},k,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{v_{r,\mathrm{RSD}},m,i} u_{v_{r,\mathrm{RSD}},m,k,i} c_{v_{r,\mathrm{RSD}},n,i} u_{v\mathrm{RSD},n,k,i} \rho_{r,m,n,k,i} \tag{E.47}$$

where

L is the number of measurement heights in the height area of the rotor;

$u_{v_{r,\mathrm{RSD}},m,k,i}$ is the standard uncertainty component k of relative wind speed measurement at m-th height in wind speed bin i;

$u_{v_{r,\mathrm{RSD}},n,k,i}$ is the standard uncertainty component k of relative wind speed measurement at n-th height in wind speed bin i;

$c_{v_{r,\mathrm{RSD}},m,i}$ is the sensitivity factor of $f_{r,\mathrm{RSD}}$ on relative wind speed at m-th height in wind speed bin i;

$c_{v_{r,\mathrm{RSD}},n,i}$ is the sensitivity factor of $f_{r,\mathrm{RSD}}$ on relative wind speed at n-th height in wind speed bin i.

The sensitivity factors $c_{v_{r,\mathrm{RSD}},m,i}$ and $c_{v_{r,\mathrm{RSD}},n,i}$ are:

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$$c_{v_{r,\mathrm{RSD}},m,i} = \frac{\partial f_{r,\mathrm{RSD},i}}{\partial v_{r,\mathrm{RSD},m,i}} = \frac{A_m}{A}\left(\frac{v_{r,\mathrm{RSD},m,i}}{f_{r,\mathrm{RSD},i}}\right)^2 \quad \text{(E.48)}$$

The same uncertainty components as given in Table E.7 shall be applied, but in terms of the remote sensing device relative wind speed measurements rather than in terms of absolute wind speed measurements. In addition, the same correlation coefficients of uncertainty components between two measurement heights as shown in Table E.7 shall be assumed for the relative wind speed measurements, unless evidence exists that other values are present.

The wind speed measured at hub height by the cup or sonic anemometer v_h, the wind shear correction factor $f_{r,\mathrm{RSD}}$ and the relative wind speeds $v_{r,\mathrm{RSD}}$ measured by the remote sensing device shall be bin averaged against the final wind speed applied for the power curve evaluation for the application of Equations (E.41), (E.47) and (E.48) (wind shear corrected and air density normalised wind speed).

E.13.10 Combining uncertainties in the wind speed measurement from REWS due to wind veer across the whole rotor $u_{\mathrm{REWS,veer},i}$

The rotor equivalent wind speed (taking consideration wind veer according to Annex Q) is dependent on wind speeds and wind directions across the rotor height range. Often, the uncertainties of wind direction and wind speed measurements can be considered as being independent from each other. Then Equation (E.38) in E.13.7 transforms to:

$$u^2_{v_{\mathrm{eq}},i} = \sum_{k=1}^{M} u^2_{v_{\mathrm{eq}},k,i} + \sum_{l=1}^{N} u^2_{v_{\mathrm{eq}},l,i} \quad \text{(E.49)}$$

where

M is the number of uncertainty sub-components of v_{eq} related to wind speed measurements;

i is the wind speed bin referring to bin averaging of power curve;

$u_{v_{\mathrm{eq}},k,i}$ is the standard uncertainty sub-component k of v_{eq} related to wind speed measurements in wind speed bin i;

N is the number of uncertainty sub-components of v_{eq} related to wind direction measurements;

$u_{v_{\mathrm{eq}},l,i}$ is the standard uncertainty sub-component l of v_{eq} related to wind direction measurements in wind speed bin i.

The left term in this equation covers all wind speed measurement uncertainties of the rotor equivalent wind speed and shall be treated according to Clause E.8, while the sensitivity factors given in Equations (E.39) and (E.49) shall be multiplied by the third power of $\cos(\phi_m)$, where m is the wind direction difference to hub height at the m^{th} measurement height. This factor shall also be introduced in Equation (E.46) for the definition of the wind shear correction factor.

The right term in this Equation (E.49) covers all wind direction measurement uncertainties of the rotor equivalent wind speed. As is explained in E.8.1, a difficulty in assessing this uncertainty is related to the fact that the uncertainties of the wind direction measurements at the different height levels are correlated with each other. Similar to Equation (E.39), the sub wind direction uncertainty components of v_{eq} in wind speed bin i shall be calculated from the uncertainty components of the wind direction measurements in single measurement heights by the method of error propagation:

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$$u^2_{v_{eq},l,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{m,i} u_{v_m,l,i} c_{n,i} u_{v_n,l,i} \rho_{m,n,l,i} \quad \text{(E.50)}$$

where

L is the number of measurement heights in the height area of the rotor;

$u_{v_m,l,i}$ is the standard uncertainty sub-component l of wind direction measurement at m-th height relative to hub height in wind speed bin i;

$u_{v_n,l,i}$ is the standard uncertainty sub-component l of wind direction measurement at n-th height relative to hub height in wind speed bin i;

$c_{m,i}$ is the sensitivity factor of v_{eq} on wind direction at height m relative to hub height in wind speed bin i;

$c_{n,i}$ is the sensitivity factor of v_{eq} on wind direction at height n relative to hub height in wind speed bin i;

$\rho_{m,n,l,i}$ is the correlation coefficient between standard uncertainty component l of wind direction measurement at height m and height n relative to hub height in wind speed bin i (wind speed bin referring to the power curve).

The sensitivity factors $c_{m,i}$ and $c_{n,i}$ are gained from the definition of the rotor equivalent wind speed by consideration of wind veer by error propagation as:

$$c_{m,i} = \frac{\partial v_{eq,i}}{\partial \varphi_{m,i}} = -\sin(\varphi_{m,i})\cos^2(\varphi_{m,i})\frac{A_m}{A}\frac{v^3_{m,i}}{v^2_{eq,i}} \quad \text{(E.51)}$$

where

A_m is the rotor segment attributed to wind speed measurement at m-th height according to Equation (5) in 9.1.3.2;

A is the rotor swept area;

$\varphi_{m,i}$ is the wind direction at m-th height relative to wind direction at hub height in wind speed bin i;

$v_{m,i}$ is the wind speed at height m in wind speed bin i;

$v_{eq,i}$ is the equivalent wind speed in bin i.

For the application of Equation (E.40), the relative wind directions $\Phi_{m,i}$ and wind speeds $v_{m,i}$ measured at the different measurement heights shall be bin averaged as function of the wind speed finally applied for the power curve evaluation (air density normalised, wind shear and wind veer corrected wind speed).

Equation (E.50) in combination with Equation (E.51) simplifies if full correlation, no correlation or anti-correlation between the uncertainty components at different measurement heights is assumed. The correlation coefficients suggested in Table E.8 shall be applied for the calculation of the uncertainties in terms of wind direction of v_{eq}. Lower correlation coefficients shall be used only if they are evident and relevant data is reported.

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Table E.8 – Suggested correlation assumptions for relative wind direction measurement uncertainties at different measurement heights

Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
Relative wind direction measurement by vanes or sonic anemometers		
Wind tunnel calibration of vanes used at height m, n and hub height	0,5	The uncertainty of the calibration of single vanes is basically correlated. But as the wind direction differences relative to hub height at heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Influence of met mast on wind direction measurements at heights m,n and hub height	0,5; 1	If the vanes at the two heights m and n are mounted in the same wat relative to the same mast structure, the uncertainties are fully correlated across the two heights m and n. However, the uncertainty itself gets 0 if the vane at hub height is also influenced in the same way by the met mast. If the vanes at the two heights m and n are mounted different relative to the mast structure, or if the mast structure differs much at two heights m and n, the uncertainties and these two heights can be considered as being uncorrelated. But as the wind direction difference relative to hub height at the two heights m and n includes the direction measurement at hub height, a correlation coefficient of 0,5 is suggested for this case.
Northing of wind direction measurement at height m, n and hub height	0,5	The uncertainty of the northing of single vanes is basically uncorrelated. But as the wind direction relative to hub height at the two heights m and n includes the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Data acquisition system (DAS) used to monitor the vanes at height m,n and hub height	0,5	The uncertainty of the DAS channels of single vanes is often basically uncorrelated. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Relative wind direction measurement by remote sensing device		
Wind tunnel calibration of reference vanes used for verification tests at heights m, n and hub height	0,5; 1	These uncertainties of the reference measurement of the verification tests are basically uncorrelated at two heights m and n. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested. An exception is the case of using the same verification test at two height m and n (e.g. if the mast used for the verification test does not cover the entire range of the rotor). Then the uncertainties are fully correlated across the two heights m and n. However, the uncertainty itself gets 0 if the same verification is also applied for hub height.
Northing of reference vanes used for verification tests at heights m, n and hub height	0,5; 1	
Data acquisition system (DAS) used to monitor reference vanes applied for verification tests at heights m, n and hub height	0,5; 1	
Mean deviation of RSD measurement and reference measurement during verification tests at heights m, n and hub height	0,5; 1	
Statistical uncertainty of verification tests at height m, n and hub height	0,5; 1	
Uncertainty of verification tests at height m, n and hub height due to a possible misalignment of the RSD	1	The uncertainty is fully correlated across the heights m and n. However, the respective uncertainty is zero for all heights m and n as the misalignment error cancels out when evaluating the difference of the wind direction at height m and n

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Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
		relative to hub height.
Uncertainty of verification tests at height m, n and hub height caused by the assumption of equal wind conditions across the probe volumes of the RSD.	1	These uncertainties are highly correlated across the heights m and n. However, the respective uncertainties are close to zero as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Uncertainty of verification tests at height m, n and hub height due to a possible separation of the centre of the measurement volume of the RSD and the position of the reference mast	1	
Uncertainty due to sensitivity of RSD measurements and environmental variables.	1	
Possible misalignment of the RSD at the power curve test	1	This uncertainties is fully correlated across the heights m and n. However, the respective uncertainties is zero for all heights m and n as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Assumption of equal wind conditions across the probe volumes of the RSD at heights m, n and hub height	1	This uncertainties is highly correlated across the heights m and n. However, the respective uncertainties are close to zero as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Monitoring wind with a met mas at the power curve test	0,5; 1	If the monitoring met mast covers the two heights m and n with different vanes, the uncertainties of the monitoring are basically uncorrelated at two heights m and n. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested in this case. If the monitoring mast provides only one measurement height that can be used to check the RSD measurement at the heights m and n, the uncertainty is fully correlated across the heights m and n. However, the respective uncertainty is then close to zero for all heights m and n as the uncertainty cancels out when evaluating the difference of the wind direction at height m (or n) and hub height.

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E.13.11 Combining uncertainties in the wind speed measurement from flow distortion due to site calibration $u_{VT,i}$

The following uncertainty components are combined to calculate the category B uncertainty for a site calibration, $u_{VT,i}$:

$$u_{VT,i,j} = \sqrt{u^2_{VT,precal,i,j} + u^2_{VT,postcal,i,j} + u^2_{VT,class,i,j} + u^2_{VT,mnt,i,j} + u^2_{VT,lgt,i,j} + u^2_{VT,coc,i,j} + u^2_{VT,rmv,i,j} + u^2_{VT,sv,i,j} + u^2_{dVT,i,j} + s^2_{VT}} \quad \text{(E.52)}$$

where

$u_{VT,i,j}$ is the uncertainty from the site calibration;

$u_{VT,precal,i,j}$ is the uncertainty related to the calibration of the anemometers;

$u_{VT,postcal,i,j}$ is the uncertainty related to the post calibration or in-situ calibration of the anemometers;

$u_{VT,class,i,j}$ is the uncertainty related to the classification of the sensors;

$u_{VT,mnt,i,j}$ is the uncertainty related to the mounting of the sensors;

$u_{VT,lgt,i,j}$ is the uncertainty due to a possible lightning finial on a top mounted anemometer;

$u_{VT,coc,i,j}$ is the uncertainty related to the change of correction value between bins;

$u_{VT,rmv,i,j}$ is the uncertainty related to the removal of the wind direction sensor between site calibration and power performance test;

$u_{VT,sv,i,j}$ is the uncertainty related to the seasonal variation between site calibration and power performance test;

$u_{dVT,i,j}$ is the uncertainty related to the data acquisition of the wind speed signal;

s_{VT} is the category A standard uncertainty of the site calibration, see C.6.1.

To obtain the uncertainty in one wind speed bin across all the directional sectors the weighted average shall be used:

$$u_{VT,i} = \frac{\sum_j u_{VT,i,j} N_{i,j}}{\sum_j N_{i,j}} \tag{E.53}$$

where $N_{i,j}$ is number of power curve data sets for wind speed bin i and wind direction bin j.

E.13.12 Combining uncertainties for the temperature measurement $u_{T,i}$

The following uncertainty components are combined to calculate the category B uncertainty for temperature, $u_{T,i}$:

$$u_{T,i} = \sqrt{u_{T,cal,i}^2 + u_{T,shield,i}^2 + u_{T,mnt,i}^2 + u_{dT,i}^2} \tag{E.54}$$

where

$u_{T,i}$ is the uncertainty of the temperature measurement;

$u_{T,cal,i}$ is the uncertainty related to the calibration of the temperature sensor;

$u_{T,shield,i}$ is the uncertainty related to the shielding of the temperature sensor;

$u_{T,mnt,i}$ is the uncertainty related to the mounting of the temperature sensor;

$u_{dT,i}$ is the uncertainty related to the data acquisition of the temperature signal.

If we make the following assumptions:

- The standard uncertainty of the temperature sensor is 0,5 °C.
- The shielding of the temperature sensor is 2 °C.
- The standard uncertainty due to mounting effects of the temperature sensor is dependent on the vertical distance from the hub height. With the temperature sensor mounted within 10 m of hub height a standard uncertainty of 1/3 °C is assumed.
- Considering a temperature range of 40 °C of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the air temperature in each bin is:

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$$u_{T,i} = \sqrt{(0{,}5\text{K})^2 + (2{,}0\text{K})^2 + (0{,}3\text{K})^2 + (0{,}1\,\% \cdot 40\text{K})^2} = 2{,}1\,\text{K} \quad \text{(E.55)}$$

E.13.13 Combining uncertainties for the pressure measurement $u_{B,i}$

The following uncertainty components are combined to calculate the category B uncertainty for pressure, $u_{B,i}$:

$$u_{B,i} = \sqrt{u_{B,cal,i}^2 + u_{B,mnt,i}^2 + u_{dB,i}^2} \quad \text{(E.56)}$$

where

$u_{B,i}$ is the uncertainty of the pressure measurement;

$u_{B,cal,i}$ is the uncertainty related to the calibration of the pressure sensor;

$u_{B,mnt,i}$ is the uncertainty related to the mounting of the pressure sensor;

$u_{dB,i}$ is the uncertainty related to the data acquisition of the pressure signal.

If we make the following assumptions:

- The pressure sensor to have a standard uncertainty of 3,0 hPa. It is assumed that the pressure is corrected to the hub height according to ISO 2533 (which, for a standard atmosphere and a height difference of 98 m between the sensor and the hub, is 11,7 hPa). The standard uncertainty due to deployment is estimated to be 10 % of the correction, which is 1,17 hPa.
- Considering a pressure range of 100 hPa of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the air pressure is:

$$u_{B,i} = \sqrt{(3{,}0\text{hPa})^2 + (1{,}17\text{hPa})^2 + (0{,}1\,\% \cdot 100\text{hPa})^2} = 3{,}2\,\text{hPa} \quad \text{(E.57)}$$

E.13.14 Combining uncertainties for the humidity measurement $u_{RH,i}$

The following uncertainty components are combined to calculate the category B uncertainty for humidity, $u_{RH,i}$:

$$u_{RH,i} = \sqrt{u_{RH,cal,i}^2 + u_{RH,mnt,i}^2 + u_{dRH,i}^2} \quad \text{(E.58)}$$

where

$u_{RH,i}$ is the uncertainty of the relative humidity measurement;

$u_{RH,cal,i}$ is the uncertainty related to the calibration of the relative humidity sensor;

$u_{RH,mnt,i}$ is the uncertainty related to the mounting of the relative humidity sensor;

$u_{dRH,i}$ is the uncertainty related to the data acquisition of the relative humidity signal.

If we make the following assumptions:

- The relative humidity sensor to have a standard uncertainty of 1 %;
- The mounting of the sensor to be 0,1 %;
- Considering a pressure range of 100 % of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the relative humidity is:

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$$u_{\mathrm{RH},i} = \sqrt{(1{,}0\,\%)^2 + (0{,}1\%)^2 + (0{,}1\,\% \cdot 100\,\%)^2} = 1{,}0\,\% \tag{E.59}$$

E.13.15 Combining uncertainties for the method related components $u_{M,i}$

The following uncertainty components are combined to calculate the category B uncertainty for related to the methodology, $u_{\mathrm{M},i}$:

$$u_{\mathrm{M},i} = \sqrt{u^2_{\mathrm{M,shear},i} + u^2_{\mathrm{M,veer},i} + u^2_{\mathrm{M,upflow},i} + u^2_{\mathrm{M,ti},i} + u^2_{\mathrm{M,sfx},i} + u^2_{\mathrm{M,tinorm},i} + u^2_{\mathrm{M,cc},i}} \tag{E.60}$$

where

$u_{\mathrm{M},i}$ is the uncertainty related to the applied methodology;

$u_{\mathrm{M,shear},i}$ is the uncertainty related to missing information regarding shear across the whole rotor;

$u_{\mathrm{M,veer},i}$ is the uncertainty related to missing information regarding wind veer across the whole rotor;

$u_{\mathrm{M,upflow},i}$ is the uncertainty related to missing information regarding upflow across the whole rotor;

$u_{\mathrm{M,ti},i}$ is the uncertainty related to missing information regarding turbulence when no hub-height meteorological mast wind speed signal is available;

$u_{\mathrm{M,sfx},i}$ is the uncertainty related to the unquantifiable seasonal effects on the turbine;

$u_{\mathrm{M,tinorm},i}$ is the uncertainty related to turbulence normalisation;

$u_{\mathrm{M,cc},i}$ is the uncertainty related to the measurement in a cold climate.

E.13.16 Combining uncertainties for the wind direction measurement with wind vane or sonic anemometer $u_{\mathrm{WV},i}$

The following uncertainty components are combined to calculate the category B uncertainty for the wind direction measurement with wind vane or sonic anemometer, $u_{\mathrm{WV},i}$:

$$u_{\mathrm{WV},i} = \sqrt{u^2_{\mathrm{WV,cal},i} + u^2_{\mathrm{WV,nm},i} + u^2_{\mathrm{WV,bo},i} + u^2_{\mathrm{WV,oe},i} + u^2_{\mathrm{WV,mda},i} + u^2_{\mathrm{dWV},i}} \tag{E.61}$$

where

$u_{\mathrm{WV},i}$ is the uncertainty related to the wind direction measured with a mast mounted wind direction sensor (wind vane or sonic anemometer);

$u_{\mathrm{WV,cal},i}$ is the uncertainty related to the calibration of the wind direction sensor;

$u_{\mathrm{WV,nm},i}$ is the uncertainty related to north marking of the wind direction sensor;

$u_{\mathrm{WV,bo},i}$ is the uncertainty related to the boom orientation on which the wind direction sensor is mounted;

$u_{\mathrm{WV,oe},i}$ is the uncertainty related to the influence of the meteorological mast on the wind direction measurement;

$u_{\mathrm{WV,mda},i}$ is the uncertainty related to the magnetic declination angle;

$u_{\mathrm{dWV},i}$ is the uncertainty related to the data acquisition of the signal from the wind direction sensor.

E.13.17 Combining uncertainties for the wind direction measurement with RSD $u_{\mathrm{WR},i}$

The following uncertainty components are combined to calculate the category B uncertainty for the wind direction measurement with RSD, $u_{\mathrm{WR},i}$:

$$u_{\mathrm{WR},i} = \sqrt{u^2_{\mathrm{WR,ver},i} + u^2_{\mathrm{WR,class},i} + u^2_{\mathrm{WR,mon},i} + u^2_{\mathrm{WR,fv},i} + u^2_{\mathrm{WR,align},i} + u^2_{\mathrm{WR,mda},i} + u^2_{\mathrm{dWR},i}} \tag{E.62}$$

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where

$u_{WR,i}$ is the uncertainty related to the wind direction measured with an RSD;

$u_{WR,ver,i}$ is the uncertainty related to the verification test of the RSD;

$u_{WR,class,i}$ is the uncertainty related to the classification of the RSD;

$u_{WR,mon,i}$ is the uncertainty related to the monitoring of the RSD;

$u_{WR,fv,i}$ is the uncertainty related to the variation in wind flow across to measured volume;

$u_{WR,align,i}$ is the uncertainty related to the alignment of the RSD;

$u_{WR,mda,i}$ is the uncertainty related to the magnetic declination angle;

$u_{dWR,i}$ is the uncertainty related to the data acquisition of the signal from the wind direction sensor.

E.13.18 Combined category B uncertainties

The category B uncertainties in each bin are combined as:

$$u_i = \sqrt{u_{P,i}^2 + c_{V,i}^2\, u_{V,i}^2 + c_{T,i}^2\, u_{T,i}^2 + c_{B,i}^2\, u_{B,i}^2}$$

$$= \sqrt{\begin{array}{l}(0{,}52\,\%\cdot P_i\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{V,i}^2\left((0{,}104\,\mathrm{m/s})^2 + (0{,}032\cdot V_i\,[\mathrm{m/s}])^2 + (0{,}034\,\mathrm{m/s} + 0{,}0034\cdot V_i\,[\mathrm{m/s}])^2\right) + \\ c_{T,i}^2((2{,}1\,\mathrm{K})^2 + c_{B,i}^2(3{,}0\,\mathrm{hPa})^2)\end{array}} \quad \text{(E.31)}$$

$$u_i = \sqrt{u_{P,i}^2 + c_{v,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2} \quad \text{(E.63)}$$

E.13.19 Combined standard uncertainty – Power curve

The combined standard uncertainties of each bin of the power curve are found by combining the category A uncertainty with all the category B uncertainties.

$$u_{c,i} = \sqrt{s_i^2 + u_i^2} = \sqrt{s_{P,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2}$$

$$= \sqrt{\begin{array}{l}s_{P,i}^2 + (0{,}52\,\%\cdot P_i\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{V,i}^2\left((0{,}104\,\mathrm{m/s})^2 + (0{,}032\cdot V_i\,[\mathrm{m/s}])^2 + (0{,}034\,\mathrm{m/s} + 0{,}0034\cdot V_i\,[\mathrm{m/s}])^2\right) + \\ c_{T,i}^2((2{,}1\mathrm{K})^2 + c_{B,i}^2(3{,}0\,\mathrm{hPa})^2)\end{array}} \quad \text{(E.32)}$$

$$u_{c,i} = \sqrt{S_i^2 + u_i^2} = \sqrt{S_i^2 + u_{P,i}^2 + c_{v,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2} \quad \text{(E.64)}$$

E.13.20 Combined standard uncertainty – Energy production

The combined standard uncertainty of AEP is found by combining individually the category A and B uncertainties bin-wise. This may be accomplished according to the full formulation of Equation (E.4) and shown in Equation (E.65) or the simplified and conservative formulation of Equation (E.5), shown in Equation (E.65):

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$$u_{\mathrm{AEP}} = N_{\mathrm{h}} \sqrt{\sum_{i=1}^{N} f_i^2 \, s_i^2 + \left(\sum_{i=1}^{N} f_i \, u_i\right)^2}$$

$$= N_{\mathrm{h}} \sqrt{\sum_{i=1}^{N} f_i^2 \, s_{\mathrm{P},i}^2 + \left(\sum_{i=1}^{N} f_i \sqrt{\begin{array}{l} (0{,}52\,\% \cdot P_i\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{\mathrm{V},i}^2((0{,}104\,\mathrm{m/s})^2 + (0{,}032 \cdot V_i\,[\mathrm{m/s}])^2) + \\ c_{\mathrm{V},i}^2((0{,}034\,\mathrm{m/s} + 0{,}0034 \cdot V_i\,[\mathrm{m/s}])^2) + \\ c_{\mathrm{T},i}^2((2{,}1\mathrm{K})^2 + c_{\mathrm{B},i}^2(3{,}0\,\mathrm{hPa})^2) \end{array}} \right)^2} \quad \text{(E.33)}$$

where

$f_i = ((F_{i+1} - F_i) + (F_i - F_{i-1}))/2$ is the average probability of wind speed in bin i.

$$u_{AEP} = N_{\mathrm{h}} \sqrt{\sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_{\mathrm{A}}} c_{k,i}^2 \, s_{k,i}^2 + N_{\mathrm{h}}^2 \sum_{k=1}^{M_{\mathrm{B}}} \left(\sum_{i=1}^{N} f_{\mathrm{i}} \, c_{k,i} \, u_{k,i}\right)^2} \quad \text{(E.65)}$$

$$u_{AEP} = N_{\mathrm{h}} \sqrt{\sum_{i=1}^{N} f_i^2 s_i^2 + \left(\sum_{i=1}^{N} f_i \, u_i\right)^2} \quad \text{(E.66)}$$

where

f_i is the relative occurrence of wind speed between V_{i-1} and V_i: $F(V_i) - F(V_{i-1})$ within bin i.

E.14 Relevance of uncertainty components under specified conditions

As per the Guide to expression of uncertainty in measurement, in some cases an uncertainty component may be evaluated and found to be insignificant and therefore not be included in the evaluation of the uncertainty of the measurement result.

In this standard, various uncertainty components only should be assigned a zero value in specific cases or when a specific set of conditions have been met. An example is the uncertainty of $u_{\mathrm{VT,coc},i,j}$ which relates to the uncertainty applied in a site calibration when wind direction bins with a change in correction factor larger than 2 % compared to the neighbouring bin are not eliminated from the data set (see C.7.3 d). Only when the decision is made not to remove such bins does $u_{\mathrm{VT,coc},i,j}$ get a value, otherwise it has value zero.

It is up to the user of this standard to determine in which cases an uncertainty component can be deemed irrelevant and hence set to zero. This should be documented (including the justification) to ensure reproducibility of the uncertainty calculation.

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E.15 Reference tables

Table E.3 – Uncertainties from site calibration

Bin No.	Wind speed	Site
i	V_i	calibration
	m/s	$u_{,}V4_{,i}$
4	2,0	0,1477
5	2,5	0,1477
6	3,0	0,1472
7	3,5	0,1473
8	4,0	0,1474
9	4,5	0,1479
10	5,0	0,1475
11	5,5	0,1480
12	6,0	0,1481
13	6,5	0,1482
14	7,0	0,1478
15	7,5	0,1478
16	8,0	0,1484
17	8,5	0,1486
18	9,0	0,1488
19	9,5	0,1489
20	10,0	0,1490
21	10,5	0,1492
22	11,0	0,1493
23	11,5	0,1494
24	12,0	0,1494
25	12,5	0,1499
26	13,0	0,1498
27	13,5	0,1499
28	14,0	0,1500
29	14,5	0,1501
30	15,0	0,1503
31	15,5	0,1503
32	16,0	0,1507
33	16,5	0,1513
34	17,0	0,1512
35	17,5	0,1523
36	18,0	0,1530
37	18,5	0,1522
38	19,0	0,1521
39	19,5	0,1539
40	20,0	0,1541
41	20,5	0,1505
42	21,0	0,1512
43	21,5	0,1548
44	22,0	0,1530
45	22,5	0,1533
46	23,0	0,1557
47	23,5	0,1567

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Table E.9 – Uncertainties from air density normalisation

Bin No.	Air density normalized wind speed	Wind speed before normalization (un-normalized)	Difference of normalised and un-normalized wind speed	Uncertainty due to air density normalization
i	$V_{\mathrm{n}\,i}$	$V_{\mathrm{un}\,i}$	$V_{\mathrm{n}i} - V_{\mathrm{un}\,i}$	$u_{\mathrm{P}I,i}$
	m/s	m/s	m/s	m/s
4	2,03	2,025	0,008	0,004
5	2,51	2,501	0,013	0,007
6	3,03	3,015	0,014	0,007
7	3,52	3,501	0,016	0,008
8	4,02	4,000	0,022	0,011
9	4,53	4,503	0,028	0,014
10	5,00	4,976	0,029	0,014
11	5,55	5,523	0,031	0,016
12	6,03	5,991	0,035	0,017
13	6,56	6,503	0,055	0,028
14	7,01	6,970	0,041	0,021
15	7,55	7,485	0,061	0,031
16	8,04	7,979	0,065	0,032
17	8,57	8,503	0,064	0,032
18	9,08	8,999	0,080	0,040
19	9,58	9,494	0,090	0,045
20	10,10	10,007	0,091	0,045
21	10,61	10,501	0,113	0,056
22	11,10	10,982	0,122	0,061
23	11,60	11,475	0,121	0,060
24	12,11	11,986	0,125	0,062
25	12,64	12,504	0,139	0,070
26	13,17	13,034	0,134	0,067
27	13,59	13,467	0,123	0,061
28	14,18	14,020	0,157	0,079
29	14,62	14,479	0,140	0,070
30	15,07	14,916	0,149	0,075
31	15,76	15,611	0,151	0,075
32	16,09	15,941	0,147	0,073
33	16,83	16,680	0,150	0,075
34	17,03	16,926	0,100	0,050
35	17,81	17,586	0,226	0,113
36	18,19	18,052	0,135	0,068
37	18,5	0,152 2	0,135	0,068
38	19	0,152 1	0,135	0,068
39	19,5	0,153 9	0,135	0,068
40	20	0,154 1	0,135	0,068
41	20,5	0,150 5	0,135	0,068
42	21	0,151 2	0,135	0,068

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Bin No.	Air density normalized wind speed	Wind speed before normalization (un-normalized)	Difference of normalised and un-normalized wind speed	Uncertainty due to air density normalization
i	$V_{n\,i}$	$V_{un\,i}$	$V_{ni} - V_{un\,i}$	$u_{P1,i}$
	m/s	m/s	m/s	m/s
43	21,5	0,154 8	0,135	0,068
44	22	0,153	0,135	0,068
45	22,5	0,153 3	0,135	0,068
46	23	0,155 7	0,135	0,068
47	23,5	0,156 7	0,135	0,068

~~Table E.4 – Sensitivity factors (database A)~~

	~~Power curve (database A)~~		~~Sensitivity factors~~		
~~Bin No.~~	~~Wind speed~~	~~Electric power~~	~~Wind speed~~	~~Air temperature~~	~~Air pressure~~
~~i~~	~~V_i~~	~~P_i~~	~~$e_{V,i}$~~	~~$e_{T,i}$~~	~~$e_{B,i}$~~
	~~m/s~~	~~kW~~	~~kW/ms~~	~~kW/K~~	~~kW/hPa~~
~~4~~	~~2,13~~	~~–3,64~~	~~1,71~~	~~0,01~~	~~0,00~~
~~5~~	~~2,49~~	~~–3,65~~	~~0,01~~	~~0,01~~	~~0,00~~
~~6~~	~~2,99~~	~~–3,78~~	~~0,27~~	~~0,01~~	~~0,00~~
~~7~~	~~3,51~~	~~–2,19~~	~~3,06~~	~~0,01~~	~~0,00~~
~~8~~	~~3,99~~	~~–0,43~~	~~3,65~~	~~0,00~~	~~0,00~~
~~9~~	~~4,50~~	~~6,04~~	~~12,83~~	~~0,02~~	~~0,01~~
~~10~~	~~4,98~~	~~27,70~~	~~44,69~~	~~0,10~~	~~0,03~~
~~11~~	~~5,52~~	~~67,39~~	~~74,00~~	~~0,23~~	~~0,07~~
~~12~~	~~5,98~~	~~111,30~~	~~94,47~~	~~0,39~~	~~0,11~~
~~13~~	~~6,51~~	~~160,95~~	~~95,05~~	~~0,56~~	~~0,16~~
~~14~~	~~7,01~~	~~209,42~~	~~95,41~~	~~0,73~~	~~0,21~~
~~15~~	~~7,50~~	~~261,96~~	~~107,51~~	~~0,91~~	~~0,26~~
~~16~~	~~8,00~~	~~327,63~~	~~132,16~~	~~1,14~~	~~0,32~~
~~17~~	~~8,50~~	~~395,23~~	~~136,16~~	~~1,37~~	~~0,39~~
~~18~~	~~8,99~~	~~462,01~~	~~134,67~~	~~1,60~~	~~0,46~~
~~19~~	~~9,49~~	~~556,06~~	~~187,71~~	~~1,93~~	~~0,55~~
~~20~~	~~10,00~~	~~629,80~~	~~144,25~~	~~2,19~~	~~0,62~~
~~21~~	~~10,47~~	~~703,06~~	~~157,30~~	~~2,44~~	~~0,69~~
~~22~~	~~11,00~~	~~786,55~~	~~156,23~~	~~2,73~~	~~0,78~~
~~23~~	~~11,50~~	~~836,48~~	~~101,15~~	~~2,90~~	~~0,83~~
~~24~~	~~11,99~~	~~893,52~~	~~116,32~~	~~3,10~~	~~0,88~~
~~25~~	~~12,49~~	~~928,61~~	~~69,27~~	~~3,22~~	~~0,92~~
~~26~~	~~13,03~~	~~956,44~~	~~51,66~~	~~3,32~~	~~0,94~~
~~27~~	~~13,50~~	~~971,30~~	~~31,58~~	~~3,37~~	~~0,96~~
~~28~~	~~14,00~~	~~980,92~~	~~19,49~~	~~3,40~~	~~0,97~~
~~29~~	~~14,48~~	~~988,17~~	~~15,10~~	~~3,43~~	~~0,98~~
~~30~~	~~15,00~~	~~993,46~~	~~10,20~~	~~3,45~~	~~0,98~~
~~31~~	~~15,49~~	~~993,71~~	~~0,50~~	~~3,45~~	~~0,98~~
~~32~~	~~15,99~~	~~995,70~~	~~3,97~~	~~3,46~~	~~0,98~~
~~33~~	~~16,54~~	~~996,22~~	~~0,96~~	~~3,46~~	~~0,98~~
~~34~~	~~17,02~~	~~996,42~~	~~0,42~~	~~3,46~~	~~0,98~~
~~35~~	~~17,48~~	~~996,48~~	~~0,12~~	~~3,46~~	~~0,98~~
~~36~~	~~17,95~~	~~996,50~~	~~0,04~~	~~3,46~~	~~0,98~~
~~37~~	~~18,49~~	~~995,71~~	~~1,48~~	~~3,46~~	~~0,98~~

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38	18,97	935,54	125,87	3,25	0,92
39	19,45	900,46	71,97	3,12	0,89
40	19,97	842,52	112,19	2,92	0,83
41	20,50	551,21	549,95	1,91	0,54
42	20,92	661,19	261,26	2,29	0,65
43	21,47	396,55	480,32	1,38	0,39
44	22,02	–6,30	738,89	0,02	0,01
45	22,60	494,34	861,43	1,72	0,49
46	23,00	231,88	656,95	0,80	0,23
47	23,56	193,49	67,81	0,67	0,19
48	24,02	–7,92	445,39	0,03	0,01
49	24,56	–6,34	2,89	0,02	0,01
50	25,03	–6,30	0,08	0,02	0,01

Table E.5 – Sensitivity factors (database B)

	Power curve (database B)		Sensitivity factors		
Bin No.	Wind speed	Electric power	Wind speed	Air temperature	Air pressure
i	V_i	P_i	$e_{V,i}$	$e_{T,i}$	$e_{B,i}$
	m/s	kW	kW/ms	kW/K	kW/hPa
4	2,13	–3,64	1,712	0,013	0,004
5	2,49	–3,65	0,014	0,013	0,004
6	2,99	–3,78	0,269	0,013	0,004
7	3,51	–2,19	3,062	0,008	0,002
8	3,99	–0,43	3,645	0,001	0,000
9	4,50	6,04	12,825	0,021	0,006
10	4,98	27,70	44,664	0,096	0,027
11	5,52	67,39	74,049	0,234	0,067
12	5,98	111,30	94,430	0,386	0,110
13	6,51	160,95	95,019	0,558	0,159
14	7,01	209,42	95,472	0,727	0,207
15	7,50	261,96	107,566	0,909	0,259
16	8,00	327,63	131,992	1,137	0,323
17	8,50	395,23	136,290	1,372	0,390
18	8,99	462,01	134,677	1,603	0,456
19	9,49	556,06	187,824	1,930	0,549
20	10,00	629,80	145,079	2,186	0,622
21	10,47	703,06	155,957	2,440	0,694
22	11,00	786,55	157,358	2,729	0,776
23	11,50	836,48	100,000	2,903	0,826
24	11,99	893,52	116,327	3,101	0,882
25	12,49	928,61	70,200	3,223	0,917
26	13,03	956,44	51,481	3,319	0,944
27	13,50	971,30	31.702	3.371	0.959
28	14,00	980,92	19,200	3,404	0,968
29	14,48	988,17	15,208	3,429	0,976

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30	15,00	993,46	10,192	3,448	0,981
31	15,49	993,71	0,408	3,449	0,981
32	15,99	995,70	4,000	3,455	0,983
33	16,54	996,22	0,909	3,457	0,983
34	17,02	996,42	0,417	3,458	0,984
35	17,48	996,48	0,217	3,458	0,984
36	17,95	996,50	0,000	3,458	0,984
37	18,49	995,71	0,556	3,457	0,983
38	18,97	996,6	0,833	3,459	0,984
39	19,42	996,1	1,111	3,457	0,983
40	19,96	994,1	3,704	3,450	0,981
41	20,51	987,4	12,182	3,427	0,975
42	20,88	996,9	25,676	3,460	0,984

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Table E.10 – Sensitivity factors

	Power curve (database B)		Sensitivity factors		
Bin No.	Wind speed	Electric power	Wind speed	Air temperature	Air pressure
i	V_i	P_i	$c_{V,i}$	$c_{T,i}$	$c_{B,i}$
	m/s	kW	kW/m/s	kW/K	kW/hPa
4	2,13	–3,64	1,712	0,013	0,004
5	2,49	–3,65	0,014	0,013	0,004
6	2,99	–3,78	0,269	0,013	0,004
7	3,51	–2,19	3,062	0,008	0,002
8	3,99	–0,43	3,645	0,001	0,000
9	4,50	6,04	12,825	0,021	0,006
10	4,98	27,70	44,664	0,096	0,027
11	5,52	67,39	74,049	0,234	0,067
12	5,98	111,30	94,430	0,386	0,110
13	6,51	160,95	95,019	0,558	0,159
14	7,01	209,42	95,472	0,727	0,207
15	7,50	261,96	107,566	0,909	0,259
16	8,00	327,63	131,992	1,137	0,323
17	8,50	395,23	136,290	1,372	0,390
18	8,99	462,01	134,677	1,603	0,456
19	9,49	556,06	187,824	1,930	0,549
20	10,00	629,80	145,079	2,186	0,622
21	10,47	703,06	155,957	2,440	0,694
22	11,00	786,55	157,358	2,729	0,776
23	11,50	836,48	100,000	2,903	0,826
24	11,99	893,52	116,327	3,101	0,882
25	12,49	928,61	70,200	3,223	0,917
26	13,03	956,44	51,481	3,319	0,944
27	13,50	971,30	31,702	3,371	0,959
28	14,00	980,92	19,200	3,404	0,968
29	14,48	988,17	15,208	3,429	0,976
30	15,00	993,46	10,192	3,448	0,981
31	15,49	993,71	0,408	3,449	0,981
32	15,99	995,70	4,000	3,455	0,983
33	16,54	996,22	0,909	3,457	0,983
34	17,02	996,42	0,417	3,458	0,984
35	17,48	996,48	0,217	3,458	0,984
36	17,95	996,50	0,000	3,458	0,984
37	18,49	995,71	0,556	3,457	0,983
38	18,97	996,6	0,833	3,459	0,984
39	19,42	996,1	1,111	3,457	0,983
40	19,96	994,1	3,704	3,450	0,981
41	20,51	987,4	12,182	3,427	0,975
42	20,88	996,9	25,676	3,460	0,984

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Table E.6 – Category B uncertainties (database A)

Bin No.	Electric power	Wind speed	Wind speed	Air temperature	Air temperature	Air pressure	Air pressure
i	$u_{P,i}$	$u_{V,i}$	$e_{V,i} \cdot u_{V,i}$	$u_{T,i}$	$e_{T,i} \cdot u_{T,i}$	$u_{B,i}$	$e_{B,i} \cdot u_{B,i}$
	kW	m/s	kW	K	kW	hPa	kW
4	6,29	0,19	0,33	2,09	0,03	3,18	0,01
5	6,29	0,19	0,00	2,09	0,03	3,18	0,01
6	6,29	0,19	0,05	2,09	0,03	3,18	0,01
7	6,29	0,19	0,60	2,09	0,02	3,18	0,01
8	6,29	0,20	0,71	2,09	0,00	3,18	0,00
9	6,29	0,20	2,53	2,09	0,04	3,18	0,02
10	6,29	0,20	8,86	2,09	0,20	3,18	0,09
11	6,30	0,20	14,81	2,09	0,49	3,18	0,21
12	6,32	0,20	19,05	2,09	0,81	3,18	0,35
13	6,35	0,20	19,35	2,09	1,17	3,18	0,51
14	6,39	0,21	19,57	2,09	1,52	3,18	0,66
15	6,44	0,21	22,27	2,09	1,90	3,18	0,82
16	6,52	0,21	27,70	2,09	2,37	3,18	1,03
17	6,62	0,21	28,85	2,09	2,86	3,18	1,24
18	6,74	0,21	28,86	2,09	3,35	3,18	1,45
19	6,93	0,22	40,68	2,09	4,03	3,18	1,75
20	7,09	0,22	31,64	2,09	4,57	3,18	1,98
21	7,28	0,22	34,91	2,09	5,10	3,18	2,21
22	7,51	0,22	35,13	2,09	5,70	3,18	2,47
23	7,65	0,23	23,03	2,09	6,06	3,18	2,63
24	7,82	0,23	26,81	2,09	6,48	3,18	2,81
25	7,93	0,23	16,19	2,09	6,73	3,18	2,92
26	8,02	0,24	12,24	2,09	6,93	3,18	3,00
27	8,07	0,24	7,58	2,09	7,04	3,18	3,05
28	8,10	0,24	4,74	2,09	7,11	3,18	3,08
29	8,13	0,25	3,72	2,09	7,16	3,18	3,10
30	8,14	0,25	2,55	2,09	7,20	3,18	3,12
31	8,14	0,25	0,13	2,09	7,20	3,18	3,12
32	8,15	0,26	1,02	2,09	7,22	3,18	3,13
33	8,15	0,26	0,25	2,09	7,22	3,18	3,13
34	8,15	0,26	0,11	2,09	7,22	3,18	3,13
35	8,15	0,27	0,03	2,09	7,22	3,18	3,13
36	8,15	0,27	0,01	2,09	7,22	3,18	3,13
37	8,15	0,28	0,41	2,09	7,22	3,18	3,13
38	7,96	0,28	35,16	2,09	6,78	3,18	2,94
39	7,84	0,28	20,44	2,09	6,53	3,18	2,83
40	7,67	0,29	32,32	2,09	6,11	3,18	2,65
41	6,91	0,29	159,68	2,09	4,00	3,18	1,73
42	7,17	0,29	76,82	2,09	4,79	3,18	2,08
43	6,62	0,30	144,22	2,09	2,87	3,18	1,25
44	6,29	0,30	224,40	2,09	0,05	3,18	0,02
45	6,80	0,31	265,85	2,09	3,58	3,18	1,55
46	6,41	0,31	205,65	2,09	1,68	3,18	0,73
47	6,37	0,32	21,58	2,09	1,40	3,18	0,61
48	6,29	0,28	125,27	2,09	0,06	3,18	0,02
49	6,29	0,29	0,83	2,09	0,05	3,18	0,73
50	6,29	0,29	0,02	2,09	0,05	3,18	0,61

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Table E.7 – Category B uncertainties (database B)

Bin No.	Electric power	Wind speed	Wind speed	Air temperature	Air temperature	Air pressure	Air pressure
i	$u_{P,i}$	$u_{V,i}$	$c_{V,i} \cdot u_{V,i}$	$u_{T,i}$	$c_{T,i} \cdot u_{T,i}$	$u_{B,i}$	$c_{B,i} \cdot u_{B,i}$
	kW	m/s	kW	K	kW	hPa	kW
4	6,29	0,19	0,33	2,09	0,03	3,18	0,01
5	6,29	0,19	0,00	2,09	0,03	3,18	0,01
6	6,29	0,19	0,05	2,09	0,03	3,18	0,01
7	6,29	0,19	0,60	2,09	0,02	3,18	0,01
8	6,29	0,20	0,71	2,09	0,00	3,18	0,00
9	6,29	0,20	2,53	2,09	0,04	3,18	0,02
10	6,29	0,20	8,85	2,09	0,20	3,18	0,09
11	6,30	0,20	14,82	2,09	0,49	3,18	0,21
12	6,32	0,20	19,04	2,09	0,81	3,18	0,35
13	6,35	0,20	19,34	2,09	1,17	3,18	0,51
14	6,39	0,21	19,58	2,09	1,52	3,18	0,66
15	6,44	0,21	22,28	2,09	1,90	3,18	0,82
16	6,52	0,21	27,66	2,09	2,37	3,18	1,03
17	6,62	0,21	28,87	2,09	2,86	3,18	1,24
18	6,74	0,21	28,86	2,09	3,35	3,18	1,45
19	6,93	0,22	40,71	2,09	4,03	3,18	1,75
20	7,09	0,22	31,82	2,09	4,57	3,18	1,98
21	7,28	0,22	34,61	2,09	5,10	3,18	2,21
22	7,51	0,22	35,38	2,09	5,70	3,18	2,47
23	7,65	0,23	22,47	2,09	6,06	3,18	2,63
24	7,82	0,23	26,81	2,09	6,48	3,18	2,81
25	7,93	0,23	16,41	2,09	6,73	3,18	2,92
26	8,02	0,24	12,20	2,09	6,93	3,18	3,00
27	8,07	0,24	7,61	2,09	7,04	3,18	3,05
28	8,10	0,24	4,67	2,09	7,11	3,18	3,08
29	8,13	0,25	3,75	2,09	7,16	3,18	3,10
30	8,14	0,25	2,55	2,09	7,20	3,18	3,12
31	8,14	0,25	0,10	2,09	7,20	3,18	3,12
32	8,15	0,26	1,03	2,09	7,22	3,18	3,13
33	8,15	0,26	0,24	2,09	7,22	3,18	3,13
34	8,15	0,26	0,11	2,09	7,22	3,18	3,13
35	8,15	0,27	0,06	2,09	7,22	3,18	3,13
36	8,15	0,27	0,00	2,09	7,22	3,18	3,13
37	8,15	0,28	0,15	2,09	7,22	3,18	3,13
38	8,15	0,28	0,23	2,09	7,22	3,18	3,13
39	8,15	0,28	0,32	2,09	7,22	3,18	3,13
40	8,15	0,29	1,07	2,09	7,21	3,18	3,12
41	8,12	0,29	3,54	2,09	7,16	3,18	3,10
42	8,15	0,29	7,54	2,09	7,23	3,18	3,13

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Table E.11 – Category B uncertainties

Bin No.	Electric power	Wind speed	Wind speed	Air temperature	Air temperature	Air pressure	Air pressure
i	$u_{P,i}$	$u_{V,i}$	$c_{V,i} \cdot u_{V,i}$	$u_{T,i}$	$c_{T,i} \cdot u_{T,i}$	$u_{B,i}$	$c_{B,i} \cdot u_{B,i}$
	kW	m/s	kW	K	kW	hPa	kW
4	6,29	0,19	0,33	2,09	0,03	3,18	0,01
5	6,29	0,19	0,00	2,09	0,03	3,18	0,01
6	6,29	0,19	0,05	2,09	0,03	3,18	0,01
7	6,29	0,19	0,60	2,09	0,02	3,18	0,01
8	6,29	0,20	0,71	2,09	0,00	3,18	0,00
9	6,29	0,20	2,53	2,09	0,04	3,18	0,02
10	6,29	0,20	8,85	2,09	0,20	3,18	0,09
11	6,30	0,20	14,82	2,09	0,49	3,18	0,21
12	6,32	0,20	19,04	2,09	0,81	3,18	0,35
13	6,35	0,20	19,34	2,09	1,17	3,18	0,51
14	6,39	0,21	19,58	2,09	1,52	3,18	0,66
15	6,44	0,21	22,28	2,09	1,90	3,18	0,82
16	6,52	0,21	27,66	2,09	2,37	3,18	1,03
17	6,62	0,21	28,87	2,09	2,86	3,18	1,24
18	6,74	0,21	28,86	2,09	3,35	3,18	1,45
19	6,93	0,22	40,71	2,09	4,03	3,18	1,75
20	7,09	0,22	31,82	2,09	4,57	3,18	1,98
21	7,28	0,22	34,61	2,09	5,10	3,18	2,21
22	7,51	0,22	35,38	2,09	5,70	3,18	2,47
23	7,65	0,23	22,77	2,09	6,06	3,18	2,63
24	7,82	0,23	26,81	2,09	6,48	3,18	2,81
25	7,93	0,23	16,41	2,09	6,73	3,18	2,92
26	8,02	0,24	12,20	2,09	6,93	3,18	3,00
27	8,07	0,24	7,61	2,09	7,04	3,18	3,05
28	8,10	0,24	4,67	2,09	7,11	3,18	3,08
29	8,13	0,25	3,75	2,09	7,16	3,18	3,10
30	8,14	0,25	2,55	2,09	7,20	3,18	3,12
31	8,14	0,25	0,10	2,09	7,20	3,18	3,12
32	8,15	0,26	1,03	2,09	7,22	3,18	3,13
33	8,15	0,26	0,24	2,09	7,22	3,18	3,13
34	8,15	0,26	0,11	2,09	7,22	3,18	3,13
35	8,15	0,27	0,06	2,09	7,22	3,18	3,13
36	8,15	0,27	0,00	2,09	7,22	3,18	3,13
37	8,15	0,28	0,15	2,09	7,22	3,18	3,13
38	8,15	0,28	0,23	2,09	7,22	3,18	3,13
39	8,15	0,28	0,32	2,09	7,22	3,18	3,13
40	8,15	0,29	1,07	2,09	7,21	3,18	3,12
41	8,12	0,29	3,54	2,09	7,16	3,18	3,10
42	8,15	0,29	7,54	2,09	7,23	3,18	3,13

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Annex F
(normative)

~~Cup anemometer~~ Wind tunnel calibration procedure for anemometers

F.1 General requirements

The general requirements for the calibration of anemometers are summarized as follows:

- ~~all transducers and measuring equipment shall have traceable calibrations. Calibration certificates and reports shall contain all relevant traceability information. All reference standards used during the calibration of the anemometer shall be stated within the test report of the calibration campaign;~~
- ~~the pitot tubes used shall be calibrated for appropriate wind speed ranges, and be documented;~~
- ~~prior to every calibration round the integrity of the experimental set-up shall be verified by means of comparative calibration of a "reference anemometer" of the institute;~~

a) the calibration of the anemometer shall be carried out in a wind tunnel that is suitable for the calibration of anemometers;

b) the calibration facility shall be recognised by IECRE or accredited in accordance with ISO/IEC 17025, being the main standard for testing and calibration laboratories;

c) all transducers and measuring equipment relevant for the calibration of anemometers shall have traceable calibrations according to ISO/IEC 17025. Calibration certificates and reports shall contain all relevant traceability information;

d) the reference wind speed shall be measured with a pitot-static tube that shall be of NPL type with ellipsoidal head according to ISO 3966. The pitot-static tube shall be calibrated for appropriate wind speed ranges, and be documented. The reference wind speed may alternatively be measured by LDA (Laser Doppler Anemometry) with well documented uncertainties;

e) consistency of the experimental set-up shall be verified by at least daily comparative calibrations of the facility's "quality control anemometer";

f) flow quality shall be ~~carried out~~ verified as required in Clause F.2;

g) the repeatability of the calibration shall be verified as required in Clause F.2;

h) anemometer calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO Guide 98-3:2008.

F.2 Requirements to the wind tunnel

~~The wind tunnel shall be well equipped and carefully prepared to carry out accurate anemometer calibrations.~~

The presence of the anemometer shall not substantially affect the flow field in the wind tunnel. During measurements the anemometer will to some extent be influenced by wind tunnel blockage and boundary effects. The blockage area ratio (*BR*) – defined as the ratio of the anemometer ~~frontal~~ projected area, perpendicular to flow direction, (including its mounting system and projected area of a spinning rotor) to the total test section area – shall not exceed ~~0,1 for open test section and~~ 0,05 ~~for closed test section~~. Blockage effects shall always be accounted for according to F.4.3.

It is recommended that the wind tunnel test section has a height of at least 1,0 m and a width of at least 1,0 m.

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The flow ~~across~~ in the cross sectional area ~~covered by~~ where the anemometer will be located, shall be uniform. ~~The flow uniformity shall be assessed prior to the anemometer's calibration. Flow uniformity can be estimated using velocity sensing devices, i.e. pitot tubes, hot wires or Laser Doppler Velocimetry and measuring flow profiles in longitudinal, transversal and vertical direction. The flow shall be uniform to 0,2 %. These investigations shall be carried out for the wind tunnel once and additionally after each modification of the wind tunnel aerodynamics.~~

Flow uniformity should be measured using velocity sensing devices, i.e. pitot tubes, hot wires or Laser Doppler Velocimetry to measure flow profiles in longitudinal, transversal and vertical direction. Over the calibration wind speed range, the maximum difference in the mean velocity between any two points inside the measurement volume shall be less than 0,2 %. The mean value shall be calculated during at least five minutes and the measurement volume shall cover the active volume of the anemometer with 50 % margin in all directions as per Figure F.1. Uniformity shall be tested over a period of at least 5 minutes for wind speeds at approximately 4 m/s, 8 m/s, 12 m/s and 16 m/s each.

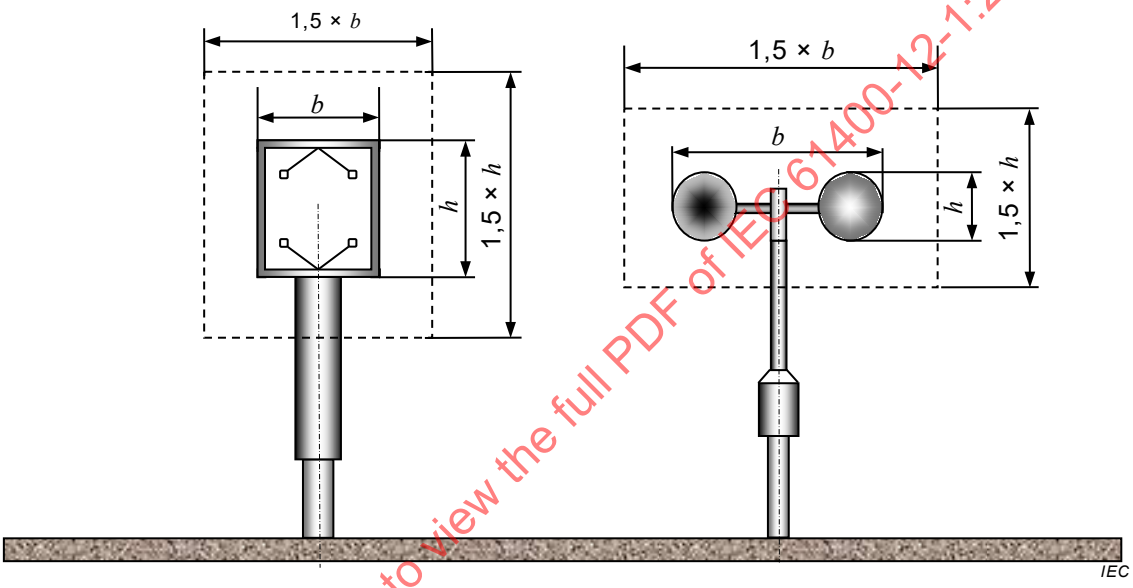

Figure F.1 – Definition of volume for flow uniformity test – The volume will also extend 1,5 x *b* in depth (along the flow)

The stability of the flow shall be measured in the middle of the volume of which uniformity was verified. The flow can be considered stable if 10 consecutive 30 s means are within 0,5 % of their average value.

Cup anemometers are very sensitive to horizontal wind gradients. Different horizontal wind gradients can be seen depending on pollution of nets and smoothing devices. Therefore, it is useful to check the horizontal wind gradient by using two identical pitot tubes. They shall be placed at the exact position where the anemometer will be placed with their heads spanning approximately the area covered by the cup anemometers rotating cups. A set of measurements shall be made and the linear regression between the dynamic pressures measured by the two pitot tubes shall be calculated. The difference in wind speed shall be less than 0,2 % over a period of at least 5 minutes. The influence due to the presence of the anemometer type to be calibrated (including mounting tube) on the flow speed measured by the pitot tube shall be verified to be less than ± 0,2 %.

The axial turbulence intensity in wind speed at the anemometer's position shall be below 2 %. The turbulence intensity shall include longitudinal wind speed fluctuations with frequencies of up to 10 Hz. The data for turbulence measurements shall be acquired for a duration of 60 s per wind speed at a sampling rate of at least 20 Hz. Turbulence assessment shall be performed for at least the flow speeds 7 m/s, 10 m/s and 13 m/s with a device that is suitable to measure wind speed fluctuations with a cut-off frequency of at least 20 Hz. Deviations from

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the above requirements shall be assessed through suitable tests and be considered in the uncertainty evaluation.

The wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position, shall be appraised using pitot tubes for a speed range of 4 m/s to 16 m/s.

The ~~facility~~ 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 reference anemometer shall be used only for checking performance of this and other anemometer facilities. The repeatability examination shall include at least 5 calibrations of the reference anemometer (over various atmospheric conditions). The maximum difference between calibrations should be less than 0,6 % at 10 m/s wind speed. This process shall be repeated after any modification or recalibration of the facility.~~ 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 facility shall prove, through ~~round robin~~ proficiency testing, that its results are comparable with other anemometer calibration facilities, according to ISO 17043. ~~The facility's average, reference anemometer calibration (as determined from repeatability tests described above) should agree with the average of the other facilities' calibrations within the 1 % over the range of 4 m/s to 16 m/s.~~

F.3 Instrumentation and calibration set-up requirements

Dedicated external signal conditioning equipment such as frequency to voltage converters, etc. shall be calibrated in isolation from the anemometer, so allowing the anemometer's calibration to be derived and reported in isolation from the signal conditioning equipment.

The resolution of the data acquisition system shall be at least 0,02 m/s. Care shall also be exercised in the case of an analogue voltage instrument, to ensure that the signal is adequately buffered to prevent its attenuation by low impedance logging equipment.

~~During calibration the anemometer shall be mounted on top of a tube in order to minimise flow distortion. This tube shall be of the same dimensions as the one on which the anemometer will be mounted in service in the free atmosphere.~~

Mounting arrangements can have dramatic effects on instrument ~~sensitivity~~ performance, particularly if the ratio of tube diameter to rotor diameter is high. Therefore, during calibration, the anemometer shall be mounted on top of a tube in order to minimize flow distortion and only one anemometer may be calibrated at a time. This tube shall be of the same diameter as the one on which the anemometer will be mounted in service in the free atmosphere. It is recommended that the vertical distance between the anemometer rotor relative to the upper and lower boundaries of the wind tunnel test section should not be less than 0,5 m. In case of a directional sensitive anemometer with respect to horizontal flow, a reference orientation has to be defined and documented and referred to during calibration. The anemometer shall be positioned at the test section perpendicular to the flow field of the wind tunnel as accurate as possible. The maximum deviation of the anemometer mounting tube is 0,2°. An example of a typical cup anemometer tilt response is shown in Figure J.1.

It is important to ensure that the anemometer is not influenced by the presence of any reference wind speed measurement equipment. Conversely, the presence of the anemometer shall not affect the flow in the region of the reference instrument. If flow distortion effects are encountered, then the pitot tube shall be repositioned. This effect can be assessed by removing and then reinstating the anemometer and afterwards the reference instrument ~~(be it a pitot tube or a reference anemometer)~~, and ascertaining whether the output of the remaining

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instrument changes. ~~To remove uncertainty caused by uncontrolled drift of the tunnel, it is suggested that this procedure is repeated several times.~~

The pitot static tubes shall be positioned in the test section ~~perpendicular to~~ aligned with the mean flow ~~field of the wind tunnel as accurate as possible~~ direction. The maximum ~~declination~~ misalignment allowed is ~~1~~ 0,5°.[31]

~~The anemometer shall be positioned at the test section perpendicular to the flow field of the wind tunnel as accurate as possible. The maximum deviation allowed is 1°. A number of studies have shown that a cup anemometer's sensitivity to a vertical angle of attack depends upon the instrument's geometry, and is generally very sensitive around vertical.~~

During calibration, the anemometer output signal shall be examined to ensure that it is not subjected to interference or noise.

F.4 Calibration procedure

F.4.1 General procedure cup and sonic anemometers

The anemometer shall run in for ~~about~~ minimum 5 min at about 10 m/s before the calibration procedure begins ~~in order to avoid the effect that large temperature variations may have on the mechanical friction of the anemometer bearings~~. Calibration shall be performed under both rising and falling wind speed in the range of 4 m/s to 16 m/s at a calibration interval of 1 m/s or less[32]. ~~By taking readings both for increasing steps and for decreasing steps, it is possible to identify whether hysteresis effects are present in the measuring equipment.~~ If heating is switched on during calibrations, it shall be noted in the calibration certificate.

~~NOTE 1 m/s intervals can also be realised with the allowance for 2 m/s jumps, for example 4, 6, 8, 10, 12, 14, 16, 15, 13, 11, 9, 7, 5 m/s.~~

The sampling frequency shall be at least 1 Hz and the sampling interval at least 30 s. This ~~time shall~~ sampling interval can be increased when low resolution anemometers are calibrated. It is important to ensure that anemometer and reference wind speed readings span the same period of time. Before collecting data at each wind speed, adequate time shall be allowed for stable flow conditions to become established, see Clause F.2. This ~~will typically~~ may take 1 min, but will vary from facility to facility. ~~Stability can be assumed if two successive 30 s means are within 0,05 m/s of each other.~~

F.4.2 Procedure for the calibration of sonic anemometers

Sonic anemometers are designed to measure 2D or 3D wind components. For the purpose of power performance measurements sonic anemometers shall be set up for measurement of horizontal wind speed preferably internally or by post processing.

During calibration the complete sonic anemometer shall be placed in the wind tunnel test section. The active part of the sonic anemometer shall be located within the test section volume. The yaw alignment shall be set at the reference calibration yaw direction, see Clause F.3. It is often advantageous to set a yaw alignment that imposes the least flow disturbance from the supports of the acoustic transceivers.

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31 Missalignment of pitot static tubes may lead to a bias in differential pressure measurement! An alignment to within 0.5°of the mean flow direction assures a bias in differential pressure reading of less than 0,1 % for the NPL type Pitot tube (see ISO 3966:2008, Figure A.5).

32 1 m/s intervals can also be realized with the allowance for 2 m/s jumps, for example 4 m/s, 6 m/s, 8 m/s, 10 m/s, 12 m/s, 14 m/s, 16 m/s, 15 m/s, 13 m/s, 11 m/s, 9 m/s, 7 m/s, 5 m/s.

The setup parameters of the sonic during its calibration shall be documented in the calibration certificate or alternatively in an annex of the calibration certificate. The calibration holds only for identical settings of the sensor and identical signal output format.

For this test, the sonic anemometer shall be calibrated at variable wind speeds according to F.4.1. Calibrations of additional yaw position (i.e. yaw angle for max. flow disturbance from the supports) may be performed if desired. Calibrations of additional yaw positions should be performed at 10 m/s as a quality control of compliance with classification results.

Status signal of the sonic anemometer (if available) shall be monitored during the calibrations. The status signal shall be used to exclude erroneous data.

F.4.3 Determination of the wind speed at the anemometer position

Air density ρ shall be calculated on the basis of the mean wind tunnel air temperature T, relative humidity Φ and barometric pressure B, using Equation (F.1) (standard uncertainty less than 10^{-3} kg/m^3):

$$\rho = \frac{1}{T}\left(\frac{B}{R_0} - \phi P_w\left(\frac{1}{R_0} - \frac{1}{R_w}\right)\right) \quad \text{(F.1)}$$

where

B is the barometric pressure [Pa];

T is the absolute temperature [K];

Φ is the relative humidity (range 0 to 1);

R_0 is the gas constant of dry air [287,05 J/kgK];

R_w is the gas constant of water vapour [461,5 J/kgK];

P_w is the vapour pressure [Pa].

Vapour pressure P_w depends on mean air temperature.

$$P_w = 0{,}0000205 \cdot \exp(0{,}0631846 \cdot T) \quad \text{(F.2)}$$

The mean flow speed at anemometer position is calculated from mean differential pressure Δp_{ref} at reference position using the equation:

$$\bar{v} = k_b \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{2k_c}{C_h}\frac{\Delta p_{ref,i}}{\rho}} \quad \text{(F.3)}$$

~~where~~

~~C_h is the pitot tube head coefficient;~~

~~k_c is the wind tunnel calibration factor as previously defined;~~

~~k_b is the blockage correction factor;~~

~~n is the number of samples within the sampling interval.~~

~~The blockage correction factor for the cases of enclosed wind tunnels should be calculated using Maskells theorem. If no blockage correction factor is calculated, then about 1/4 of the blockage ratio shall be used for the uncertainty calculation for closed wind tunnels and 1/16 for open wind tunnels.~~

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$$\bar{v} = f\left(k_b, k_i, k_p, \bar{v}_p, \ldots\right) a k_c \frac{1}{n} \sum_{i=1}^{n} \sqrt{\frac{2\Delta p_{ref,i}}{\rho}} \quad \text{(F.3)}$$

where

α is the pitot static tube head coefficient;

k_c is the wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position;

$f\left(k_b, k_i, k_p, \bar{v}_p, \ldots\right)$ is a correction function due to interference between the anemometer including its mounting tube and the wind tunnel flow;

k_b is the interference correction factor due to blockage;

k_i is the correction factor due to interference between the anemometer (including mounting tube) and test section enclosure, also including flow effects due to mounting tubes extending through the enclosure;

k_p is the correction factor due to interference caused by the anemometer (including mounting tube) on the velocity measured by the pitot tube;

$\bar{v}$ is the average wind speed at the anemometer position;

$\bar{v}_p$ is the average wind speed at the reference position;

n is the number of samples within the sampling interval.

The correction function $f\left(k_b, k_i, k_p, \bar{v}_p, \ldots\right)$ should be equal to one for a test section without an anemometer and its supporting tube. The influence of the correction function on the calibration results shall be assessed and included in the calibration facility setup report and uncertainty calculation.

F.5 Data analysis

A linear regression analysis shall be carried out on the calibration data for the estimation of the following regression parameters: Offset, slope, regression coefficient, standard uncertainty ~~in the slope and intercept and the covariance of the slope and intercept of the wind speed~~. The wind speed values shall be regressed upon the anemometer outputs. ~~Although it may seem logical to regress anemometer output on wind speed, it is more convenient to do the reverse. During calibration the anemometer output is normally known to a high degree of accuracy, whereas the wind speed measurement is much less certain.~~

If the correlation coefficient, r, for the data is less than 0,999 95 then ~~the calibration~~ it shall be ~~repeated~~ checked if it is caused by anemometer non-linearity or due to other reasons. ~~If the coefficient is still insufficiently high, then either the calibration facility is inadequate or the anemometer is excessively non-linear and shall not be used.~~ In case of anemometer non-linearity, it shall be documented in the certificate.

F.6 Uncertainty analysis

It is important to identify the uncertainty of the horizontal wind speed incident upon the anemometer. It is required that an uncertainty analysis is carried out in accordance with the ISO/IEC Guide 98:2008 ~~to the expression of uncertainty~~ comprising both ~~type~~ category A and ~~type~~ category B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall take account of:

a) flow speed measurement uncertainty (pitot tubes, transducers, air density evaluation, etc.);

~~– frequency measurements;~~

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~~– flow variability in the vicinity of the anemometer.~~

b) wind tunnel calibration ~~including blockage effect~~ factor;

c) wind tunnel correction factors through the correction function $f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ defined in Equation (F.3);

d) the influence of wind tunnel cross section size shall be assessed as part of the uncertainty analysis;

e) measurement of anemometer output;

f) the influence of non-vertical anemometer alignment shall be considered for each anemometer type in the uncertainty assessment;

g) statistical uncertainty due to short term scatter of the anemometer output (variation of the indicated anemometer signal, i.e. fluctuation of the angular rotor velocity, bias from signal generation, sampling bias, over the averaging time);

h) uncertainty due to the difference between the result of the wind tunnel performing the calibration and the average result of other wind tunnels as determined through proficiency testing to the extent not covered by other uncertainty components;

i) uncertainty due to linearization of calibration expression.

F.7 Reporting format

The relevant documentation shall provide information on the procedure followed and the facility used for calibrating the anemometers (~~test~~ report on the calibration ~~campaign~~ facility setup) and on the individual anemometer calibration ~~(anemometer calibration report)~~.

The ~~test~~ calibration facility setup report ~~on the calibration campaign~~ shall contain the following information as a minimum:

a) description of the wind tunnel (including test section, settling chamber, flow straighteners, fan arrangement);

b) sketch of the wind tunnel showing the ~~exact~~ positions of anemometer and pitot tube(s) in the test section;

c) flow quality measurements;

d) blockage ~~correction factor~~ effect assessment;

e) influence of mounting height of the anemometer;

f) influence of bottom plate;

g) influence of mounting position into reference measurement;

h) influence of the correction function;

i) turbulence measurements;

j) instrumentation certificates;

k) measurement procedure;

l) data evaluation procedure;

m) repeatability documentation of the anemometer calibration;

n) uncertainty analysis;

o) deviations from these requirements.

The calibration report of an anemometer shall as a minimum contain the following information:

1) make, type and serial number of the tested anemometer and cup serial number if transported separately;

2) specification of yaw orientation during calibration (yaw sensitive devices);

3) tube diameter of the mounting system;

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4) make, type and serial number of external converters~~, if taken (i.e. frequency-to-voltage converters)~~;

5) name and address of the customer;

6) signatures from the persons who carried out the calibration, checked the results and approved their issue;

7) name of the wind tunnel;

8) environmental conditions during calibration (air temperature, air pressure and humidity);

9) regression parameters (offset, slope, regression coefficient~~, standard uncertainty in the slope and intercept and the covariance of the slope and intercept of the wind speed~~);

10) uncertainty due to linearization (scatter of residuals);

11) uncertainty due to the correction function $f(k_{\mathrm{b}}, k_i, k_{\mathrm{p}}, \bar{v}_{\mathrm{p}}, \ldots)$;

12) tabular and graphical presentation (deviations from linear regression line amplified) of all calibration points and regression results;

13) uncertainty associated to each measuring point;

14) reference to the corresponding calibration ~~campaign~~ facility set up report;

15) date of the calibration;

16) photo showing the anemometer and the mounting in the wind tunnel.

F.8 Example uncertainty calculation

As it is practically impossible to measure the flow velocity at the place of the anemometer and as the sensor in the wind tunnel experiences a significantly smaller flow field as in the free atmosphere, corrections are necessary. The optimization of the wind tunnel in terms of the corrections as well as the determination of the correction factor is crucial for the calculation of the measurement uncertainty.

Ideally, the uncertainty calculation should be applied independently to each wind speed calibration condition used in a calibration test. For this example, take a notional calibration point of 10 m/s using a wind tunnel rated at 25 m/s.

Table F.1 deals with each uncertainty source ~~in turn, dealing~~; first with those of ~~type~~ category B.

To avoid repetition, a detailed assessment of barometric pressure measurement has been left out, as it can be dealt with in the same way as temperature measurement.

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Table F.1 – Example of evaluation of anemometer calibration uncertainty

Error source, u_i	Discussion	Value, u_i	Sensitivity value, c_i	$u_i c_i$ m/s
u_f, wind tunnel correction factor, ~~k_f~~ f	~~A comparison with tunnels, which corresponds to the current status of the technology show that a correction factor of 0,5 % on wind speed is needed, i.e. k_f = 1,005. It is suggested that a standard uncertainty of half the difference between the corrected and uncorrected value should be applied~~ An uncertainty on the correction factor $f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ based on investigation of calibration influence factors.	~~0,0025~~	~~$C_f = v/k_f$~~ ~~= 10 m/s/1,005~~ ~~= 9,95 m/s~~	~~0,025~~
u_t, wind tunnel calibration factor, k_c	Wind tunnel calibration can be carried out by using two pitot tubes, one at the permanent reference position and one at the location to be occupied by the test anemometer. By swapping the two pitot systems, all category B errors can be eliminated, and standard regression analysis can be applied to yield a correction factor (the intercept being forced through the origin) and a related ~~type~~ category A standard uncertainty. Assume the correction has a value of 1,02 and the standard uncertainty is 0,01.	0,01	C_t = 0,5 v/k_c = 0,5 x 10/1,02 = 4,90 m/s	0,049
u_B, blockage correction factor, k_b	If a solid object is positioned in the flow of the wind tunnel, the flow will be affected depending on the relation between object size and wind tunnel area. Conditional on the spatial dimensions of the specimen, a raise in the flow velocity occurs in a closed measurement section because of the continuity. In an open measurement section, the current will be widened, which is equivalent to a speed reduction. Assuming the blockage effect is known the uncertainty value of 0,1 % is appropriate. The calibration facility setup report shall present the calculations applied and estimated value of the correction factor and the associated uncertainty.	0,001	$C_f = v/k_b$ =10 m/s/1,001 ≈ 10 m/s	0,01
u_{ki}, position correction factor, k_i	An anemometer needs a certain free space (depending on the size of the mounting pipe and the anemometer) below and above it, to experience the same flow conditions as in free atmosphere. Therefore the centre of the measurement section is not necessarily the best position for the specimen. If the wind tunnel is small and thus the mounting pipe is too short, an error of up to 2 % may occur. Only from a certain lengths of the mounting pipe, the influence begins to decrease. This free length amounts to approximately 50 cm above the base plate. Assuming the position effect is known, the uncertainty value of 0,1 % may be appropriate.	0,001	$C_P = v/k_p$ =10 m/s/1,001 ≈ 10 m/s	0,01
u_p, position correction factor, k_p	The flow around the anemometer exerts some influence on the flow around the reference pitot tube. Assuming the influence effect is known, the uncertainty value of 0,1 % of the effect may be appropriate.	0,001		
u_{FD}, flow correction factor, k_{FD}	Mostly, anemometers are mounted on measurement masts of considerable length – a situation which cannot be reproduced in the wind tunnel. If an anemometer is mounted on a tube stub and if this stub is mounted in a wind tunnel with an open measurement section, the current can evade downward. This means a loss of impetus for the anemometer and thus a systematic error. By installing a base-plate, this	0,001	$C_{FD} = v/k_{FD}$ =10 m/s/1,001 ≈ 10 m/s	0,01

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Error source, u_i	Discussion	Value, u_i	Sensitivity value, c_i	$u_i c_i$ m/s
	loss can be considerably reduced. Assuming a base-plate is installed, the standard uncertainty value of 0,1 % is appropriate otherwise the influence has to be examined.			
$u_{p,t}$ pressure transducer ~~sensitivity~~, $K_{p,t}$	~~Assume the pressure transducer is rated at 500 N/m². At 10 m/s wind speed, the pressure will be about 60 N/m². Assuming the 'limits' on error are quoted by the manufacturer to be 0,2 % of full scale (1 N/m²), and assuming this to relate to a triangular uncertainty distribution, then the equivalent standard deviation can be derived as 1 × 1/√6 or 0,40 N/m².~~ ~~Assuming also that the transducer sensitivity, $K_{p,t}$ is 5000 N/m² per V (100 mV max output), then the standard uncertainty at 60 N/m² $u_{p,t}$ equates to 33 N/m² per V~~ The calibration certificate for the pressure transducer shows a maximum uncertainty of 0,5 Pa in the range from 0 Pa to 500 Pa.	~~33~~ 0,5 Pa	$c_{p,t}$ = 0,5 $v/K_{p,t}$ = 0,5 × 10/5 000 = 0,001	~~0,033~~ 0,000 5
$u_{p,s}$ pressure transducer signal conditioning gain, $K_{p,s}$ and $u_{p,d}$ pressure transducer data sampling conversion $K_{p,d}$	~~Assume that the signal conditioning is designed to raise the maximum transducer output voltage (100 mV) to the full scale range of the data system (10 V), then the required gain is 100. Thus $K_{p,s}$ = 0,01. Assuming a standard uncertainty of 0,2 %, this gives a value of $u_{p,s}$ of 0,00002~~ ~~The resolution of the data system is defined by the full scale values, for example 12 bits (4 096 values) for 10 V or $K_{p,d}$ of 0,00244 V. The quantisation limits are half of this i.e. 0,00122 V, and since a rectangular distribution is appropriate, the related standard uncertainty is 0,00122/√3 or 0,000704 V~~ The calibration of the equipment used to measure the pressure transducer output shows a maximum uncertainty of 0,000 15 V in the range from 0 V to 10 V.	~~0,00002~~ 0,000 15 V ~~0,000704~~	$c_{p,s}$ = 0,5 $v/K_{p,s}$ = 0,5 × 10/0,01 = 500 ~~$c_{p,d}$ =0,5 $v/K_{p,d}$ = 0,5 × 10/ 0,00244 = 2049~~	0,010 ~~0,004~~
$u_{T,t}$ ambient temperature transducer, $K_{T,t}$ $u_{T,s}$ temperature signal conditioning gain, $K_{T,s}$ and $u_{T,d}$ temperature signal digital conversion, $K_{T,d}$	~~Temperature may appear to be somewhat difficult to handle, because whereas the foregoing theory assumed a zero offset in the relationship connecting temperature to transducer output, in reality a very high offset exists. Typically a temperature system might be quoted as giving a 4 mA to 20 mA current range for a −20 °C to 30 °C temperature range. Rather than trying to restructure the mathematics, it is possible to take a lateral approach. Assume the transducer is quoted as being good to 0,2 °C. Assuming a triangular distribution, this relates to a standard uncertainty of 0,08 °C. We know this is the temperature error attributable to the transducer, rather than the complete temperature chain. Going back to the basic equation for wind speed in terms of the physical T, B and p parameters, it is easy by varying T (from say 15 °C, 288 K up to 15,08 °C, 288,08 K) to determine the corresponding change in wind speed. This comes out, for 10 m/s, as 0,001 m/s. This value can be inserted directly in the last column of the table without reference to the third and fourth columns, which were based on the more general analytical approach~~ ~~Assume the current output from the temperature sender unit is fed to a 500 Ω precision resistor, to give a 2 V to 10 V output for the temperature~~	~~n/a~~ 0,1 °C ~~0,0008~~	$c_{T,t}$ = 0,5 $v/K_{T,t}$ n/a ~~$c_{T,t}$ = 0,5 $v/K_{T,s}$ = 0,5 × 10/2~~	0,001 ~~0,002~~

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Error source, u_i	Discussion	Value, u_i	Sensitivity value, c_i	$u_i c_i$ m/s
	~~range. The gain $K_{T,s}$ is thus 2 mA/V. Assuming the resistor has a standard uncertainty of 0,2 Ω, then the gain will have a corresponding uncertainty of 0,0008 mA/V~~ ~~As for the pressure transducer signal line in the case above, the standard uncertainty of the quantisation is 0,000704 V.~~ ~~For 15 °C temperature, the voltage seen by the d/a system will be in the region of 7,6 V, giving a nominal converted value of 3113.~~ ~~The conversion uncertainty $u_{T,d}$ is then no more than 0,0000023 V~~ The calibration of the equipment used to measure the temperature shows a maximum uncertainty of 0,1 ºC in the range from 10 ºC to 30 ºC.	~~0,0000023~~	~~= 2,5~~ ~~$c_{T,d}$ = 0,5 $v/K_{T,d}$~~ ~~= 0,5 × 10/~~ ~~0,00244~~ ~~= 2049~~	~~0,004~~
u_h pitot tube head coefficient, C_h	The head coefficient of a pitot tube depends upon the angle of attack of the wind. Two error sources are possible, one related to the accuracy with which the pitot tube is set up in alignment with the mean flow direction, and the other due to turbulent variations in instantaneous flow direction. Assume the nominal head coefficient, C_h, is 0,997, and assume also that it is possible to deduce that the standard deviation on angle of attack is 2°. Relevant ISO standards suggest this will give rise to a 0,1 % change in head coefficient.	0,000 997	C_h = –0,5 v/C_h = –0,5 × 10/0,997 = –5,015	0,005
u_{pcal} pitot tube calibration	From the calibration certificate of the pitot tube, an uncertainty of 0,25 % in the range of 4 m/s to 16 m/s may be used.	0,002 5	C_{ph} = –0,5 v/C_h = –0,5 × 10/0,997 = –5,015	
$u_{B,t}$ sensitivity of barometer, $K_{B,t}$ $u_{B,s}$ signal conditioning gain on barometer, $K_{B,s}$ $u_{B,d}$ digital conversion of barometer signal, $K_{B,d}$	~~The barometer can be treated in much the same way as the temperature probe, since it to will have a large physical offset.~~ ~~Similar approach as for other signal processing parameters~~ ~~Similar approach as for other data acquisition channels~~ The calibration of the barometer shows a maximum uncertainty of 0,5 hPa in the range from 900 hPa to 1 100 hPa.	0,5 hPa	$c_{B,t}$ = –0,5 $v/k_{B,t}$ ~~$c_{B,s}$ = 0,5 $v/K_{B,s}$~~ ~~$c_{B,d}$ = 0,5 $v/K_{B,d}$~~	
s_A statistical uncertainty in the mean of the wind speed time series	Assume the turbulence intensity is 2 %, and that 2 Hz sampling over 30 s is used, giving 60 samples. The standard uncertainty in the mean value of 10 m/s is then given by $\sqrt{1/60 \cdot 0{,}02 \cdot 10}$	0,026	1	0,026
u_p, humidity correction to density, k_p or u_φ, relative humidity, φ	~~It is possible to show that $c_\rho^2 u_\rho^2$ is equivalent to $c_\varphi^2 u_\varphi^2$ (where u_φ is the uncertainty in relative humidity and c_φ is the sensitivity of derived wind speed to humidity) if c_ρ is dominated by c_φ rather than c_B or c_T. This is normally the case.~~ ~~Assume relative humidity, φ, is measured from a hand-held meter as 50 % to an accuracy of 5 % within 95 % confidence. φ = 0,5 and u_φ = 0,025~~	~~u_φ = 0,025~~ u_φ = 0,02 %RH	c_ρ = 0,032	0,001

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Error source, u_i	Discussion	Value, u_i	Sensitivity value, c_i	$u_i c_i$ m/s
	The calibration of the relative humidity measurement equipment shows an uncertainty of less than 2 % in the range 10 to 95 %. A value of 2 % is selected for the calculation. $c_\varphi = \frac{\partial \bar{v}}{\partial k_p} \cdot \frac{\partial k_p}{\partial \varphi} = \frac{1}{2} \frac{\bar{v}}{k_p} 0{,}378 \frac{P_w}{B}$ At 15 °C, P_w = 1 700 Pa and assuming B = 1013 mbar = 101 300 Pa, k_p is evaluated as 0,997 and c_φ (at 10 m/s) is 0,032.			

The combined standard uncertainty can be obtained by taking the root mean square of the contributory uncertainties in the right hand column. For the values which have been dealt with, this amounts to ~~0,07~~ 0,06 m/s.

The example shows that ~~type~~ category B error is liable to dominate. Extending the calibration period can help reduce the ~~type~~ category A uncertainty, but will have no effect on ~~type~~ category B. Furthermore, ~~type~~ category B error sources, although not correlated with one another for a particular wind speed, are fully self-correlated across wind speeds, meaning that good apparent calibrations (good straight lines) can be obtained, whilst still retaining significant uncertainty.

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Annex G
(normative)

Mounting of instruments on the meteorological mast

G.1 General

Appropriate arrangement of instruments on the meteorological mast is important for accurate wind turbine testing.

~~In particular, the anemometer shall be located to minimize flow distortions, especially from mast and boom influences. The least flow distortion of an anemometer is found by mounting the anemometer on top of the meteorological mast. When anemometers are mounted on booms alongthe mast , flow distortion from both the mast and the boom shall be taken into account. other instruments on the mast should be mounted close to hub height but in a way that avoids interference with the anemometer.~~

The arrangement of anemometers for power performance tests shall include a primary hub height anemometer and a control anemometer. The purpose of the control anemometer is to provide a means of in-situ consistency checking of the primary hub height anemometer as described in Annex K. Before using an anemometer classified for power performance tests, it is recommended that the geometry of the anemometer is checked with the geometry description that corresponds to the anemometer type on which the classification was made. In particular, the anemometer shall be located to minimize flow distortions, especially from mast and boom influences. When minimal flow distortion across a wide wind direction range is required, then this is obtained with a single top-mounted anemometer. However, a side-by-side arrangement of two top-mounted anemometers provides redundancy and a robust method of anemometer consistency checking with only marginally increased flow distortion if both adequate horizontal separation and a stable mounting structure for the anemometers are achieved. When anemometers are mounted on side booms at elevations below the meteorological mast top, flow distortion from both the meteorological mast and the boom is significant and shall be taken into account. Irrespective of the type of mounting arrangement, care shall be taken to ensure that the boom structure is sufficiently stable to avoid significant vibrations. Those other instruments on the meteorological mast which are required to be mounted close to hub height (control anemometer, wind vanes, temperature and pressure sensors) should be mounted in a way that avoids interference with the primary anemometer.

G.2 ~~Preferred method of top mounting of~~ Single top-mounted anemometer

~~The preferred method for mounting the anemometer is on top of the meteorological tower with no other instruments or equipment nearby. All provisions of this section must be met in order to achieve negligible distortion of the wind measurements.~~

~~The anemometer shall be mounted on a round vertical tube, with the same outer diameter as used during calibration, which carries the cable to the anemometer inside. The angle deviation from vertical should be less than 2°, and it is recommended to use an inclinometer. The tube shall be no larger in diameter than the body of the anemometer and shall support the anemometer cups at least 0,75 m above the meteorological tower and any other flow disturbances. The bracket connecting the anemometer to the vertical tube shall be compact, smooth, and symmetrical. If necessary to hold the anemometer steady, the small-diameter vertical tube may be mounted on another tube of larger diameter in order to ensure that no parts of the meteorological mast extend beyond a 1:5 cone whose vertex is at the height of the anemometer cups. Other instruments must be positioned at least 1,5 m below the anemometer cups. These instruments and their supporting brackets to a boom may extend beyond the 1:5 cone. Figure G.1 shows an example of a top mounting configuration.~~

To achieve negligible flow distortion of the wind speed measurements over a wide wind direction range, a single top-mounted anemometer is the ideal configuration. Where this

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configuration is adopted all provisions of this section shall be met. However, careful consideration should be given to whether sufficiently robust anemometer consistency checks against a lower elevation anemometer can be achieved with this configuration. This is particularly the case where the meteorological mast is of large cross-sectional area and as a consequence the lower anemometer is subject to more significant meteorological mast interference effects than the top-mounted anemometer or in cases where large variations in wind shear are experienced.

The anemometer shall be supported such that the anemometer cups[33] are at least 1,5 m above the meteorological mast and any other sources of flow disturbance and such that no parts of the support structure or meteorological mast shall extend outside of a 11:1 half cone[34] whose vertex is coincident with the anemometer cups. The anemometer shall be mounted on a round vertical tube of the same (± 0,1 mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer. The combined length of the tube and anemometer (measured to the anemometer cups) shall be at least 0,75 m. Furthermore the anemometer shall be held steady, which may necessitate the mounting of the small-diameter vertical tube concentric with another tube of larger diameter to provide a stable structure. This additional tube cannot be of greater diameter than the anemometer body for a height of 1,5 m below the cups. The bracket connecting the anemometer to the vertical tube shall be compact, smooth, and symmetrical. Where the anemometer is designed for internal cable routing in the support tube, then the cable shall be routed inside the vertical tube. For other configurations (e.g. pig tail), then the cable should be spirally wound around the vertical tube (approximately 3 turns/m or similar to that used during calibration and classification). The anemometer should be calibrated with the same cable attachment and routing configuration as is to be used in the field. The anemometer (and mounting tube) inclination from vertical shall be less than 2°. It is recommended that this is verified by measurement. No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside of the 11:1 half cone to a distance of at least 4 m below the anemometer cups. In this case, the control anemometer for the top-mounted anemometer shall be a side-mounted anemometer located at least 4 m and no more than 6 m below the top-mounted anemometer and otherwise satisfying the requirements for side-mounted anemometers in Clause G.4. Figure G.1 shows an example of a top-mounting configuration.

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33 Where the anemometer is an allowable type of anemometer other than a cup anemometer (e.g. an ultrasonic anemometer), then “cups” should be interpreted as “sensor measuring elements” throughout this annex.

34 The cone is defined such that the base of the cone is of diameter equal to the characteristic width (maximum width of the mast or protrusions for a distance of 4 m below the cups) of the mast and the height of the cone equals 11 times the radius of the cone base.

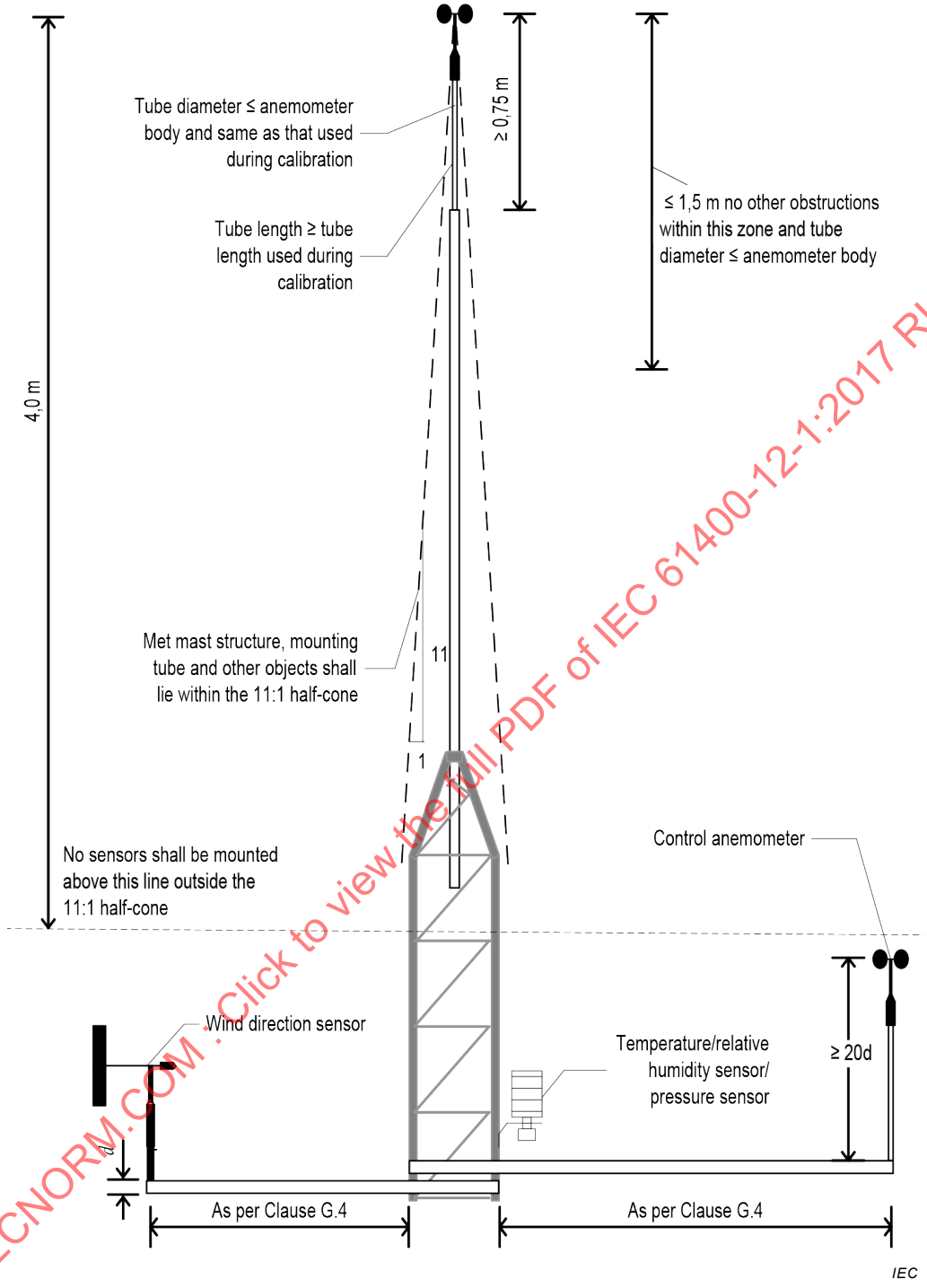

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Figure G.1 – Example of a top-mounted anemometer and requirements for mounting

G.3 ~~Alternative method of top mounting of~~ Side-by-side top-mounted anemometers

~~Alternative methods of anemometer mounting shall be considered to have increased uncertainty in wind speed measurement due to flow distortion. Relatively small distortion is obtained when two cup anemometers are top mounted side-by-side with adequate separation from the tower and each other. In the side-by-side arrangement the two vertical tubes and anemometer mounting brackets shall meet the requirements described in Clause G.2. The anemometer cups must be mounted above the boom by a minimum of 15 times the boom diameter, but 25 times the boom diameter is recommended. The anemometers shall be separated by at least 1,5 m and no more than 2,5 m. Figure G.2 shows an example of a side-by-side configuration. The primary cup anemometer shall be defined before the test begins. The other anemometer is the control anemometer. The measurement sector shall be restricted so that the control cup anemometer does not affect the primary cup anemometer. The uncertainty due to flow distortion of other instruments and mast and boom must be determined.~~

In the side-by-side arrangement all mounting conditions in Clause G.2 shall be met in addition to those specified here. The anemometer cups shall be mounted above the boom by a minimum of 20 times the boom diameter, but 25 times the boom diameter is recommended. The boom, consisting of both the horizontal portion and vertical stems, shall be of round cross-section. The anemometers shall be separated by at least 2,5 m and no more than 4,0 m. No parts of the meteorological mast shall extend beyond a 11:1 half cone whose vertex is coincident with the midpoint between the cups of the two top-mounted anemometers (the top boom itself is excluded from this requirement provided that it meets the foregoing dimensional criteria). No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside the 11:1 half cone to a distance of at least 4 m below the anemometer cups. Figure G.2 shows an example of a side-by-side configuration. It is recommended that the boom is mounted concentric with the meteorological mast axis or centrally on the upwind side of the meteorological mast. The influence of one anemometer on the other shall be assessed and the measurement sector restricted such that the overall uncertainty of the wind speed measurement remains within the desired limits. The uncertainty due to flow distortion from other instruments, the meteorological mast and booms shall be determined.

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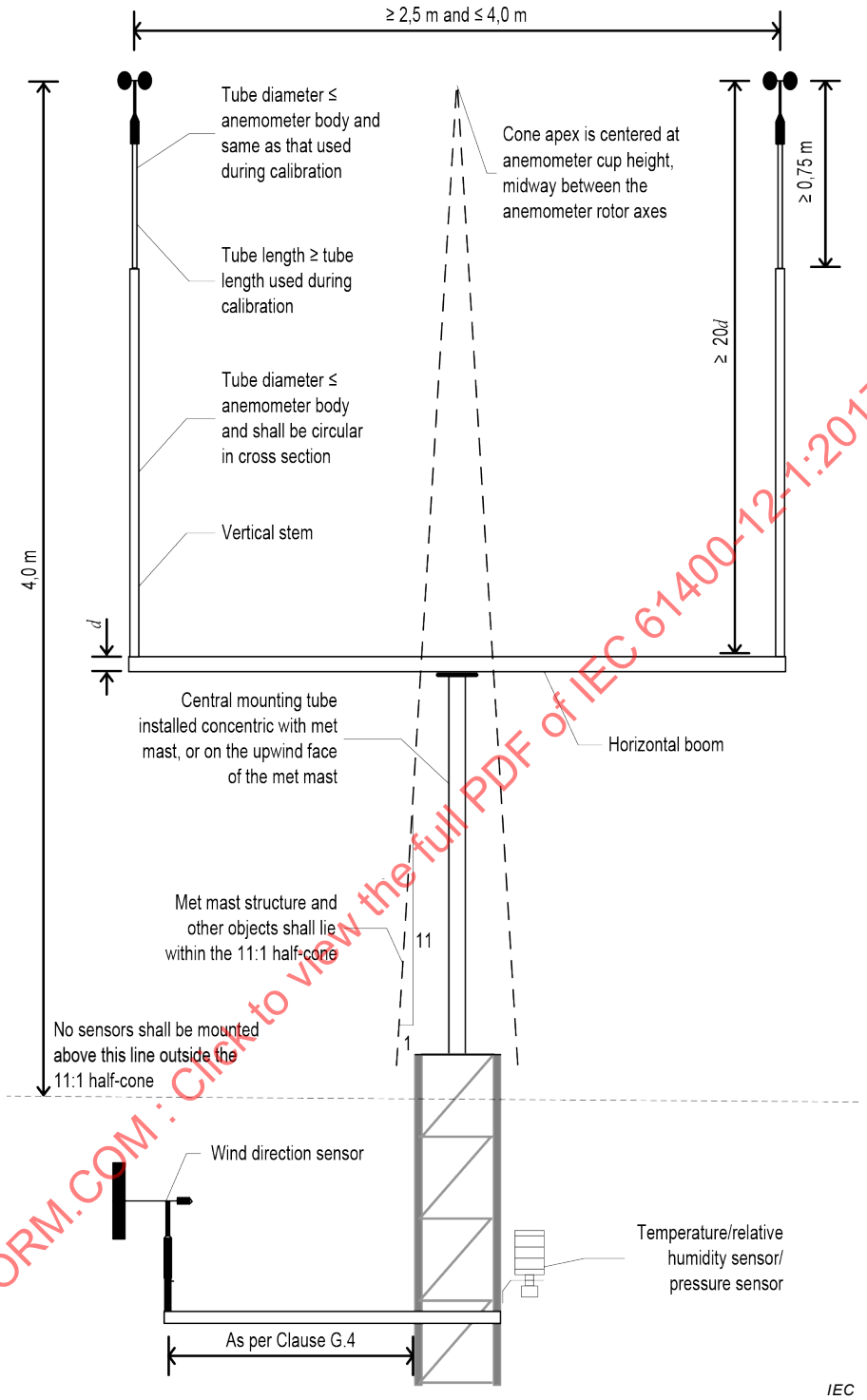

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Figure G.2 – Example of alternative top-mounted primary and control anemometers positioned side-by-side and wind vane and other instruments on the boom

G.4 ~~Boom mounting of cup anemometers~~ Side-mounted instruments

G.4.1 General

~~Boom-mounted cup anemometers are influenced by flow distortion of both the mast and the boom. The influence of a round tubular boom is 0,5 % for a distance of the cup rotor 15 boom diameters above the boom. Flow distortion due to booms should be kept below 0,5 %.~~

Side-mounted instruments such as anemometers and wind direction sensors are influenced by flow distortion from the meteorological mast, boom and guy wires. The influence of a round tubular boom is 0,5 % at a separation distance of 20 boom diameters above the boom. Flow distortion at the anemometer cup location due to booms should be kept below 0,5 %. The anemometer shall be mounted on a round vertical tube of the same (± 0,1 mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer. Wind direction sensors should be mounted at a distance from the meteorological mast of no less than half of that recommended for anemometers. There shall be at least 20 boom diameter vertical separation from side-mounted instruments to booms above. This separation requirement applies where a side-mounted anemometer is being used as a control anemometer for another side-mounted anemometer at a different height as well as to the case where side-mounted anemometers at different heights are being used for wind shear measurement. In the case where the side-mounted anemometer is being used as a control anemometer to another side-mounted anemometer, the vertical separation to the primary instrument shall be in the range 4 m to 6 m where the side booms are on the same side of the mast as each other and pointing in the same direction. Alternatively the control anemometer side boom may be mounted at the same height as the other side-mounted anemometer but pointing in a different direction such that the flow distortion requirements at both anemometer locations are satisfied within the measurement sector.

An anemometer operating in the wake of the meteorological mast is highly disturbed. Measurements obtained in this condition ~~may~~ shall not be used in the power performance analysis. Flow distortion upstream of the meteorological mast can be significant. Adequate separation ~~must~~ shall be allowed between the ~~cup~~ anemometer and the meteorological mast to keep meteorological mast flow distortion ~~effects to an acceptably low level~~ below 1 %. Guidance for appropriate anemometer ~~tower~~ to meteorological mast separation is given in G.4.2 and G.4.3.

Wakes from ~~tower~~ meteorological mast guys can have a strong influence on ~~cup~~ anemometers over surprisingly long distances. Location of ~~cup~~ anemometers ~~in the vicinity of upstream~~ downstream of guys shall be avoided.

It is largely up to the user to determine what degree of disturbance and hence uncertainty is acceptable, but a suitable aim should be to avoid meteorological mast and boom induced flow distortions greater than 1 % and 0,5 %, respectively.

Meteorological masts can either be of cylindrical or lattice construction. The required separation of the anemometer from the ~~tower~~ meteorological mast depends upon the type of meteorological mast and solidity.

G.4.2 Tubular meteorological masts

An approximation of the flow disturbance in the vicinity of a tubular meteorological mast can be obtained from Figure G.3. This figure shows an iso-speed plot of the flow around a tubular meteorological mast from a Navier-Stokes analysis. The least disturbance can be seen to occur if facing the wind at 45°. More generally, it can be seen that there is a retardation of the flow upwind of the meteorological mast, acceleration around it, and a wake behind it. Due to the complexity of the flow in the mast wake influenced region, Figure G.3 is to be considered accurate only for the upwind zone of least disturbance as indicated by the green shading in the figure.

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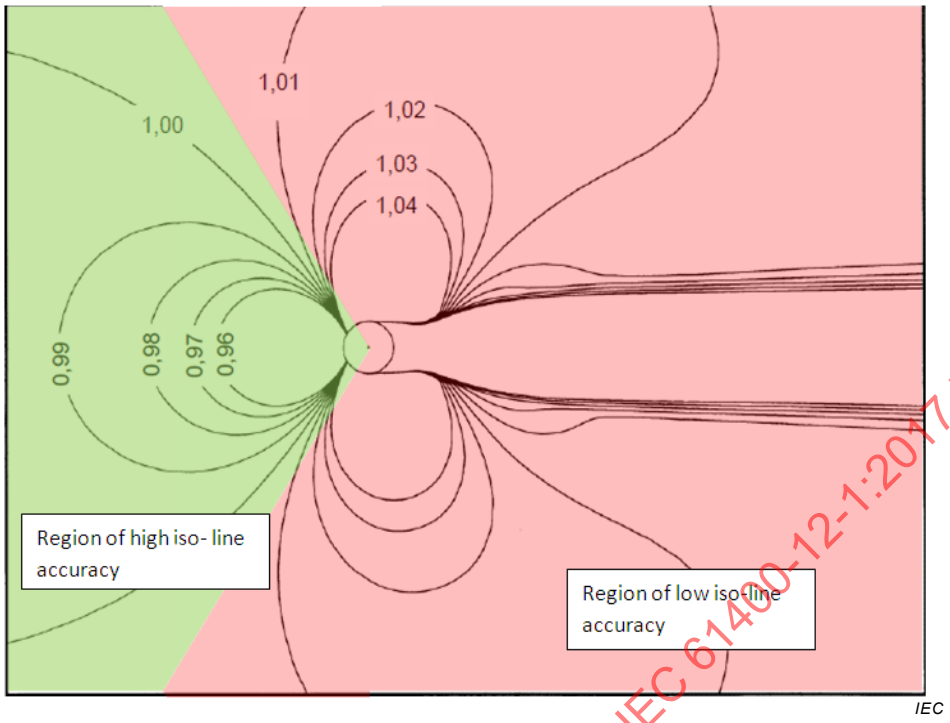

NOTE The speed is normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computations for which the green shaded region on the left is considered accurate and the red shaded region on the right inaccurate due to inaccuracies modelling flow in and behind the separation zone.

Figure G.3 – Iso-speed plot of local flow speed around a cylindrical meteorological mast~~, normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computations~~

~~For winds within 45° of the line from the anemometer to the meteorological mast, the largest relative wind speed is seen when the winds are aligned with the anemometer and mast. Figure G.4 shows the relative wind speed as a function of distance Note, however, that wind speed distortion may be higher than shown in Figure G.6 if winds approach from angles greater than 45° from the anemometer – mast alignment.~~

It is evident from Figure G.3 that for an anemometer mounted within the ±45° sector relative to the wind direction on the upwind side of the meteorological mast that the greatest distortion of the wind speed relative to free stream occurs when the anemometer is directly upwind of the meteorological mast. Figure G.4 shows the relative wind speed as a function of distance upwind of the meteorological mast[35].

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35 Note that wind speed distortion may be higher than shown in Figure G.4 if winds approach from angles greater than 45° from the anemometer – mast alignment.

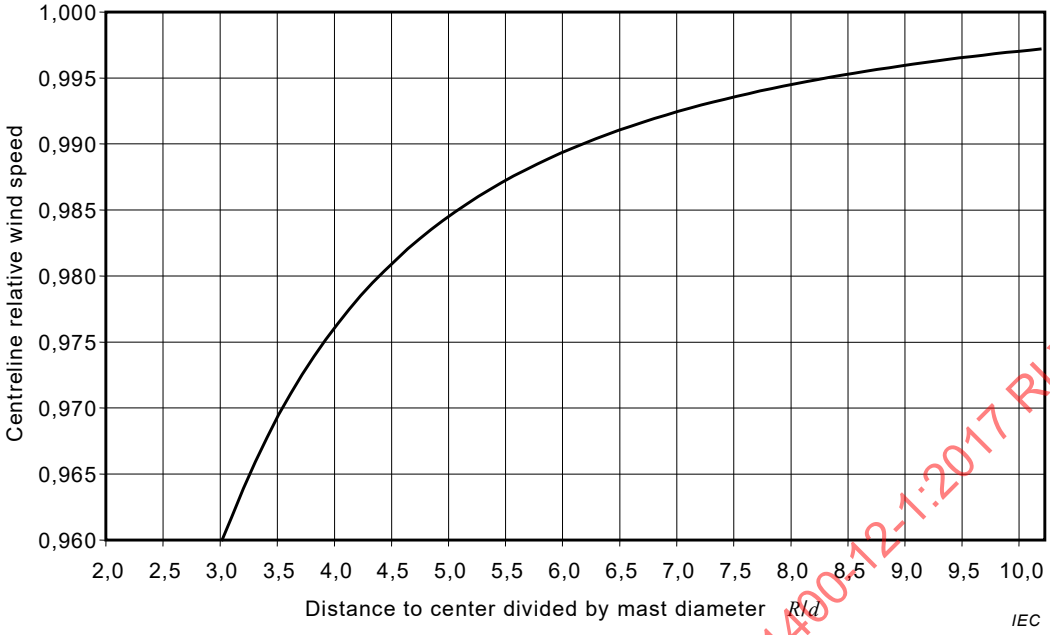
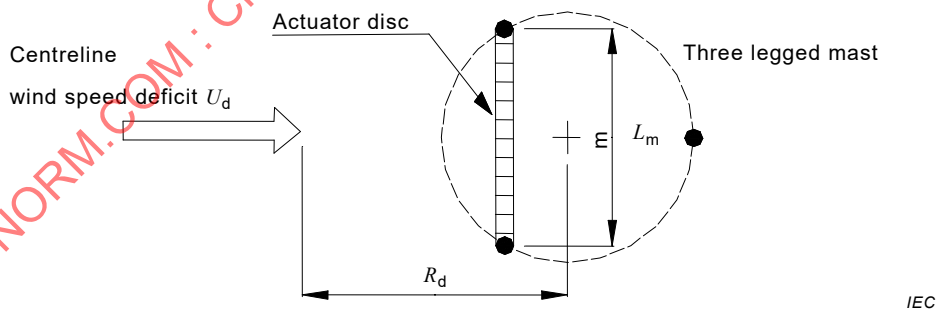


Figure G.4 – Centreline relative wind speed as a function of distance R_d from the centre of a tubular meteorological mast and meteorological mast diameter d

A 99,5 % relative wind speed is seen to occur at R_d/d of 8,2. The corresponding value for a 99 % relative wind speed is 6,1.

G.4.3 Lattice meteorological masts

Analysis of the flow around a lattice structure can be based upon a combination of actuator disc and Navier-Stokes theory and analysis. The degree to which flow is disturbed by the meteorological mast is a function of the solidity of the meteorological mast, the drag of the individual members, the orientation of the wind and the separation of the measurement point from the meteorological mast. Figure G.5 shows the dimensions of interest on a top-view of a triangular lattice meteorological mast.



NOTE The figure shows the centreline wind speed deficit, the actuator disc representation of the meteorological mast with the leg distance L_m and distance R_d from the centre of the meteorological mast to the point of observation.

Figure G.5 – Representation of a three-legged lattice meteorological mast ~~showing the centre-line wind speed deficit, the actuator disc representation of the mast with the leg distance L and distance R from the centre of the mast to the point of observation~~

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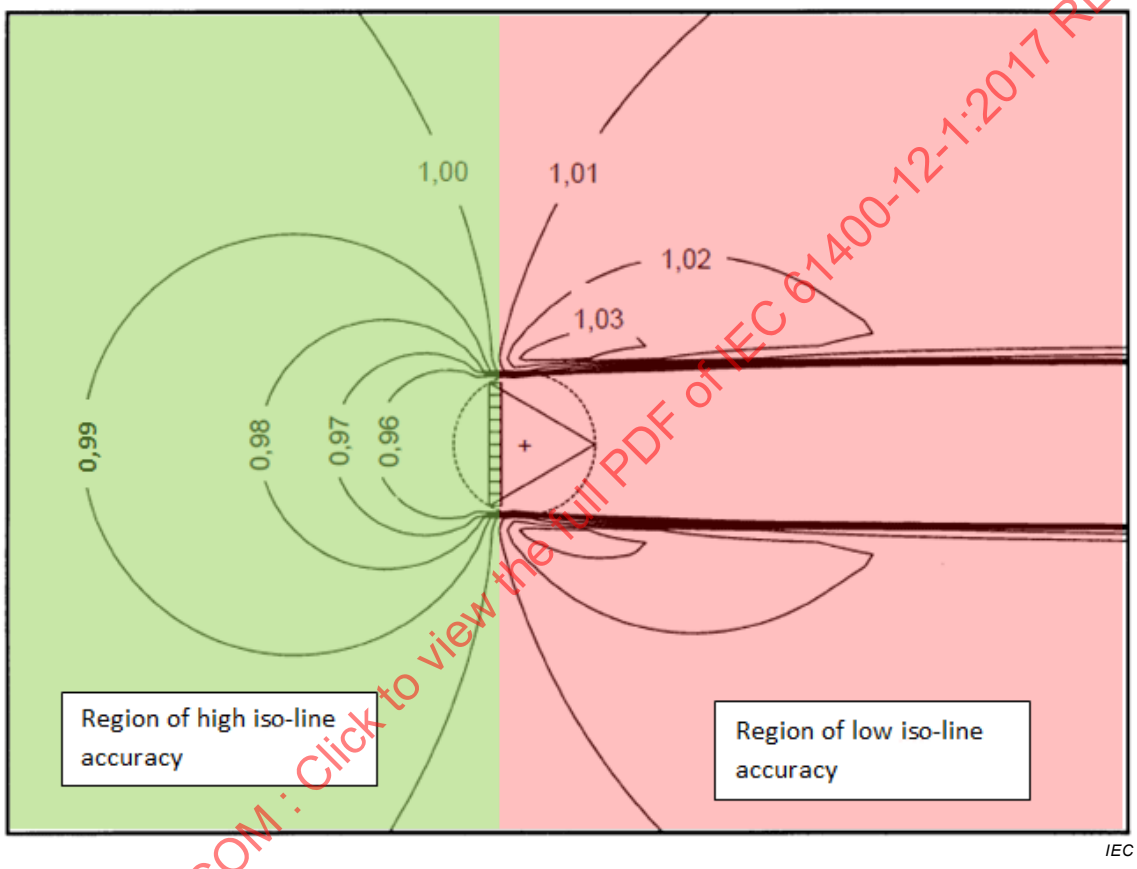
The flow distortion is a function of the assumed thrust coefficient, C_T, which in turn depends upon the ~~porosity~~ solidity of the meteorological mast and the drag on the individual members. C_T can be regarded as the total drag force per unit length of the ~~tower~~ mast, divided by the dynamic pressure and the ~~face width, L~~ leg distance L_m[36].

Figure G.6 shows the computed flow around a lattice ~~tower~~ meteorological mast having a C_T of 0,5. At typical distances of the anemometer $R_d > 2$ times the meteorological mast leg distance, this flow disturbance is very little affected by ~~tower~~ meteorological mast orientation (whether the face or a corner is oriented into the wind), and it can therefore be assumed to be the same. However, Figure G.6 is to be considered accurate only for the upwind zone of least disturbance as indicated by the green shading in the figure.



NOTE The speed is normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computation and actuator disc theory for which the green shaded region on the left is considered accurate and the red shaded region on the right inaccurate due to inaccuracies modelling flow in and behind the separation zone.

Figure G.6 – Iso-speed plot of local flow speed around a triangular lattice meteorological mast with a C_T of 0,5 ~~normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computation and actuator disc theory~~

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36 The leg distance shall represent the face width. For significant leg diameters (leg diameter > 5 % of face width) one leg diameter should be added to the distance between the leg centres to get the leg distance.

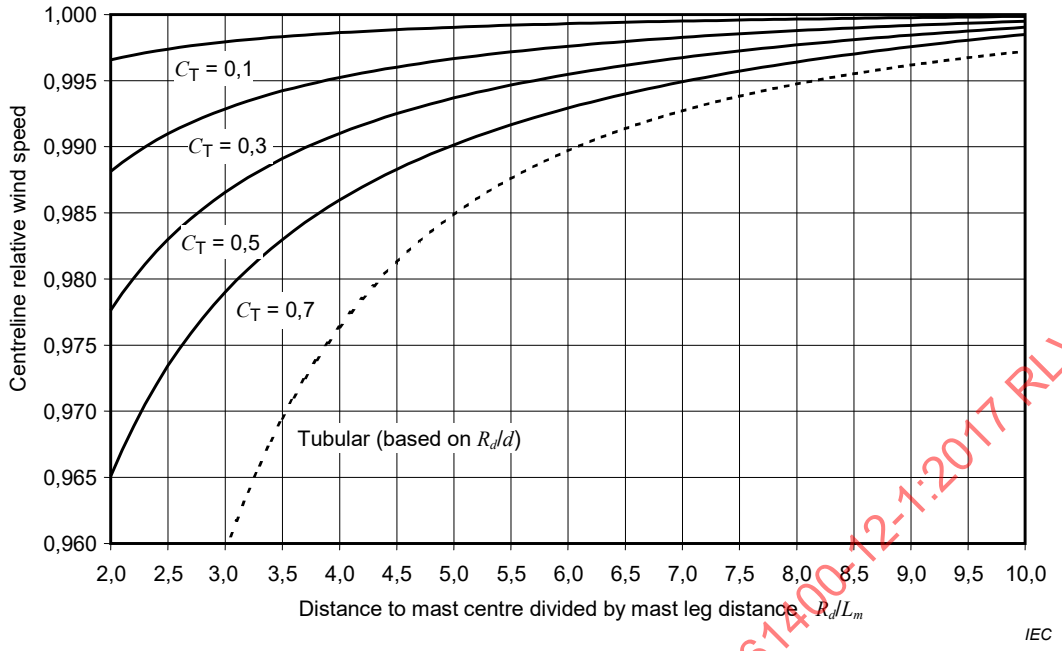

Figure G.7 – Centreline relative wind speed as a function of distance R_d from the centre of a triangular lattice meteorological mast of ~~face width L~~ leg distance L_m for various C_T values

~~If the measurement sector is 90° or less~~ When the flow direction is perpendicular to a meteorological mast face, minimum distortion is obtained when the anemometer is placed at an angle of 90° to the ~~centre of the measurement sector~~ flow direction. Otherwise, the flow distortion may be determined by considering the upwind deficit as a function of distance. Figure G.7 shows the computed centreline relative wind speeds for lattice towers having various C_T values. Note, however, that wind speed distortion may be higher than shown in Figure G.7 if winds approach from angles greater than 100° from the anemometer ~~mast~~ boom alignment.

The equation below may be used to estimate the centreline wind speed deficit U_d as a function of C_T and R_d/L_m:

$$U_d = 1 - \left(0{,}062 C_T^2 + 0{,}076 C_T\right) \cdot \left(\frac{L_m}{R_d} - 0{,}082\right) \quad \text{(G.1)}$$

C_T can be estimated from local building codes or, within the ranges specified, from Table G.1. In this table, the solidity ~~ϕ~~ S is defined as the ratio of the projected area of all structural members on the side of the ~~tower~~ meteorological mast to the total exposed area.

Table G.1 – Estimation method for C_T for various types of lattice ~~tower~~ mast

Type of ~~tower~~ mast	Plan section	Expression for C_T	Valid range
Square cross-section, members with sharp edges		4,4(1 – ~~ϕ~~ S)~~ϕ~~ S	0,1 < ~~ϕ~~ S < 0,5
Square cross-section, round members		2,6(1 – ~~ϕ~~ S)~~ϕ~~ S	0,1 < ~~ϕ~~ S < 0,3
Triangular cross-section, round members		2,1(1 – ~~ϕ~~ S)~~ϕ~~ S	0,1 < ~~ϕ~~ S < 0,3

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Alternatively, if the desired maximum centreline wind speed deficit is specified, the distance R_d may be obtained from the following equation:

$$R_d = \frac{L}{\frac{1-U_d}{(0{,}062C_T^2 + 0{,}076C_T)} + 0{,}082} \quad \text{(G.2)}$$

For a lattice ~~tower~~ meteorological mast with a C_T of 0,5 and a 99,5 % centreline wind speed deficit R_d shall be 5,7 times the meteorological mast leg distance L_m. A wind speed deficit of 99 % will reduce the distance R_d to 3,7 times the meteorological mast leg distance.

The above equations and charts represent somewhat idealised meteorological mast geometry and flow conditions. It should be noted that the flow interference will be significantly more complex in those cases where secondary support structures such as lattice work, cross-bracing, cable ladders, flanges and attachment brackets are also present at or near the height level of the anemometer or where the flow direction is not parallel to the meteorological mast cross section axis of symmetry. Figure G.8 illustrates the CFD derived flow (from the left) where the relative position and hence influence of the cross-bracing on the flow distortion changes with height. Note that the distortion is asymmetric but that the optimum location for minimum flow distortion is still at 90° to the flow direction.

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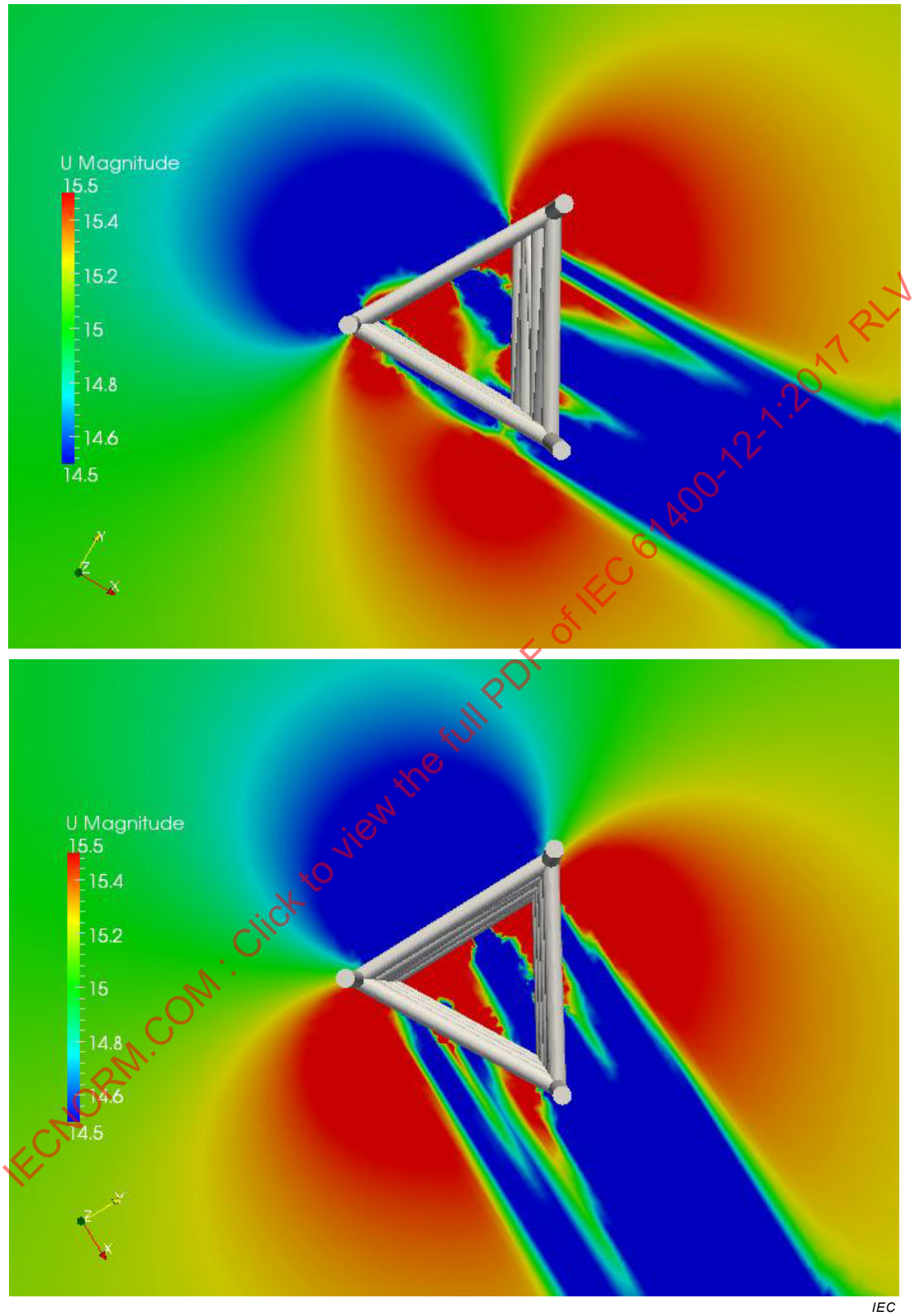

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Figure G.8 – 3D CFD derived flow distortion for two different wind directions around a triangular lattice meteorological mast (C_T = 0,27) – For flow direction see the red arrow lower left in each figure

G.5 Lightning protection

A lightning finial (attractor) can protect the top-mounted instruments. If lightning protection is installed, a number of precautions shall be taken. The lightning finial should be mounted at the top of the meteorological mast in such a way that:

~~a) an adequately sized earth connection should be strapped to the tower base;~~

a) the anemometer is separated horizontally by at least 30 times the finial diameter from the finial;

b) ~~it affords the top mounted anemometers with a 60º protection umbrella and in such a way that~~ the anemometer ~~never~~ is not in the wake of the finial when the wind is in the measurement sector;

Where these conditions cannot be met, then the flow distortion on the anemometer shall be assessed and an additional uncertainty shall be added.

G.6 Mounting of other meteorological instruments

The control anemometer should be located as close to the primary anemometer as possible, whilst still satisfying the minimum separation requirements of Clauses G.2 to G.4, in order to provide a good correlation between the two instruments during the test. This correlation should be validated to ensure that the primary anemometer does not change its calibration during the test. However, the control anemometer ~~may~~ shall not interfere with the primary anemometer and shall also be free of flow disturbance from other instruments.

The wind ~~vane~~ direction sensor shall be mounted ~~at a minimum of 1,5 m~~ 4 m to 10 m below the primary anemometer ~~but within 10 % of hub height based on its distance above ground level at the meteorological mast~~. It shall be mounted so that flow distortion effects are minimized with respect to the measurement sector. The horizontal separation of the wind direction sensor from the meteorological mast should be at least half that required for an anemometer.

Except in the case where a meteorological mast shorter than hub height is being used in conjunction with a remote sensing device, temperature, humidity and pressure sensors ~~should~~ shall be located ~~close to~~ within 10 m 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 Clauses G.2 and G.3. The temperature sensor shall be mounted in a radiation shield. The pressure sensor may be mounted in a weatherproof box. However, care should be taken to ensure that the box is properly vented so that pressure readings are not influenced by the pressure distribution around the box.

If the meteorological mast available for the power performance test is shorter than hub height (specifically when a shorter meteorological mast is used in conjunction with a remote sensing device as defined in Annex L), temperature, humidity and pressure sensors shall be located at a height within 1,5 m to 10 m of the primary anemometer. Atmospheric pressure shall be adjusted to hub height following this standard. Furthermore, the air temperature shall be adjusted to hub height assuming that the atmosphere varies according to ISO 2533:1975. Alternatively a temperature sensor shall be mounted on the wind turbine nacelle. The sensor shall be mounted at least 1 m above the nacelle and upwind of any existing ventilation systems.

Examples of suitable arrangements for other ~~boom-mounted~~ meteorological instruments and top-mounted anemometers are shown in Figure G.1 and Figure G.2.

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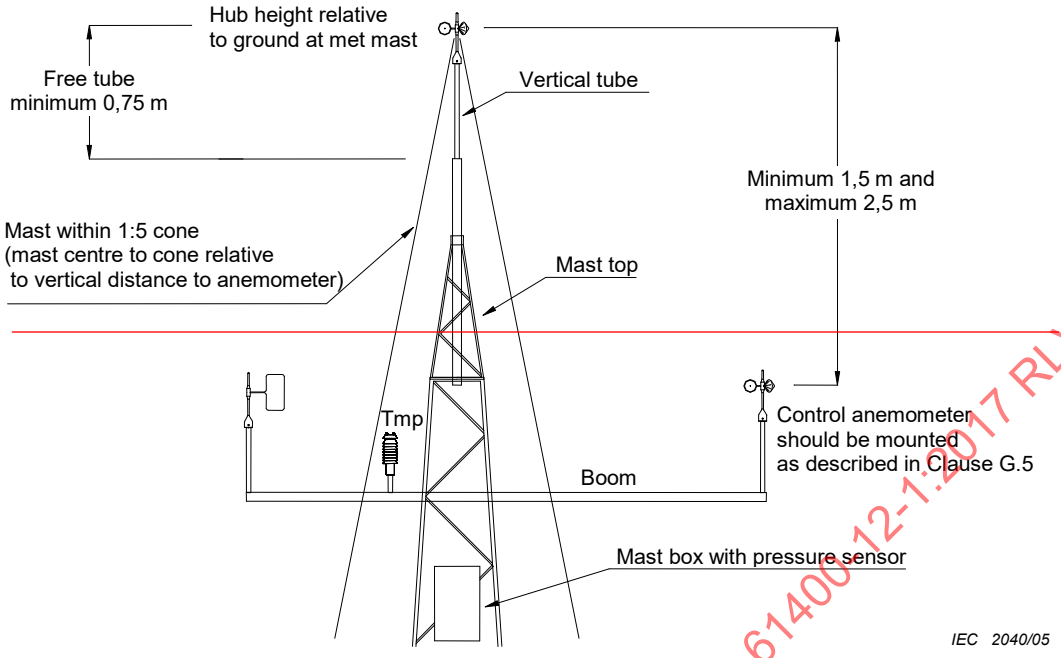
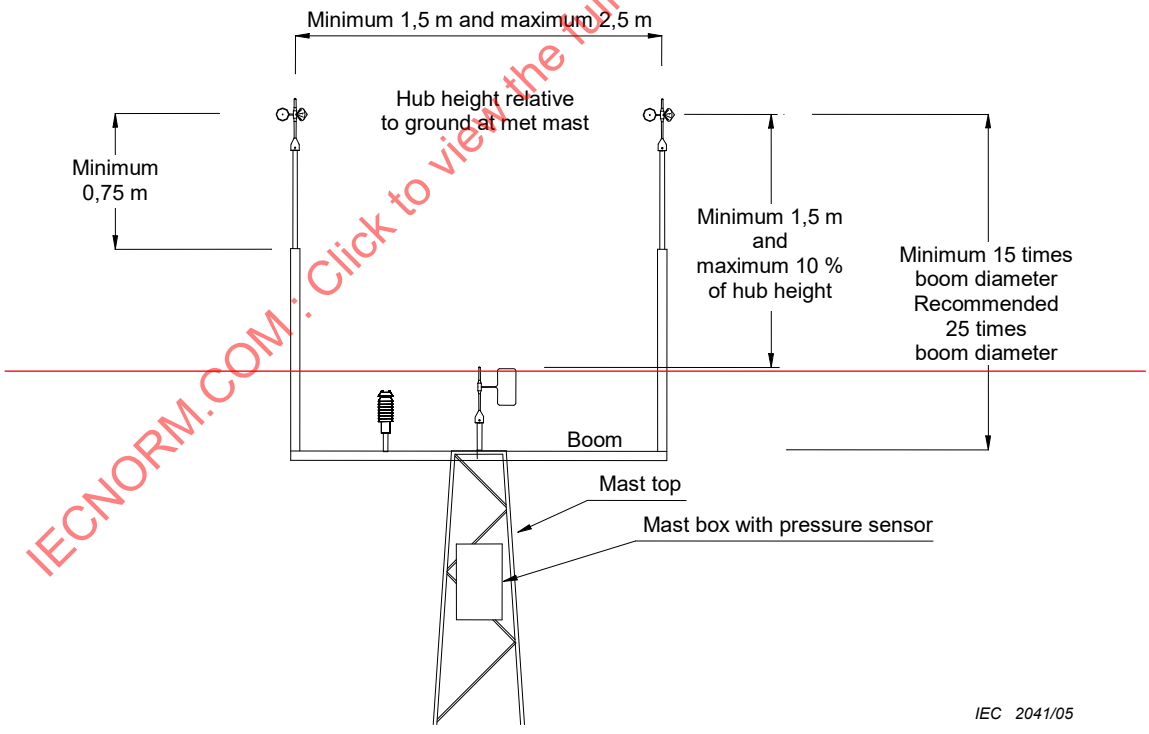


~~Figure G.3 – Example of a top-mounted anemometer and mounting of control anemometer, wind vane and other sensors on a boom~~



~~Figure G.4 – Example of top-mounted primary and control anemometers positioned side-by-side, wind vane and other instruments on the boom~~

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Annex H
(normative)

Power performance testing of small wind turbines

H.1 General

Small wind turbines (as defined by IEC 61400-2) require special provisions for power performance testing. In particular, wind turbines used to charge batteries shall be tested in a way that is representative of normal operation but that reduces or eliminates the influence of the particular battery configuration and condition used during testing, and wind turbines that use inverters for grid connection shall be tested in conjunction with those inverters to give results representative of normal operation. In all cases the relevant power is useful power to the consumer, thus power is the power injected into the grid for grid connected wind turbines, similarly power delivered to the batteries for battery charging wind turbines. When testing a small wind turbine, all requirements described in this standard shall be met with the following additions and changes.

H.2 Definitions

Maximum power, P_{60}: maximum one-minute average power output a wind turbine in normal steady-state operation will produce (peak instantaneous power output can be higher).

Reference power: the averaged power level in the 11 m/s wind speed bin.

Reference annual energy production: The AEP measured at 5 m/s annual average wind speed, Rayleigh distributed, using the sea level density corrected power curve.

H.3 Wind turbine system definition and installation

With respect to 6.2, the following is required:

a) ~~in 5.1:~~ when characterising battery charging performance, the wind turbine generator system shall include the wind turbine, wind turbine tower, wind turbine controller, wiring between the wind turbine and the load~~. The wind turbine generator system includes the~~, and charge controller, which is a voltage protection device that reduces wind turbine power output when batteries are fully charged. It may include a dump load that is used to dissipate energy from the wind turbine when the batteries are fully charged. The wind turbine generator system does not include a battery bank because it is considered part of the load. Other energy storage devices may be substituted for batteries throughout this clause;

b) ~~in 5.1:~~ when characterising system output to a grid, the wind turbine generator system shall include the wind turbine, wind turbine tower, wind turbine controller, wiring between the wind turbine and the load~~, charge controller and dump load (if used) as noted above~~, and any additional controllers. In addition, the system may include a voltage inverter. If a transformer is installed between the voltage inverter and the grid, it may be considered as either part of the wind turbine generator system or the load. If the grid-connected wind turbine system incorporates a battery bank and/or dump load, it shall be considered part of the system;

c) ~~also in 5.1:~~ the wind turbine shall be connected to an electrical load that is representative of the load for which the wind turbine is designed. In the case of battery charging applications, the load consists of a battery bank, a voltage regulator, and a means to dissipate the power that passes through the voltage regulator (or dump load). In the ideal test set-up, the battery bank does not store energy produced by the wind turbine. Rather all wind turbine output is routed through the voltage regulator. Therefore, the battery bank may be smaller than typically recommended for the wind turbine as long as voltage at the

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connection of the wind turbine to the load can be maintained within the specifications stated below;

d) ~~also in 5.1:~~ the wind turbine shall be installed using the manufacturer's specified mounting system. If a wind turbine is not supplied with a specific mounting system, the wind turbine generator should be mounted at a hub height of at least 10 m;

e) ~~also in 5.1:~~ in order to minimize differences in results due to wiring between the wind turbine and the load, ~~the connection to the load shall be no closer than the base of the turbine tower and no farther than three times the tower height~~ the total wire run length, measured from the base of the tower to the load, shall be at least 8 rotor diameters. Wiring between the small wind turbine and the load shall be in accordance with the manufacturer's specifications for this wire run length. If the specifications provide for a range of wire sizes, wires shall be sized as close as possible to the average of that range. If no specifications are provided, the wiring shall be sized so that voltage drop between the wind turbine generator and the load is equivalent to 10 % of nominal voltage at rated power;

f) ~~also in 5.1:~~ the voltage regulator shall be capable of maintaining voltage at the connection of the wind turbine to load within 10 % of the settings given in Table H.1 over the full range of power output of the wind turbine. The 1-minute average of the load voltage ~~must~~ shall be within 5 % of the settings given in Table H.1 to be included in the usable data set.

H.4 Meteorological mast location

With respect to 6.3.2 the following is required:

a) ~~in 5.2.1:~~ if it is more practical to mount the anemometer on a long boom that is connected to the wind turbine tower, a separate meteorological mast is not required. To minimize the ~~potential~~ flow distortion on the small wind turbine rotor from the wake from the anemometer, the wind vane and their mounting hardware ~~to influence flow into a small rotor~~, all such components shall be located at least 3 m away from any part of the wind turbine rotor. In addition, the anemometer mounting should be configured to minimize its cross-sectional area above the level that is 1,5 rotor diameters below hub height. The boom shall be installed such that structural vibrations are not introduced into the wind speed signal;

b) for vertical axis wind turbines hub height is defined as the height of the centroid of the swept area of the wind turbine rotor;

c) for vertical axis wind turbines the distance between wind turbine and meteorological mast is illustrated in Figure H.1.

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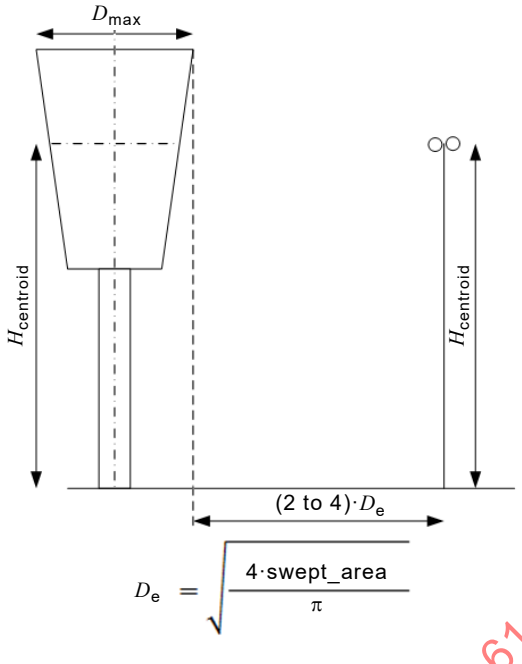

Figure H.1 – Definition of hub height and meteorological mast location for vertical axis wind turbines

H.5 Test equipment

a) In 7.1 when measuring DC outputs for battery charging wind turbines with a swept area of 40 m^2 or less, the use of measurement equipment with an accuracy of 2 % or better is permitted for the purposes of measuring current and power, rather than the 0,5 % accuracy referred to in 7.1;

b) in 7.1: wind turbine output power shall be measured at the connection to the load as defined in Clause H.3;

c) also in 7.1: in addition to electric power, voltage at the connection to the load shall be measured to ensure compliance with the requirements listed in Clause H.3;

d) also in 7.2.2: the anemometer mounting guidance provided in Annex G should be followed. If deviations are made the reason for doing so needs to be documented in the test report and additional uncertainty shall to be added to the analysis. In extreme cases, it is permissible to temporarily use an anemometer other than the control anemometer if it can be demonstrated that a good correlation exists between the control anemometer and this third anemometer. Additional uncertainty will have to be used in the analysis to accommodate for the uncertainties in the correlation;

e) also in 7.2.3: anemometer shall be mounted at the top of a meteorological mast at hub height ± 2 % relative to the ground at the meteorological mast;

f) in 7.2.6: no wind shear needs to be measured;

g) in 7.4: measurement of relative humidity and correction for it is optional;

h) also in 7.4: the air temperature sensor, air pressure sensor and humidity sensor, if used, shall be mounted so that they are at least 1,5 rotor diameters ~~below~~ vertical distance from hub height ~~even if such mounting results in a location less than 10 m above ground level~~ and within 100 m horizontal distance of the hub;

i) in 7.7: monitoring of small wind turbine status is ~~required only when the turbine controller provides an indication of turbine faults~~ recommended but is not mandatory.

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H.6 Measurement procedure

a) in 8.2: if the wind turbine's charge controller reduces wind turbine output at the optional, high voltage setting, the ~~device~~ charge controller may be adjusted to a higher voltage. If the ~~device~~ charge controller is adjusted, the test report shall document the settings before and after adjustment. Any other adjustments to the wind turbine's controls ~~must~~ shall be clearly reported;

b) in 8.3: pre-processed data shall be of 1 min duration. All subsequent references to 10-min data sets in the standard shall apply to 1 min data sets when testing small wind turbines;

c) in 8.4: add bullet for data rejection

– 1 min average of the load voltage is not within 5 % of the settings given in Table H.1;

d) in 8.5: the database shall be considered complete when it has met the following criteria:

1) each wind speed bin between 1 m/s below cut-in and 14 m/s shall contain a minimum of 10 min of sampled data;

2) the total database contains at least 60 h of data with the small wind turbine within the wind speed range defined in bullet 1);

3) in the case of furling wind turbines, the database should include completed wind speed bins characterizing performance when the wind turbine is furled.

e) it is recommended that additional performance data be obtained to quantify the effect that changes of battery bank voltage have on wind turbine performance. These additional power curves should be obtained by setting the battery bank voltage to the optional low and high settings listed in Table H.1, and by obtaining at least 30 h of data using 1-min pre-averaging. When reporting these power curves, the tables and graphs shall clearly indicate that they show performance at optional low and high voltage settings and shall indicate those voltage settings. It is recommended that a single graph be used to show the variation of power with wind speed and battery bank voltage.

Table H.1 – Battery bank voltage settings

Nominal voltage V	Required setting V	Optional low setting V	Optional high setting V
12	12,6	11,4	14,4
24	25,2	22,8	28,8
36	37,8	34,2	43,2
48	50,4	45,6	57,6
Other	2,1*	1,9*	2,4*
* Volts per cell			

H.7 Derived results

a) in 9.1: for wind turbines with passive power control such as furling or blade fluttering, wind speed shall be sea level normalised using Equation (14) (wind speed ~~adjustment~~ normalisation), Equation (13) (power ~~adjustment~~ normalisation), or an alternative method. Documentation ~~must~~ shall be provided to justify the use of an alternative method. However, if the wind turbine is already adjusted to adapt to the site specific air density, this should be reported and no additional normalisation is allowed;

b) in 9.1.6: for small wind turbines, the turbulence correction is not recommended, however if it is carried out it shall be reported whether the method is applied for 1 min averages instead of 10 min averages of the measured power and wind speed, and either are permitted. If the turbulence correction is applied the power curves both with and without turbulence correction shall be reported and clearly identified;

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c) in 9.3: in cases where the small wind turbine does not shut down in high winds, AEP measured and AEP ~~projected~~ extrapolated shall be calculated as though cut-out wind speed were the highest, filled wind speed bin or 25 m/s, whichever is greater.

H.8 Reporting

in Clause 10: in addition to the information listed in Clause 7, the description of the wind turbine and the test set-up shall include:

a) wiring sizes, conductor material, types, lengths and connectors used to connect the wind turbine to the load;

~~b) measured resistance of wiring between the inverter and the load or between the turbine and the load if no inverter is used,~~

b) voltage setting(s) for any over or under-voltage protection devices that are part of the small wind turbine generator system;

c) nominal battery bank voltage (e.g. 12 V, 24 V, 48 V);

d) battery bank size (i.e. amp-hour capacity), battery type and age;

e) description including make, model, and specifications of the voltage regulation device used to maintain the battery bank voltage within specified limits;

f) reference power;

g) the calculated annual energy production based on AEP measured and a Rayleigh wind speed distribution with an average wind speed of 5 m/s and the sea level density normalised power curve shall be reported as the Reference Annual Energy;

h) the 1 min turbulence intensity for each data set (sequential, unbroken, time series) as a scatter plot across the observed wind speed range.

H.9 Annex A – Assessment of influence cause by wind turbines and obstacles at the test site

a) The requirements in Table A.1 may be relaxed to accommodate small wind turbines but additional uncertainty should be included for the wind speed uncertainty. However, do not disregard other sections of Annex A (i.e. the method for excluded sectors due to obstacles).

H.10 Annex B – Assessment of terrain at test site

a) In recognition of the typical environments where small wind turbines are installed the maximum slope requirements in Table B.1 may be increased to 10 % for all distances and all directions. However, additional uncertainty in wind speed should be added.

H.11 Annex C – Site calibration procedure

a) in C.3.2: additional measurements to characterize wind shear are not recommended. This includes vertical wind speed and wind veer measurements;

b) In Clause C.5: disregard analysis for wind shear and atmospheric stability;

c) also in Clause C.5: wind shear measurements are not required at both meteorological masts;

d) also in Clause C.5: for each 1-minute data point, the wind speed ratio shall be calculated, which is the hub height wind speed at the wind turbine meteorological mast location divided by the hub height wind speed at the reference meteorological mast;

e) in C.5.1 and C.5.2: these subclauses will be disregarded;

f) in C.5.3: this subclause will be used for site calibration analysis;

g) for site calibration for small wind turbines, it is acceptable to use the wind turbine support tower rather than a meteorological mast at the wind turbine location, provided that flow distortion requirements are satisfied.

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Annex I
(normative)

Classification of cup and sonic anemometry

I.1 General

An anemometer is an instrument to measure wind speed. As such, it is subjected to external conditions that may influence the wind speed measurement through the operational characteristics of the instrument. Known general influence parameters of cup anemometers are turbulence, air temperature, air density, and average flow inclination angle. Anemometers being used for power performance measurements shall be assessed for these influential parameters[37] and operational uncertainties, as required in Annex D (Table D.1). The method of classification of a type of anemometer, described in this annex, shall be used in order to determine operational uncertainties. This method of classification is similar in approach to classification of power transducers, see IEC 60688.

At least two examples of a type of anemometer shall be assessed. Any design change of external geometry or internal design changes that may influence friction torque of a cup anemometer requires a new assessment.

Before using an anemometer with a classification for power performance tests it is recommended that the geometry of the anemometer be checked with the type description that corresponds to the classification.

Cup and sonic anemometers are wind measurement instruments that may be used for power performance measurements. In order to transfer traceability they shall be calibrated in a wind tunnel according to Annex F. Wind tunnel calibrations are performed under controlled environmental conditions with a smooth and low turbulent flow. However, during measurements and operation in the field, these instruments are subject to turbulent flow and environmental conditions that can deviate significantly from wind tunnel calibration conditions. The field conditions may significantly influence the instrument characteristics and cause the instrument output to deviate from wind tunnel calibrations. If the ranges of the influential parameters during field operation are determined, then the systematic deviations may be analysed and the deviations in instrument output may be put into a classification scheme.

Known influence parameters on cup anemometer measurements are turbulence, air temperature, air density, and average upflow angle. Known influence parameters on sonic anemometer measurements are wind direction, upflow angle, and air temperature. These influence parameters shall be considered in the classification. Other environmental parameters may influence the instruments. If such influence parameters are known to give systematic deviations, the influence shall be analysed and included in the classification scheme. Furthermore, the combined effect of all influential parameters shall be assessed. The systematic deviations due to influential parameters shall be analysed according to the procedures described in Annex J resulting in a classification specification of the type of anemometer. At least five samples of the anemometer type shall be assessed. Modification of an anemometer type that may influence the output requires a new assessment. Change in geometry of the anemometer type, measurement principle, software algorithm for calculation of the output, software settings, or supporting structure geometry, requires a new assessment.

The classification method only considers normal operation of the sensors. The method does not consider, for example wear, malfunctioning or icing (see Annex O).

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[37] Other known influential parameters are snow, ice and rime. If these parameters are covered by the normal operation of the anemometer, uncertainty due to these parameters shall also be assessed.

I.2 Classification classes

The classification of an anemometer type is divided into five classes dependent on the purpose. Class A, B, C and D are based on predefined terrain and climate ranges, see Table I.1. Class A and C shall be used for terrain that meets the requirements in Annex B and in type A terrain in C.3.1. Class B and D shall be used for terrain that does not meet the requirements in Annex B. Class B and D could be used in terrain type B in C.3.1. If information about the influence parameter ranges during the measurements are available then class S may be used.

Class S is a special class, where the influence parameter ranges may be defined by the user, see Table I.1. This may be for a special climate, for example cold climate conditions, see Annex O. The class S may also be used for uncertainty estimate for a measurement campaign where the influence parameter ranges are determined during the measurements. Class S may be used for measurements in type A, B and C terrain, see C.3.1.

The classification number k shall be used in determination of the wind speed operational characteristics uncertainty, as listed in Annex D (Table D.1).

Annex B provides an assessment of the terrain to evaluate if the flow distortion due to the terrain will be significant. For classification of cup and sonic anemometers, this terrain assessment supports the definition of the classification classes A, B, C and D.

Class A: Associated with terrain that meets the requirements of Annex B and with general influence parameter ranges for this type of terrain.

Class B: Associated with terrain that does not meet the requirements of Annex B and with general influence parameter ranges this type of terrain.

Class C: Same as class A but with temperatures down to –20 °C.

Class D: Same as class B but with temperatures down to –20 °C.

For terrain or climate that deviates from classes A to D a class S climate may be specified.

Class S: Associated with conditions that deviates from class A, B, C or D. In this class, the user defines the influence parameter ranges. This may be due to special or user defined terrain or climate conditions.

I.3 Influence parameter ranges ~~and classes~~

The minimum required influence parameter ranges of cup and sonic anemometer classification are listed in Table I.1.

~~The influence parameter ranges may be applied in either of two ways. One way is to apply general influence parameter ranges from which a class number k is derived. The class number k is associated with the assessment of anemometer response deviations by variation of all influence parameters through the influence parameter ranges.~~

I.4 Classification of cup and sonic anemometers

The classification of an anemometer is specified by the amount of systematic deviations from calibrated values (calibration according to Annex F) where the systematic deviations are determined for values varying within the influence parameter ranges. For a sonic anemometer and for directional sensitive cup anemometers, a reference direction that is used for calibrations according to Annex F shall be defined for the instrument type. The systematic deviations shall be derived for all values that are relevant for the class determination between min and max values for each parameter.

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The class number k_n of an anemometer sample number n shall be determined as the maximum ~~anemometer response deviation (from the horizontal wind speed input) in the wind speed range corresponding to the formula~~ systematic deviation from the wind tunnel calibration value, weighted with a wind speed function ε_i :

$$k_n = 100 \cdot \max\left|\varepsilon_i / w_i\right| \quad \text{(I.1)}$$

where

k_n is the class number of anemometer sample number n (n=1…5 or more);

w_i is a weighting function in m/s that defines the deviation envelope, see Equation (I.2);

~~$\varepsilon_{\max,i}$ is the maximum deviation for any wind speed bin i in the wind speed range in m/s;~~

ε_i is the deviation in m/s for influence parameter combination i.

The weighting function w_i averages the influence of absolute and relative deviations[38]:

$$w_i = 5 \text{ m/s} + 0{,}5 \cdot U_i \quad \text{(I.2)}$$

where

U_i is the wind speed in m/s for influence parameter combination i.

~~General parameter ranges are divided into two classes, dependent on whether the terrain meet the requirements in Annex B (class A influence parameter ranges, see Table I.1) or whether a site calibration is needed (class B influence parameter ranges, see Table I.1).~~

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38 A class number of 1 corresponds to 1 % at 10 m/s but more than 1 % below 10 m/s and less than 1 % above 10 m/s.

Table I.1 – Influence parameter ranges (10 min averages) of Classes A, B, C, D and S

	~~Class A~~ ~~Terrain meets requirements in Annex B~~		~~Class B~~ ~~Terrain does not meet requirements in Annex B~~	
	~~Min~~	~~Max~~	~~Min~~	~~Max~~
~~Wind speed range to cover [m/s]~~	~~4~~	~~16~~	~~4~~	~~16~~
~~Turbulence intensity~~	~~0,03~~	~~0,12 + 0,48/V~~	~~0,03~~	~~0,12 + 0,96/V~~
~~Turbulence structure $\sigma_u/\sigma_v/\sigma_w$[39]~~	~~1/0,8/0,5 (non-isotropic turbulence)~~		~~1/1/1 (isotropic turbulence)~~	
~~Air temperature (°C)~~	~~0~~	~~40~~	~~−10~~	~~40~~
~~Air density (kg/m^3)~~	~~0,9~~	~~1,35~~	~~0,9~~	~~1,35~~
~~Average flow inclination angle (°)~~	~~−3~~	~~3~~	~~−15~~	~~15~~

	Class A **Terrain meets requirements in Annex B**	**Class B** **Terrain does not meet requirements in Annex B**	**Class C** **Terrain meets requirements in Annex B**	**Class D** **Terrain does not meet requirements in Annex B**	**Class S**[40] **Special class with user defined ranges**
	Range	Range	Range	Range	Range
Wind speed V (m/s)	4 to 16	4 to 16	4 to 16	4 to 16	4 to 16
Turbulence intensity	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	User defined
Turbulence structure $\sigma_u/\sigma_v/\sigma_w$[41]	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	User defined or 1/0,8/0,5*
Air temperature (°C)	0 to 40	−10 to 40	−20 to 40	−20 to 40	User defined
Air density (kg/m^3)	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	User defined
Average upflow angle (°)	−3 to 3	−15 to 15	−3 to 3	−15 to 15	User defined
Wind direction (°)[42]	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups: 0° to 360° Sonics: user defined
* A non-isotropic Kaimal turbulence spectrum with turbulence length scale 350 m.					

~~The other way to apply influence parameter ranges is to specify a special class S, with a required low class number k, for which the influence parameter ranges are separately specified. The influence parameter ranges for class S shall be presented in an equivalent table to Table I.1.~~

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~~39 For assessment of a class using simulation, it is suggested the wind spectrum is a Kaimal wind spectrum with a longitudinal turbulence length scale of 350 m, see IEC 61400-1.~~

40 The influence parameter ranges determined during a power performance measurement includes some parameters that are measured as part of the performance measurement: wind speed, turbulence, air temperature, air density. The upflow angle may be determined during a site calibration by mounting a bi-vane or three-dimensional sonic anemometer at hub height on the meteorology mast temporarily mounted at the wind turbines foundation. Upflow angle on the turbine may be determined with a spinner anemometer.

41 For generation of artificial wind, see for example Clause J.4.

42 If a cup anemometer is directional sensitive (should be investigated on at least one sample), then directivity shall be included in the classification. For sonic anemometers directivity shall always be included in the classification, but for class S the wind direction range may be defined by the user.

~~The selection of an anemometer class for a specific measurement depends on the terrain or the accuracy that is needed for the measurement.~~

~~Class A: Associated to terrain that meets the requirements of Annex B, and with general influence parameter ranges for this type of terrain.~~

~~Class B: Associated to terrain that does not meet the requirements of Annex B and with general influence parameter ranges for complex terrain.~~

~~Class S: Associated to a specified accuracy, where the influence parameter ranges are restricted to allow for the specified accuracy of the anemometer. Alternatively, the class may be associated to influence parameter ranges that are not specifically covered by class A or class B or to influence parameter ranges that are verified during the power performance measurements[43].~~

For the five anemometer samples being tested for classification, the class is determined by the average of the k values plus half the range divided by $\sqrt{3}$ assuming a rectangular distribution (see Equation (I.3)).

$$k = \frac{1}{5}\sum_{n=1}^{5} k_n + \frac{k_{\max} - k_{\min}}{2} \cdot \frac{1}{\sqrt{3}} \tag{I.3}$$

A classification ~~of an anemometer is specified by the class number k and the class type~~, referring to a certain class, is expressed by kA, kB or kS, for example 1,7A or 2,5S. The operational characteristics standard uncertainty (see Table D.1) of a cup or sonic anemometer may be derived from the classification assuming a rectangular uncertainty distribution, in which case the standard uncertainty to be used in the power performance uncertainty assessment is:

$$u_{v2j} = (0{,}05\ \mathrm{m/s} + 0{,}005 \times U_j) \times k / \sqrt{3} \tag{I.4}$$

An example of a classification is described in Annex J.

I.5 Reporting format

Classification reporting of the wind speed sensor shall specify all relevant details of the sensor, including all settings. Documentation of the class of a sonic anemometer shall specify the programmed configuration for which the classification is valid.

Relevant documentation shall be provided with detailed information on the procedures followed, the measurements performed as background for the classification, and documentation of the facilities and instruments used.

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~~43 The influence parameter ranges determined during a power performance measurement includes the parameters already measured: wind speed, turbulence, air temperature, air density. The average flow inclination may be determined during a site calibration by mounting a bi-vane or three-dimensional sonic anemometer at hub height on the meteorology mast at the wind turbines foundation.~~

Annex J
(~~informative~~ normative)

Assessment of cup and sonic anemometry

J.1 General

Assessment of anemometry for classification ~~may~~ shall be derived from traceable wind tunnel tests, other laboratory tests~~, field tests,~~ and associated modelling ~~and extrapolation~~ of anemometer characteristics. A thorough assessment method should also include ~~both wind tunnel tests and~~ verification field tests~~, and the tests should be mutually verified~~.

An assessment of a type of cup or sonic anemometer ~~should~~ shall include verified procedures to ~~incorporate~~ determine the influence of the following basic characteristics ~~on the cup anemometer operation~~ (also note Table I.1):

- tilt angular response characteristics;
- ~~friction torque in bearings.~~
- yaw angular response characteristics;
- temperature induced effects on the anemometer performance.

Additionally, for cup anemometers the following characteristics shall be assessed:

- dynamic effects due to ~~different~~ rotor ~~acceleration and deceleration~~ torque characteristics.

~~Clauses J.3 and J.4 describe two examples of assessments. An actual assessment of a type of cup anemometer may be based on the examples, but can also be based on other assessment methods, as long as they include verified procedures to incorporate influence of the basic characteristics.~~

Clause J.2 describes procedures for measuring anemometer characteristics. Clause J.3 describes a method for classification of cup anemometers with an example and Clause J.4 describes a method for classification of sonic anemometers. An actual assessment shall be based on the methodologies in Clauses J.3 and J.4, but could also be based on other assessment methods, as long as they include verified procedures to incorporate influence of the parameters in Table I.1. Clause J.5 presents a method for field comparison of anemometers.

J.2 Measurements of ~~cup~~ anemometer characteristics

~~J.2.1 Angular response characteristics measured in wind tunnel~~

~~The angular response of an anemometer is measured in a wind tunnel. For three wind speeds (fairly distributed in the range 4 m/s to 16 m/s, recommended 5, 8 and 12m/s) the flow inclination should be varied at least in the range from –30° to +30° and the angular characteristics should be measured with a resolution of 2°. An example (including the 'ideal' cosine shape) is shown in Figure J.1.~~

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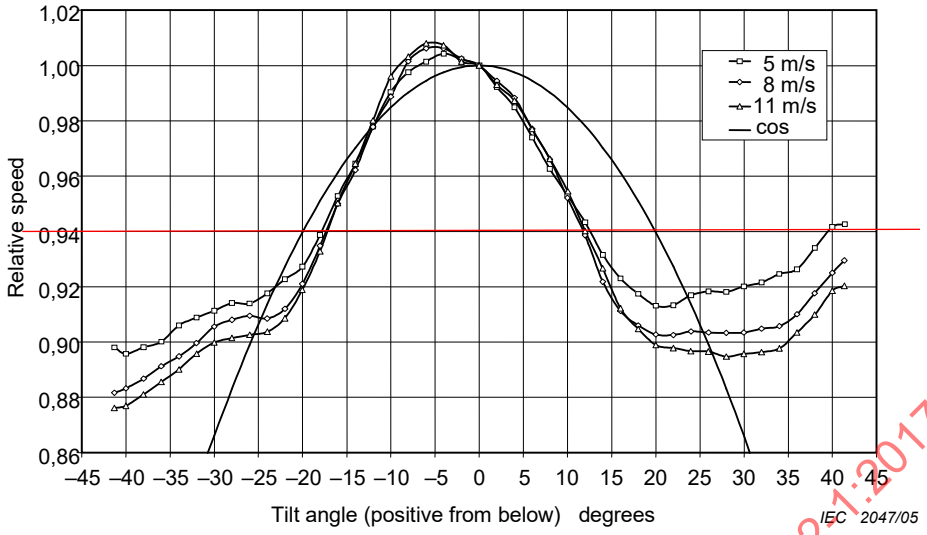

Figure J.1 – Measured angular response of a cup anemometer compared to cosine response

J.2.2 Measurement of acceleration and deceleration forces in wind tunnel

The torque on the cup anemometer rotor can be measured in a wind tunnel by attaching a thin shaft to the top of the cup anemometer rotor, and through the shaft to rotate the cup anemometer at off-equilibrium rotational speeds compared to wind tunnel air speed. The reaction torque on the shaft, which is equal to the cup anemometer rotor torque, can then be measured. It is necessary to have more detailed and accurate measurements closer to the equilibrium speed ratio. An example of a torque measurement, where the wind tunnel speed was kept constant at 8 m/s and the rotational speed of the rotor was varied is shown in Figure J.2.

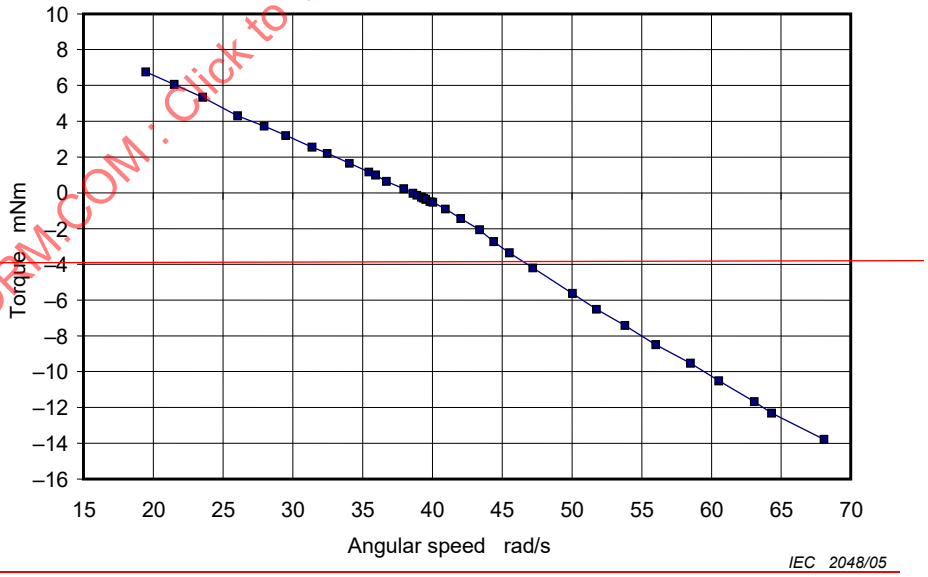

Figure J.2 – Wind tunnel torque measurements on a cup anemometer at 8 m/s

J.2.3 Measurement of friction torque in bearings

Friction torque measurements must be made by replacing the cup anemometer rotor with a flywheel, and by measuring the deceleration from a rotational speed corresponding to about 20 m/s. The torques acting on the rotor are the friction torque in bearings and the air friction

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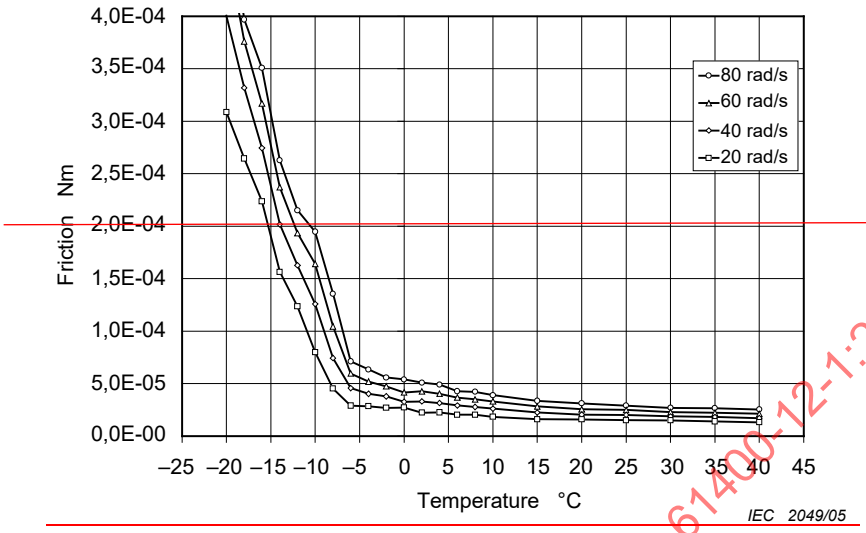
~~torque on the flywheel, which is subtracted from the measured torque. Figure J.3 shows an example of friction torque measurements.~~



~~Figure J.3 – Example of bearing friction torque measurements~~

~~J.2.4 Free field comparison measurements~~

~~In a free field comparison measurement, a cup anemometer and a wind tunnel calibrated three-dimensional ultrasonic anemometer are top mounted as shown in Clause G.2. Only 10 min average measurements in a relatively small sector perpendicular to the boom are acceptable. An acceptable database has to be collected for a range of turbulence intensity (for instance from 0,04 to 0,14).~~

~~J.3 An assessment method based on wind tunnel and laboratory tests and free field comparisons for a class S1 cup anemometer~~

~~J.3.1 Angular characteristic in turbulent flow for different mean flow angles~~

~~J.3.1.1 Mean flow 0°~~

~~The angular response in turbulent flow has to be calculated for different mean flow inclinations. As an example, a flat terrain situation with mean horizontal flow (0° mean flow inclination) will be considered first. The turbulence is described by the turbulence intensity~~

$$~~TI = \sigma_u / U~~ \qquad ~~(J.1)~~$$

~~where~~

~~σ_u standard deviation of the horizontal wind speed;~~

~~U horizontal mean wind speed.~~

~~The angular response characteristic of an cup anemometer in turbulent flow depends on the vertical components of the turbulent flow. The standard deviation of the vertical wind speed component is smaller than the standard deviation of the horizontal component (for classification purposes a relation $\sigma_v = 0{,}8\sigma_u$ shall be used).~~

~~The probability of flow angles (positive for flow coming from below) is derived for different turbulence intensities, see Figure J.4:~~

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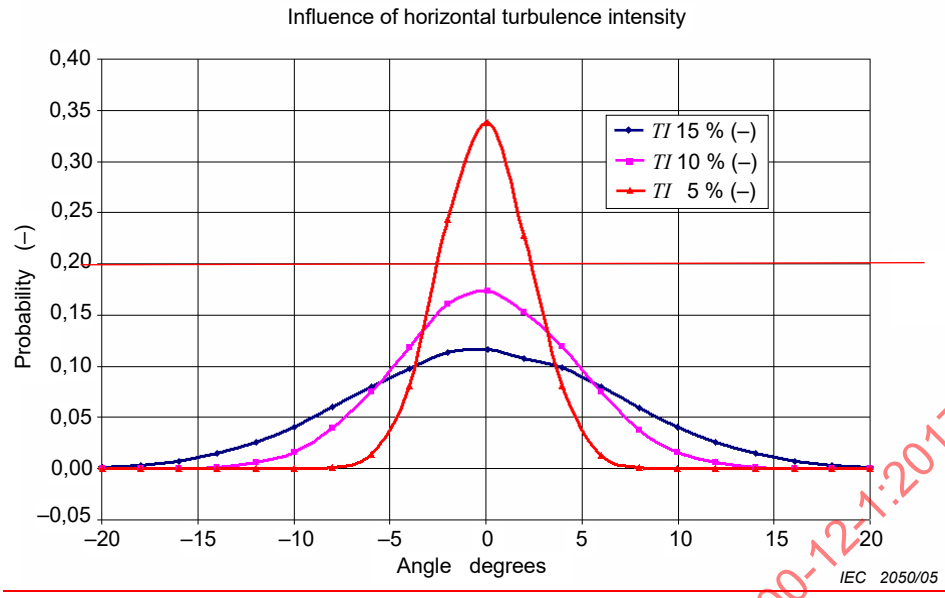

Figure J.4 – Distribution of vertical wind speed components assuming a fixed ratio between horizontal and vertical standard deviation in wind speed

As a next step the probabilities given in Figure J.4 are multiplied with the difference between the angular characteristics and the ideal cosine shape in Figure J.5 for all angles (see Figure J.5a, resulting in a value representing the deviation between the classified anemometer and the ideal anemometer for a specific turbulence intensity. (e.g. 0,8 % for TI = 0,15 in Figure J.4). These deviations are plotted in Figure J.5b for the whole turbulence intensity range up to TI=0,2.

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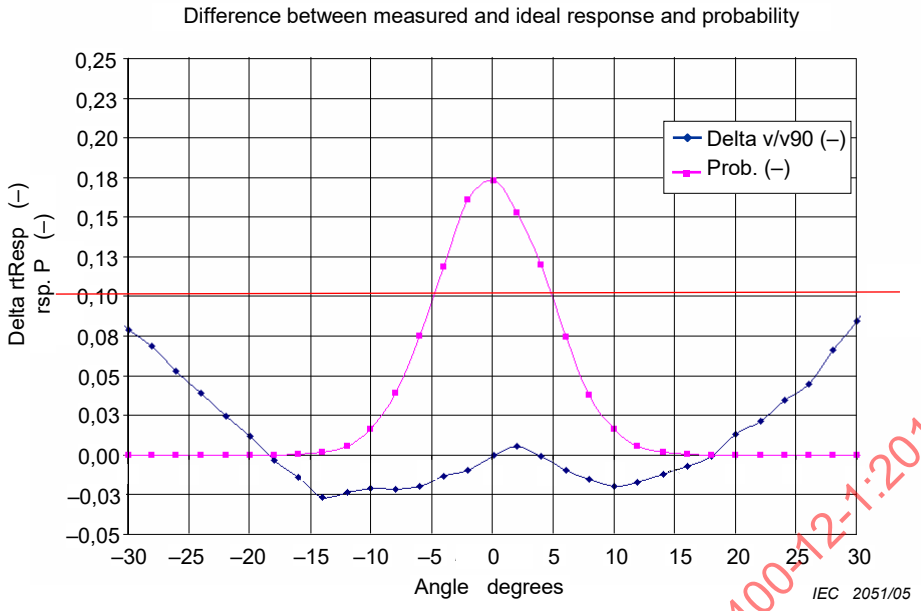

Figure J.5a

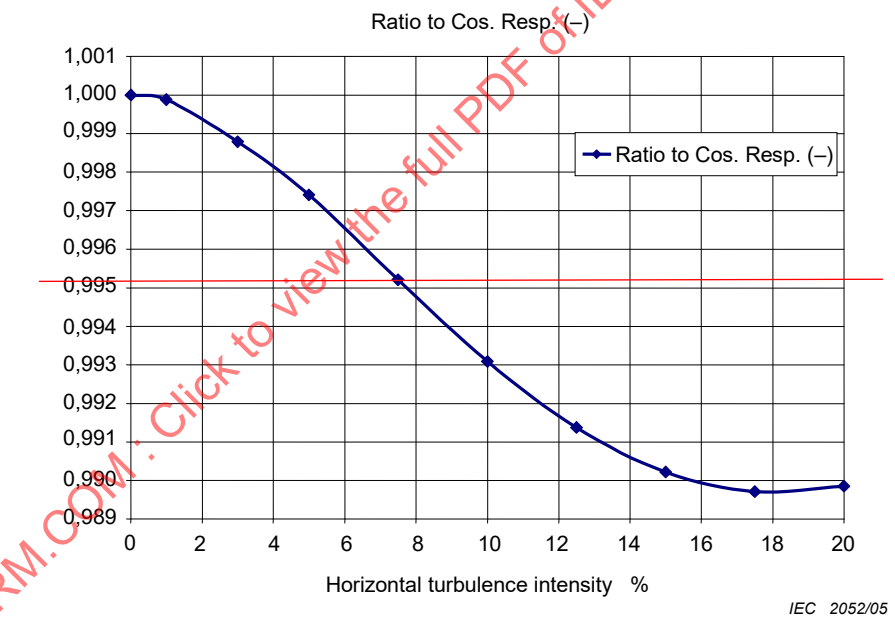

Figure J.5b

Figure J.5 – Calculation of the total deviation with respect to the cosine response

J.3.1.2 Mean flows –20° to +20°

If the mean flow differs from 0° in complex terrain, the probability of flow angles has its maximum at the mean flow angle as shown in Figure J.6.

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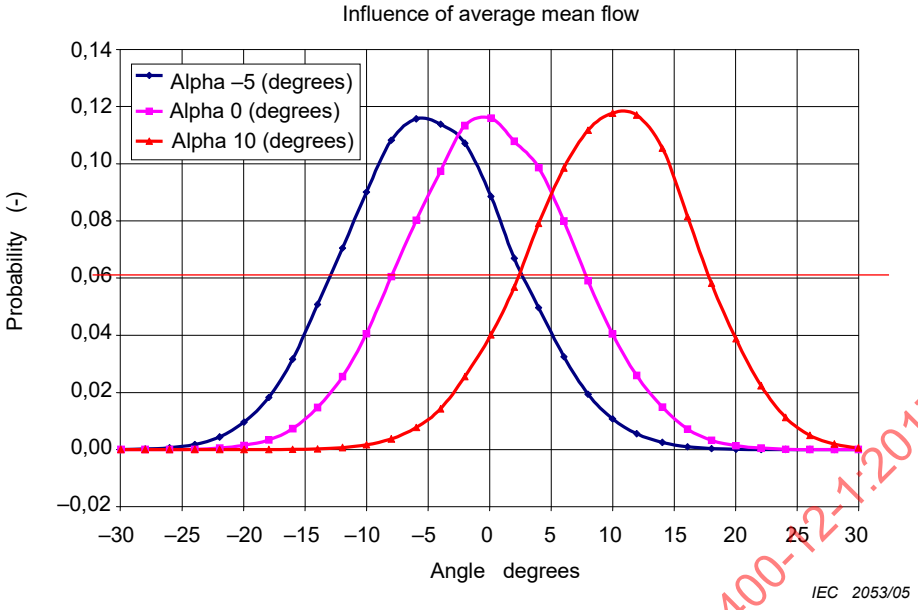

Figure J.6 – Probability distributions for three different average angles of inflow

For mean flow inclinations between −20° and +20° (in 5° steps) and varying turbulence intensity fluctuations of the vertical wind speed the anemometers response has to be calculated and the deviation from an ideal cosine response has to be reported (see Figure J.7).

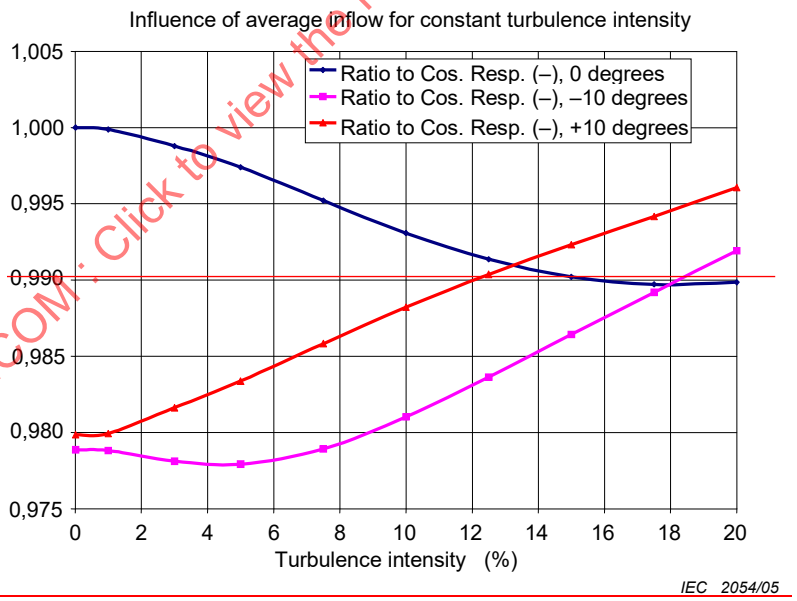

Figure J.7 – Total deviation from cosine response for three different average angles of inflow over horizontal turbulence intensity

From these results, a range of mean flow angles and turbulence intensities can be defined for which the anemometer is a class 1 anemometer. Within these operational ranges, the classified cup anemometer deviates less than 1 % from the ideal cosine response.

J.3.2 Dynamic effects due to non-stationary flow conditions

Additionally to the above described effects due to non-stationary flow conditions caused by the angular characteristics of the cup anemometer, some anemometers tend to have a kind of

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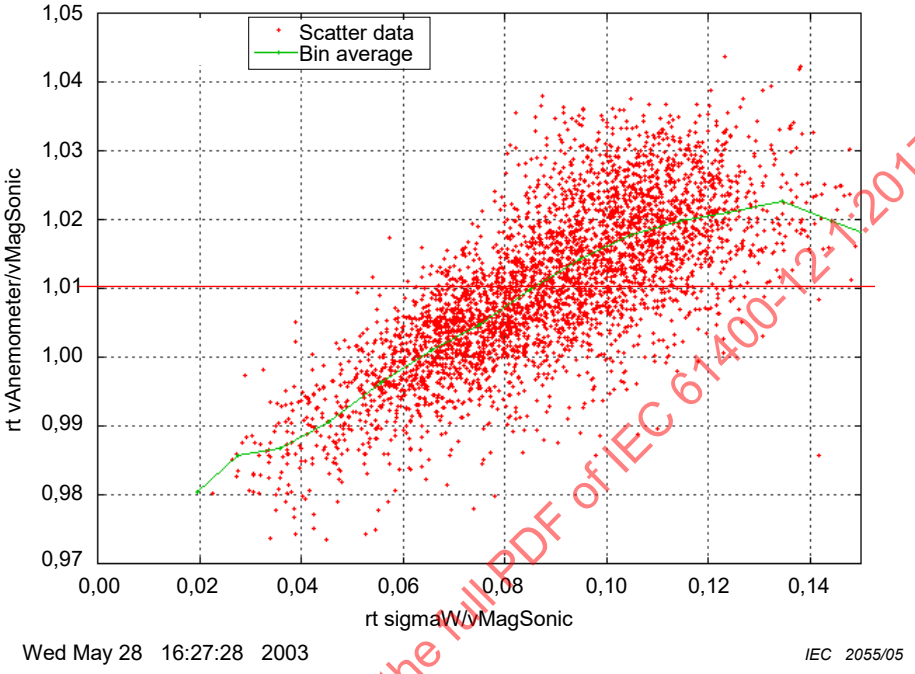
~~dynamic effect, often referred to as aerodynamic over-speeding. This effect must be classified by field tests.~~

~~A field comparison at 30 m height has to be performed. The cup anemometer to be classified should be compared to a calibrated ultrasonic anemometer. The over-speeding effect (expressed as the slope of the difference between the cup and the ultrasonic anemometer) in relation to the turbulence intensity should be measured and reported, see Figure J.8.~~



~~Figure J.8 – Example of an anemometer that does not fulfil the slope criterion~~

~~A class 1 anemometer should have a slope <0,05, corresponding to an over-speeding effect of less than 1 %, for a turbulence intensity range of 0,2 (20 %).~~

~~J.3.3 Friction in bearings~~

~~Calibrations of anemometers in wind tunnels are often made at ambient indoor temperatures, while the anemometers are operational under a wide range of temperatures. The deviation in output of the anemometer under such temperature variations should be investigated . A class 1 anemometer should not deviate by more than 1 % within the operational temperature range.~~

~~As deviations according to the above procedures can be negative or positive, a class 1 anemometer should not have a total deviation of more than 1 % within the operational influence parameter ranges of the power curve measurement.~~

~~J.4 An assessment method based on wind tunnel and laboratory tests and cup anemometer modelling~~

~~J.4.1 Method~~

~~This method is based on measurements of basic characteristics of a cup anemometer type in a wind tunnel and the laboratory and simulations with a cup anemometer model and artificial wind data in order to determine the response for all influence parameter ranges.~~

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J.4.2 Cup anemometer modelling

With measured basic characteristics of a cup anemometer: normal accredited calibration, angular characteristics, torque coefficient versus speed ratio, and friction, and with a few physical properties: rotor inertia, area of one cup and radius to the centre of the cups, the response to any wind input can be derived with a suitable cup anemometer model, that is fitted well to all the basic characteristics. The following model may be used.

The response of the cup anemometer is derived from the driving torque differential equation, where the torque on the rotor is a sum of aerodynamic torque and friction torque:

$$I\frac{d\omega}{dt} = Q_A + Q_f \tag{J.2}$$

The aerodynamic torque Q_A is a function of the instantaneous wind speed vector $\vec{U} = \{u, v, w\}$ with the inflow angle and the scalar:

$$\alpha = \arctan\frac{w}{\sqrt{u^2+v^2}}, \quad \left|\vec{U}\right| = \sqrt{u^2+v^2+w^2} \tag{J.3}$$

An equivalent horizontal wind speed can be found by applying the angular characteristics with the inflow angle and the scalar of the wind speed vector:

$$U_{eq} = F_\alpha(\alpha, \left|\vec{U}\right|) \cdot \left|\vec{U}\right| \tag{J.4}$$

The aerodynamic torque can now be expressed as:

$$Q_A = \frac{1}{2}\rho A R U_{eq}{}^2 C_{QA}(\lambda) \tag{J.5}$$

where

ρ is the air density;

A is the cup area of one cup;

R is the radius to a cup;

U_{eq} is the equivalent horizontal wind speed;

U_t is a threshold wind speed (derived as the remaining of the calibration offset when the friction influence has been subtracted; if friction is zero the threshold wind speed is equal to the calibration offset);

C_{QA} is the generalized aerodynamic rotor torque coefficient.

The generalized aerodynamic rotor torque coefficient is derived from the wind tunnel torque measurements where U_{eq} in this case is equal to the tunnel wind speed:

$$C_{QA} = C_{QA}(\lambda) = \frac{Q_A}{\frac{1}{2}\rho A R U_{eq}{}^2} \tag{J.6}$$

The generalized aerodynamic rotor torque coefficient is a function of the speed ratio:

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$$\lambda = \frac{\omega R}{U_{eq} - U_t} \qquad \text{(J.7)}$$

The friction torque is a function of the temperature and the rotational speed as found from the friction measurements:

$$Q_f = Q_f(T, \omega) \qquad \text{(J.8)}$$

J.4.3 Influence parameter range variations and class determination

The influence parameter ranges may be varied by the use of a turbulence model that generates artificial three-dimensional wind. Exposing the cup anemometer model for 10 min time traces of such artificial wind, the response of the cup anemometer is derived. The deviation from the exact value, which is derived for the wind speed definition from the same wind data, is determined for all the influence parameter ranges, and the deviations now determine the class. Figure J.9 describes an example of derived deviations for Class A influence parameter range variations. The resulting class associated with the cup anemometer assessment is Class 2.0A.

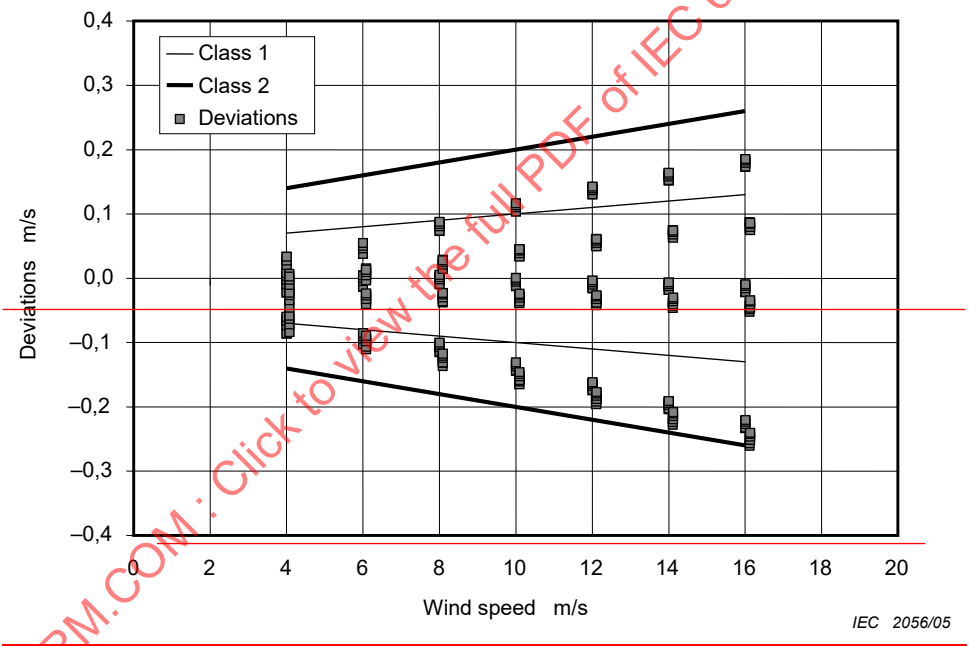

Figure J.9 – Example of deviations of a Class 2.0A cup anemometer

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J.2.1 Measurements in a wind tunnel for tilt angular response characteristics of cup anemometers

The tilt angular response is the measured wind speed at inclined flow angles relative to the measured wind speed at non-inclined flow. The tilt angular response of a cup anemometer shall be measured in a wind tunnel that fulfils the requirements described in Annex F. Additionally it shall be documented that the wind tunnel is sufficient in height for obtaining accurate tilt response characteristics.

The behaviour of an anemometer is strongly influenced by the free space around and especially underneath and above the anemometer. It is important that the tilting mechanism is designed in such a way that the centre of the sensing part of the anemometer is fixed but free to rotate, and the bottom plate of the wind tunnel shall be closed in order to prevent adverse

flow effects. Therefore no translatory motion may be performed by the rotor, instead only an inclination of the rotor plane is realized.

The tilt angle response may be measured with two alternative methods, one using a sweep and the other using fixed positions.

The determination of the anemometer's response to quasi statically inclined flow should be performed with the help of an automatic tilt angle device installed in the wind tunnel. During the measurements, the anemometer is slowly tilted back and forth with a very slow sweep rate (less than 0,05°/s) so the influence on the results due to the angular speed can be neglected. Sweeps may only be used if the wind speed in the wind tunnel is kept within 0,5 % of the nominal wind speed for all tilt angles.

At non-inclined flow, the tilt angle shall be fixed and measurements shall be performed for 300 s to ensure that sufficient data is collected for the zero bin (±0,5°). This zero bin data is used for normalisation of the tilt angular response.

Recording of tilt angle, wind tunnel wind speed and anemometer output shall be made simultaneously and averaged. It can be meaningful to incorporate a finer resolution of the bin-averaging algorithm to account for higher gradients in the tilt angle response around zero degrees.

The tilt angular response should alternatively be determined by stepwise fixed position measurements, where the response at each angle is determined by Annex F wind tunnel calibration at selected nominal wind speeds in the wind speed range.

Measurement matrix recommendations:

a) definition of flow angle: positive for upwards flow on cup rotor;

b) tilt angle range and steps: at least –30° to +30° (for example ±0°, ±1°, ±2°, ±3°, ±4°, ±6°, ±8°...±30°);

c) wind speed range and steps: 4 m/s to 16 m/s (for example 4 m/s, 8 m/s, 12 m/s and 16 m/s);

d) bin averaging range for the sweep method: bin width max 2°.

An example of tilt angular response (including the "ideal" cosine shape) is shown in Figure J.1.

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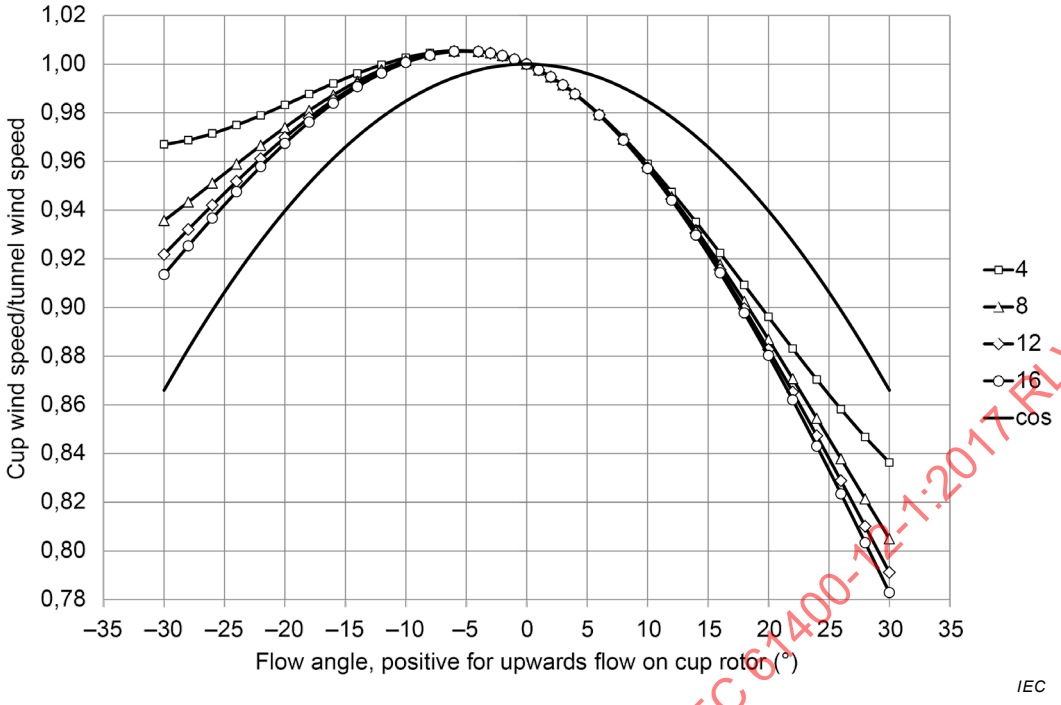

Figure J.1 – Tilt angular response $V_\alpha / V_{\alpha=0}$ of a cup anemometer as function of flow angle α compared to cosine response

J.2.2 Wind tunnel measurements of directional characteristics of cup anemometers

The design of certain cup anemometers (e.g. asymmetric housing shape, asymmetric cable entries, etc.) may have an adverse effect of the anemometer wind speed signal with respect to the horizontal flow direction and the reference direction used for calibration (yaw sensitivity). This effect is not desired since it usually cannot be corrected for. It may contribute substantially to the total uncertainty in the wind speed measurement. Yaw sensitivity measurements shall be conducted at wind speeds of 4 m/s, 8 m/s, 12 m/s, and 16 m/s.

J.2.3 Wind tunnel measurements of cup anemometer rotor torque characteristics

The dynamic response of a cup anemometer to wind is governed by Equation (J.1), where I is the mass moment of inertia, ω is the angular velocity, t is time, Q_A is the aerodynamic rotor torque and Q_F is the torque due to friction (mainly in bearings).

$$I \frac{\mathrm{d}w}{\mathrm{d}t} = Q_A - Q_F \qquad \text{(J.1)}$$

The net torque, Q_A – Q_F, on the cup anemometer rotor, and thus the rotor torque characteristics, can be measured in a wind tunnel.

The aerodynamic torque can be measured by forcing the rotor to turn at off-equilibrium specific angular speeds while measuring the torque with a torque sensor.

The aerodynamic rotor torque on the cup anemometer is equal to the reaction torque on the shaft, measured with the torque sensor, minus friction torque. Measurements close to the equilibrium angular speed should be very accurate and detailed. An example of a torque measurement, where the wind tunnel speed was kept constant at 8 m/s and the rotational speed of the rotor was varied, is shown in Figure J.2.

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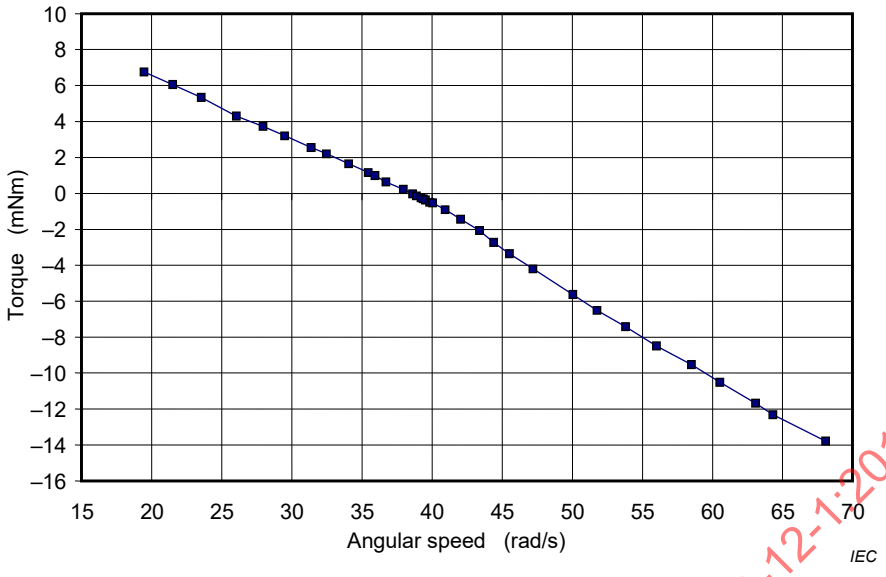

Figure J.2 – Wind tunnel torque measurements $Q_A - Q_F$ as function of angular speed ω of a cup anemometer rotor at 8 m/s

J.2.4 Wind tunnel measurements of step responses of cup anemometers

The rotor torque characteristics may alternatively be measured with a step response method in a wind tunnel. This method is less precise than the method in J.2.3 because linear torque characteristics on either side of the equilibrium speed ratio (torque coefficient equal to zero, see J.3.2) shall be assumed.

A step response is a method where a cup anemometer, in a wind tunnel of constant flow speed, is forced to an off-equilibrium rotational speed, above or below the equilibrium wind speed, where the recovery to equilibrium angular speed is monitored. The recovery region close to equilibrium is the important part of the recovery. It is recommended to use the data from the recovery region between 50 % and 98 % of the equilibrium rotor speed during the acceleration tests, and between 150 % and 102 % during the deceleration tests when fitting the torque coefficient lines.

The method to force the anemometer to operate off-equilibrium can be made by attaching a thin shaft to the top of the cup anemometer rotor, and extending it through a hole in the tunnel wall to a motor. The rotational speed is controlled by the motor, which is mechanically disengaged from the rotor when the measurement of the acceleration or deceleration is to start.

Alternatively, the off-equilibrium state can be achieved by applying one or more jets of compressed air to the one or the other side of the cup anemometer rotor. However, care shall be taken not to disturb the upstream wind in the tunnel.

The off-equilibrium starting states should be well outside the rotational range for the analysis (50 % to 150 % of equilibrium rotor speed) to ensure the excitation device is not influencing the data used for fitting.

In case the torque characteristics can be expressed by a linear relationship on either side of torque equilibrium (torque equal to zero), then the step response can be expressed with the equation:

$$u(t) = u_t - \Delta u \cdot \exp\left(\frac{t - t_0}{\tau}\right) \quad \text{(J.2)}$$

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where

$u(t)$ is the measured wind speed by the cup anemometer at time t using the ordinary calibration function;

u_t is the tunnel wind speed;

Δu is the difference between wind tunnel wind speed and the indicated wind speed of the cup anemometer, at the beginning of the step response measurement, at time t_0;

t is the time;

τ is the time constant to be determined for the step response (τ_{low} for step response from below and τ_{high} for step response from above).

In fitting the data to the two unknown constants τ and t_0, it is useful to reformulate Equation (J.2) and to use linear regression to determine the time constant τ :

$$\ln\left(\frac{u_t - u(t)}{\Delta u}\right) = \frac{t - t_0}{\tau} \tag{J.3}$$

An example of using the step response method results to determine the linear torque from the time constants is further described in J.3.2.

J.2.5 Measurement of temperature induced effects on anemometer performance

Temperature induced effects influencing the anemometer performance shall be assessed.

J.2.5.1 Measurement of friction torque in a cup anemometer

The temperature-dependant effects due to bearing friction shall be assessed by a flywheel test in a climate chamber [11].

Friction torque measurements shall be made by replacing the cup anemometer rotor with a flywheel, and by measuring the deceleration from a rotational speed corresponding to 20 m/s. There are two torques acting on the rotor, friction torque in the bearings[44] and air friction torque on the flywheel (which shall be subtracted from the measured torque). The tests shall be performed at temperatures from –20 °C to +40 °C at least with a 5 °C graduation. For each temperature the friction may be expressed with a second order polynomial with three constants F_0, F_1 and F_2.

$$Q_F = F_0 + F_1\omega + F_2\,\omega^2 \tag{J.4}$$

Figure J.3 shows an example of friction torque in bearings as function of temperature for fixed rotational speeds.

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44 There may be friction torque due to other causes than bearing friction, for example friction due to signal generation. Such torque shall be included in the friction torque measurements.

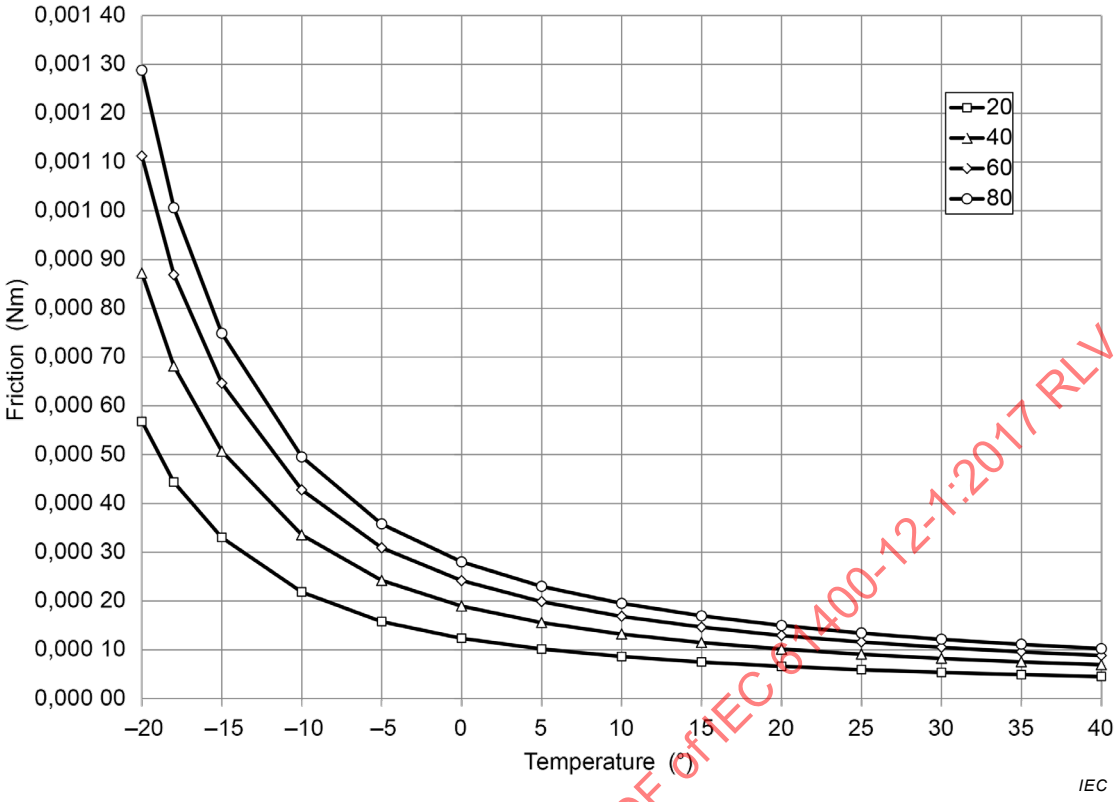

Figure J.3 – Example of bearing friction torque Q_F as function of temperature for a range of angular speeds ω

J.2.5.2 Wind tunnel tests at different temperature and wind speeds

Influence of temperature effects on a whole anemometer (cup anemometers as well as sonic anemometers) may be verified with climate wind tunnel tests. The tests may be performed at temperatures according to Table J.1 from –20 °C to +40 °C at a 5 °C graduation. The tests may be conducted at 4 m/s, 8 m/s, 12 m/s and 16 m/s. The wind speed deviations from the standard calibration of the anemometer may then be determined. Caution shall be exercised to ensure that the findings of the wind tunnel tests are not biased by undesired effects (e.g. the accretion of rime upon the anemometer rotor). The results should be compared to simulated values calculated with the cup anemometer model in J.3.2.

J.2.6 Wind tunnel measurements of directional characteristics of sonic anemometers

The directional influence on the output of sonic anemometers shall be measured in a wind tunnel that fulfils the requirements described in Annex F.

The determination of the anemometer's response to quasi statically inclined/and or yawed air flow shall be performed with the help of an automatic tilt and yaw angle device installed in the wind tunnel. During the measurements, the anemometer is positioned in a fixed tilt angle. The yaw direction may be specified for fixed yaw positions with measurements for 30 s averages, or it may be yawed continuously with a sweep rate of about 1°/s[45]. The yawing shall be performed for the pre-defined measurement sector of the sonic. The tilt angle of the sonic shall be fixed for the following tilt angles: 0°, ±2°, ±5°, ±10°, ±15°, ±20°, ±30°. Tilt angles should be added or omitted if there is clear evidence that they are needed or unneeded. The measurements shall be performed for the wind speeds: 4 m/s, 8 m/s, 12 m/s, and 16 m/s. For

45 The use of fixed yaw directions improves measurement accuracy while the use of a slow sweep rate method is an advantage to reveal the detailed changes that may occur.

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each direction, the deviation of the indicated wind speed of the sonic anemometer from the ordinary calibration at the reference direction shall be derived.

J.3 A cup anemometer classification method based on wind tunnel and laboratory tests and cup anemometer modelling

J.3.1 Method

The classification method shall use an appropriate cup anemometer model to determine deviations due to influence parameters according to Table I.1. The cup anemometer model shall be verified to be able to include all the influential parameters properly. The method shall be based on the wind tunnel and laboratory measurements described in Clause J.2. Furthermore, the method shall use an artificial wind generator in order to generate three-dimensional time domain input wind data for the cup anemometer model. The deviations ε_i shall be determined from the differences between the 10 min horizontal wind speed input averages from the artificial wind generator and the 10 min cup anemometer model response averages.

J.3.2 Example of a cup anemometer model

J.3.2.1 General

The example cup anemometer model is a physical model that simulates cup anemometer response in time domain, see references [7] and [8]. Some physical properties of the cup anemometer shall be measured and used throughout the assessment. These are: rotor inertia I, frontal area of one cup A and radius R from shaft centre to the centre of the cups.

The response of the cup anemometer to the three-dimensional wind shall be derived from a torque equilibrium differential equation, where the torque on the rotor consists of aerodynamic torque minus friction torque (right hand side of equation), see Equation (J.1).

From the differential equation the angular speed of the cup anemometer ω is found, and using the wind tunnel calibration values, the response from the resulting aerodynamic torque and friction torques due to wind variations is determined. The aerodynamic torque Q_A is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind generator. From the wind vector the upflow angle and the scalar of the wind vector is determined:

$$\alpha = \arctan\left(\frac{w}{\sqrt{u^2 + v^2}}\right) \tag{J.5}$$

$$\left|\vec{U}\right| = \sqrt{u^2 + v^2 + w^2} \tag{J.6}$$

An equivalent horizontal wind speed is found by multiplying the scalar of the wind vector with the angular response measured in wind tunnel for the instantaneous upflow angle:

$$U_{eq} = F_\alpha\left(\alpha, \left|\vec{U}\right|\right) \cdot \left|\vec{U}\right| \tag{J.7}$$

Here $F_\alpha\left(\alpha, \left|\vec{U}\right|\right)$ is the tilt angular response of the cup anemometer as shown in Figure J.1.

The aerodynamic torque can be expressed by a generalized torque curve which has been verified to be valid for all wind speeds and all rotational speeds [11]:

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$$Q_A = \frac{1}{2}\rho A R U_{eq}^2 C_{QA}(\lambda) \tag{J.8}$$

where

ρ is the air density;

A is the cup area of one cup;

R is the radius to a cup;

U_{eq} is the equivalent horizontal wind speed;

C_{QA} is the generalized aerodynamic rotor torque coefficient.

The generalized aerodynamic rotor torque coefficient is derived from the wind tunnel torque measurements in J.2.3 or J.2.4 where U_{eq} in this case is substituted by the tunnel wind speed:

$$C_{QA} = C_{QA}(\lambda) = \frac{Q_Q}{\frac{1}{2}\rho A R U_{eq}^2} \tag{J.9}$$

The generalized aerodynamic rotor torque coefficient is a function of the speed ratio:

$$\lambda = \frac{\omega R}{U_{eq} - U_t} \tag{J.10}$$

where

U_t is a threshold wind speed (derived as the remaining of the calibration offset when the friction influence has been subtracted; if friction is zero, the threshold wind speed is equal to the calibration offset).

In case the rotor torque coefficient can be characterized by two linear curves on either side of the torque equilibrium then two corresponding time constants can be determined by wind tunnel step response measurements, see J.2.4 and [9]. The linear torque characteristics can then be determined from the τ values, for low and high speed ratios respectively, from the equation:

$$K = -\frac{2I(u_0 + \Delta u - U_t)}{\rho A R^2 (u_0 + \Delta u)^2 \tau} \tag{J.11}$$

The generalized aerodynamic rotor torque coefficient can then be expressed by:

$$\text{for } \lambda \le \lambda_0 : C_{QA} = K_{low}(\lambda - \lambda_0) \text{ and for } \lambda > \lambda_0 : C_{QA} = K_{high}(\lambda - \lambda_0) \tag{J.12}$$

where

λ_0 is the speed ratio for $C_{QA} = 0$.

An example of the rotor torque coefficient is shown in Figure J.4.

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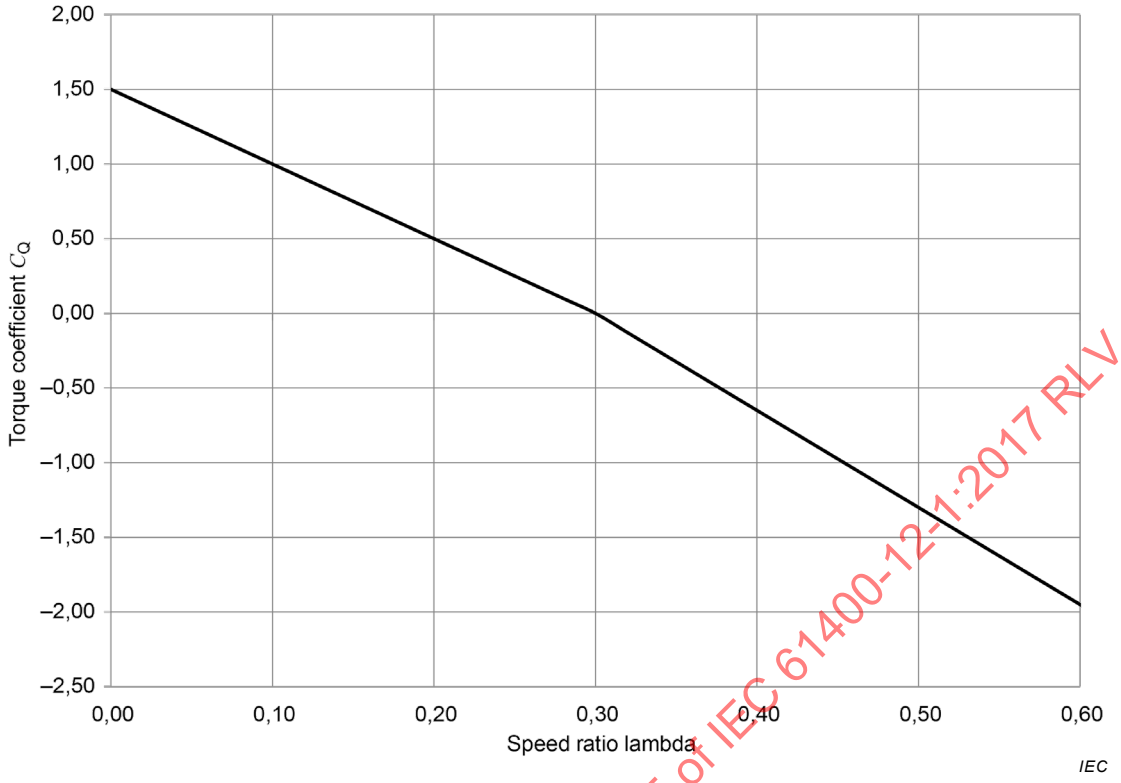

Figure J.4 – Example of rotor torque coefficient C_{QA} as function of speed ratio λ derived from step responses with K_{low} equal to –5,5 and K_{high} equal to –6,5

The friction torque is a function of the temperature and the rotational speed as found from the friction measurements in J.2.5.1:

$$Q_F = Q_F(T, \omega) \tag{J.13}$$

J.3.2.2 Influence parameter range variations and example class determination

The influence parameter ranges shall be varied by using a turbulence model that generates artificial three-dimensional 10 min time series wind speeds with a sample speed of at least 10 Hz. Exposing the cup anemometer model for such artificial winds, the responses of the cup anemometer are derived and the deviations from the horizontal wind speed of the artificial winds are found. The deviations for all combinations of the influence parameter ranges may be derived by a Monte Carlo process. The deviations determine the class as expressed in Equation (J.1). An example of classification of a cup anemometer is shown in Figure J.5 and with the characteristics shown in Figure J.3 and Figure J.4 and with the data presented in Table J.1 and Table J.2. Other data related to the classification are shown in Table J.3.

Deviations for Classes A, B, C and D of all influence parameters are shown in Figure J.5 and Figure J.6. The resulting classes are 1,69A, 6,56B, 8,01C and 9,94D. The cup anemometer with class 1,69A thus meets the requirements of 1,70A for use in terrain that meets the requirements in Annex B and in type A terrain in C.3.1 for temperatures above 0 °C, but not for temperatures below 0 °C with class 8,01C. The cup anemometer do not meet the recommended requirements of a class 2.5B or 2.5D for terrain that do not meet the requirements in Annex B.

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Table J.1 – Tilt angle response of example cup anemometer

Wsp V (m/s)	**4**	**8**	**12**	**16**
Angle α (°)	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$
–30	0,967 005	0,935 689	0,921 815	0,913 545
–28	0,968 769	0,943 307	0,932 028	0,925 304
–26	0,971 484	0,951 098	0,942 067	0,936 683
–24	0,974 941	0,958 908	0,951 805	0,947 569
–22	0,978 933	0,966 583	0,961 111	0,957 850
–20	0,983 253	0,973 974	0,969 863	0,967 413
–18	0,987 695	0,980 930	0,977 934	0,976 148
–16	0,992 055	0,987 304	0,985 199	0,983 945
–14	0,996 131	0,992 948	0,991 538	0,990 698
–12	0,999 722	0,997 717	0,996 829	0,996 301
–10	1,002 628	1,001 468	1,000 954	1,000 648
–8	1,004 651	1,004 057	1,003 793	1,003 637
–6	1,005 594	1,005 344	1,005 233	1,005 166
–4	1,005 262	1,005 188	1,005 155	1,005 136
–3	1,004 558	1,004 526	1,004 513	1,004 505
–2	1,003 462	1,003 452	1,003 448	1,003 446
–1	1,001 951	1,001 950	1,001 949	1,001 949
0	1,000 000	1,000 000	1,000 000	1,000 000
1	0,997 595	0,997 594	0,997 593	0,997 593
2	0,994 750	0,994 740	0,994 736	0,994 734
3	0,991 490	0,991 458	0,991 445	0,991 437
4	0,987 838	0,987 764	0,987 731	0,987 712
6	0,979 458	0,979 208	0,979 097	0,979 030
8	0,969 803	0,969 209	0,968 945	0,968 789
10	0,959 068	0,957 908	0,957 394	0,957 088
12	0,947 450	0,945 445	0,944 557	0,944 029
14	0,935 147	0,931 964	0,930 554	0,929 714
16	0,922 359	0,917 608	0,915 503	0,914 249
18	0,909 287	0,902 522	0,899 526	0,897 740
20	0,896 133	0,886 854	0,882 743	0,880 293
22	0,883 101	0,870 751	0,865 279	0,862 018
24	0,870 397	0,854 364	0,847 261	0,843 025
26	0,858 228	0,837 842	0,828 811	0,823 427
28	0,846 801	0,821 339	0,810 060	0,803 336
30	0,836 325	0,805 009	0,791 135	0,782 865

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Table J.2 – Friction coefficients of example cup anemometer

Temp	F0	F1	F2
(°C)	(Nm)	(Nms)	(Nms^2)
–20	2,000E-04	2,000E-05	–8,000E-08
–18	1,563E-04	1,563E-05	–5,714E-08
–15	1,163E-04	1,163E-05	–4,000E-08
–10	7,692E-05	7,692E-06	–3,077E-08
–5	5,556E-05	5,556E-06	–2,222E-08
0	4,348E-05	4,348E-06	–1,739E-08
5	3,571E-05	3,571E-06	–1,429E-08
10	3,030E-05	3,030E-06	–1,212E-08
15	2,632E-05	2,632E-06	–1,053E-08
20	2,326E-05	2,326E-06	–9,302E-09
25	2,083E-05	2,083E-06	–8,333E-09
30	1,887E-05	1,887E-06	–7,547E-09
35	1,724E-05	1,724E-06	–6,897E-09
40	1,587E-05	1,587E-06	–6,349E-09

Table J.3 – Miscellaneous data related to classification of example cup anemometer

Cup diameter	75 mm
Cup area A	0,004 417 87 m^2
Radius to cup centre R	65 mm
Rotor inertia I	0,000 2 kgm^2
Equilibrium speed ratio λ_0	0,3
Calibration temperature	20 °C
Calibration barometric pressure	1 013 hPa
Calibration air density ρ	1,203 821 kg/m^3
Calibration turbulence intensity	0,003
Calibration turbulence structure	Isotropic $\sigma_u/\sigma_v/\sigma_w$ = 1/1/1
Calibration coefficients A and B	0,679 55 and 0,258 70
Calibration friction coefficients F_0, F_1 and F_2 at 20 °C	see Table J.3 for 20 °C
Torque coefficient slopes K_{low} and K_{high}	–5,0 and –6,5

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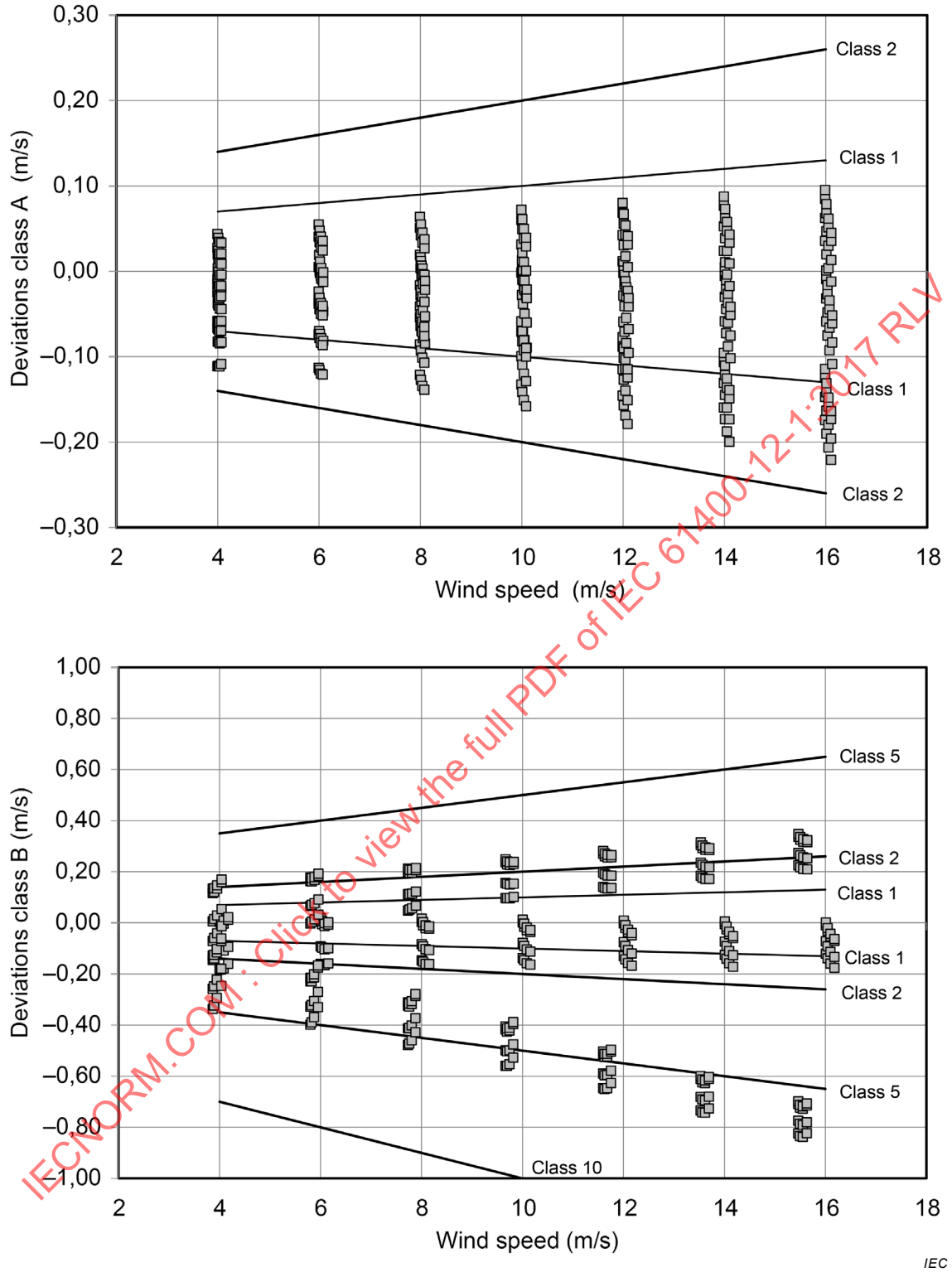

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Figure J.5 – Classification deviations of example cup anemometer showing a class 1,69A (upper) and a class 6,56B (lower)

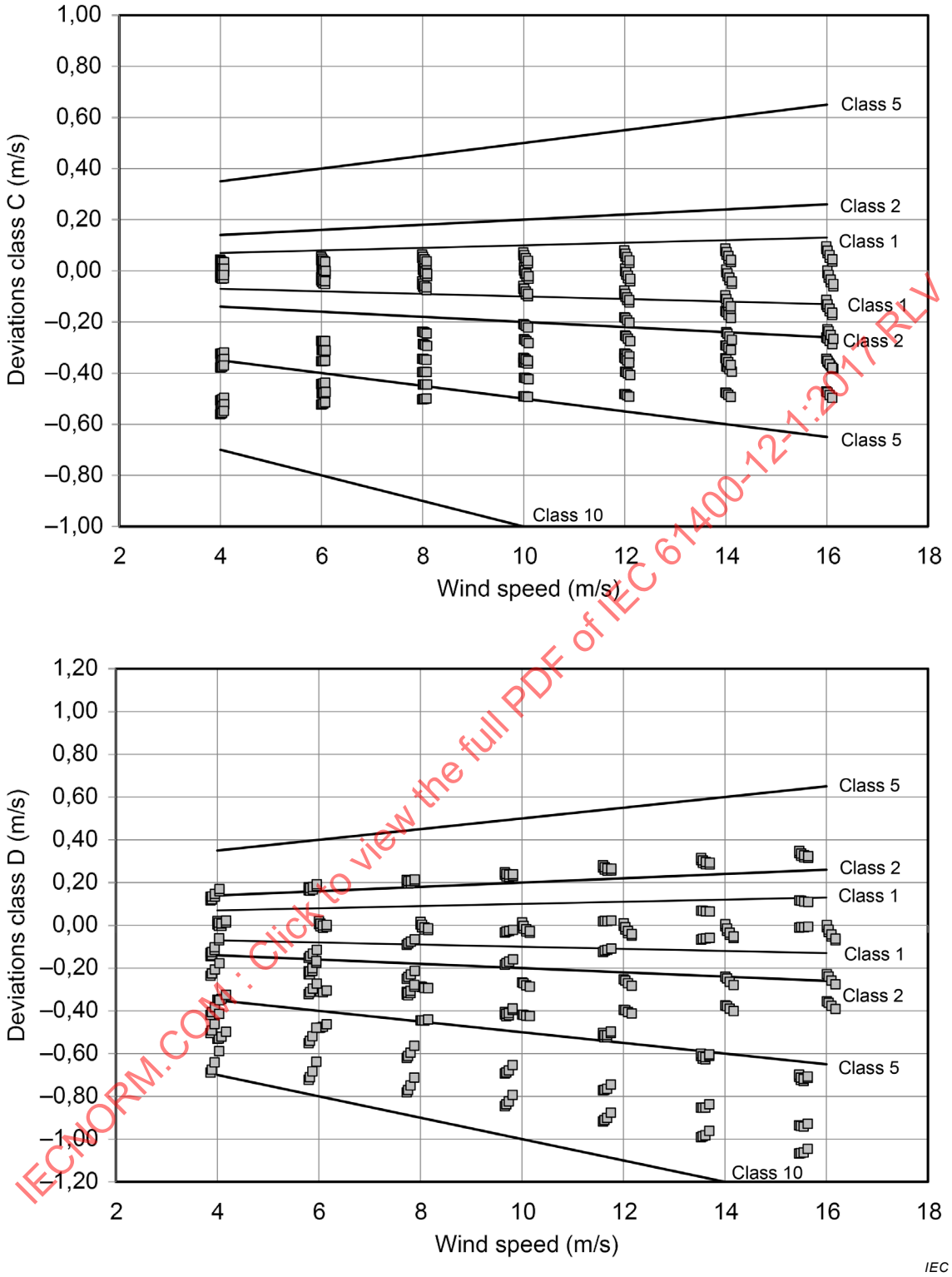

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Figure J.6 – Classification deviations of example cup anemometer showing a class 8,01C (upper) and a class 9,94D (lower)

J.4 A sonic anemometer classification method based on wind tunnel tests and sonic anemometer modelling

The classification method uses a sonic anemometer model to determine deviations due to influence parameters. The method is based on wind tunnel and laboratory measurements as described in J.2.6 and J.2.5.2. Furthermore, the sonic anemometer classification method uses

an artificial wind generator similar to the one for the cup anemometer model, see J.3.2, in order to generate three-dimensional time domain input wind data for the sonic anemometer model.

The response of the sonic anemometer is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind generator. From the wind vector the upflow angle and the scalar of the wind vector is determined by Equations (J.5) and (J.6). The response is then determined by interpolation in the measured data from the wind tunnel measurements:

$$U_{\text{sonic}} = F_{\alpha,\gamma}\left(\alpha, \gamma, \left|\vec{U}\right|\right) \cdot \left|\vec{U}\right| \tag{J.14}$$

where

$F_{\alpha,\gamma}(\alpha, \gamma, \left|\vec{U}\right|)$ is the tilt and yaw response function for the sonic anemometer.

Deviations are determined from differences between sonic anemometer model responses and artificial wind data averages, see J.3.2.2. The relevant influence parameters are tilt and yaw angular responses and temperature induced effects.

J.5 Free field comparison measurements

In a free field comparison measurement, two anemometers can be compared. The comparison measurement can be used to verify that the methods being used in classification of the instruments are consistent, see J.3 and J.4. The comparison of anemometers requires that both anemometers are calibrated in the same wind tunnel. The setup in the field should be made according the mounting procedures for two top-mounted anemometers as described in Annex G, using the maximum distance between them. A 3D ultrasonic anemometer (U, V, and W calibrated) shall be mounted on a boom below the two sensors to measure the environmental influence parameter ranges (flow angle, turbulence, turbulence spectrum), for a class S measurement campaign classification analysis. Additionally, air temperature shall be measured on the same boom for determination of the temperature range, and air pressure shall be measured for determination of the air density range. Time traces of the 3D sonic shall be recorded, while 10 min average measurements in a relatively small sector perpendicular to the boom are acceptable for the two anemometers under comparison. An acceptable database (at least 180 h) shall be collected for a wind speed range of 4 m/s to 16 m/s and a range of turbulence intensities (for instance from 0,04 to 0,14). Comparison of two anemometers should then be made by deriving a class S classification of the two anemometers from laboratory tests, and comparing these with the field measurements.

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Annex K
(~~informative~~ normative)

In-situ comparison of anemometers

K.1 General

It shall be proved that an anemometer used for power ~~curve~~ performance measurements does not change its calibration during the measurement period. The anemometer can be calibrated in a wind tunnel after the measurement period to show the differences to the ~~first~~ calibration before the measurement period. Another ~~possibility~~ method is ~~a so called~~ the in-situ comparison made by comparing the primary anemometer to a control anemometer installed in close proximity ~~to it~~ during the measurement ~~campaign~~ period. It should be noted that this method does not identify a gradual degradation of the calibration of the anemometer if the control anemometer degrades ~~with~~ at a similar rate. The in-situ comparison should be repeated on a regular basis to identify problems at an early stage.

K.2 Prerequisite

During the measurement ~~campaign~~ period the two anemometers are installed on the meteorological mast according to Annex G. The primary anemometer is used for the power performance measurements. The other is the control anemometer, and is used for the in-situ comparison. The anemometers can be installed in ~~two~~ three variants:

a) variant 1: top mounted according to Clause G.2;

b) variant 2: alternative top mounted according to Clause G.3;

c) variant 3: both anemometers side-mounted according to Clause G.4.

K.3 ~~Realisation~~ Analysis method

Two databases will be compared using the 10 min average values recorded during the power performance measurement period ~~are all taken into account~~.

~~The data are filtered for a narrow wind direction sector (e.g. ±20° or ±40° with the centre 90° to the boom, dependent of the measurement sector) and into a wind speed range of 6 m/s to 12 m/s. The relation between the measurements of the two anemometers should be analysed by the method of bins into bins of 1 m/s (control anemometer wind speed).~~

~~From the first part of the measurement period until the completion of all 1 m/s bins (at least three values per bin and for maximum eight weeks) a linear regression is performed with the control anemometer as dependent variable and the primary anemometer used for the power curve measurement as independent variable.~~

~~After determination of the linear regression coefficients the following formula can be used:~~

$$V_{\text{control_corr}} = m \cdot V_{\text{control}} + b$$

~~Depending on the types of anemometers, it may be necessary to use a higher order formula for a better fit. The intention is to show a possible change over time in the behaviour of an anemometer, not an absolute calibration.~~

The first database includes data that starts directly after the installation of the anemometers. The second database includes data for the last part of the power performance measurement period. Each database shall meet the following requirements:

a) cover a range from 4 m/s to 12 m/s;

b) wind directions shall be in the valid measurement sector;

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c) each wind speed bin shall have a minimum of 3 points of data. There are two possible choices of binning the data as follows:

   1) Binning option 1: Wind speed bins of 1 m/s width, centred on 1,0 m/s values, based on the control anemometer wind speed from one wind direction bin not larger than ± 15°.

   2) Binning option 2: Wind speed bins of 4 m/s width centred on 2 m/s, 6 m/s, 10 m/s and 14 m/s[46] based on the control anemometer wind speed and wind direction bins of 10°.

d) include a wind direction sector with the meteorological mast free of wakes of any wind turbines and with the anemometers free of wakes of the meteorological mast as follows:

   1) In the case of side-by-side anemometer mounting (variant 2) and using only wind speed binning for one wind direction sector (binning option 1), the wind direction sector should include the wind direction that is 90º to the boom direction and in acceptable wind directions;

   2) In the case of a top-mounted anemometer (variant 1), the wind direction bin(s) shall be out of the wake of the meteorological mast. Therefore the horizontal connection lines (see Figure K.1 and Figure K.2) between the centre of the control anemometer and any part of the meteorological mast shall have a minimum angular distance of 45º to the border of the bin(s).

e) maximum duration shall be 8 weeks.

The wind direction bin(s) used for the analysis shall be clearly stated in the report.

If 1 m/s wind speed bins and one wind direction bin of 30° (binning option 1) are applied, a linear regression is performed with the primary anemometer as the dependent variable and the control anemometer as the independent variable. This regression will be used to calculate the estimated primary anemometer wind speed, termed $V_{\text{primary_est}}$.

$$V_{\text{primary_est}} = m \cdot V_{\text{control}} + b \tag{K.1}$$

where

m is the slope of the regression relating V_{control} to $V_{\text{primary_est}}$;

b is the offset of the regression relating V_{control} to $V_{\text{primary_est}}$;

V_{control} is the wind speed of the control anemometer.

The intention is to show a change over time in the behaviour of an anemometer, not an absolute calibration.

If 4 m/s width wind speed bins and 10° wind direction bins (binning option 2) are applied, a piecewise linear interpolation between wind speed bins in each wind direction bin from the first database can be used to estimate the primary anemometer wind speed based on:

$$V_{\text{primary_est}} = \frac{V_{\text{primary},i} - V_{\text{primary},i-1}}{V_{\text{control},i} - V_{\text{control},i-1}} \left(V_{\text{control}} - V_{\text{control},i-1}\right) + V_{\text{primary},i-1} \tag{K.2}$$

In this case, only data of the control anemometer within the wind speed bins covered by the first database in each wind direction bin shall be used for the evaluation of the in-situ comparison in the second database. Equation (K.2) may be used for extrapolation up to the borders of the covered wind speed bins. If there is only one wind speed bin covered in a wind direction bin, the ratio of the bin averages of the wind speeds measured by the primary

46 Note that this wind speed range of 0 m/s to 16 m/s is for this interim analysis step only and that the final analysis is to be based on the 4 m/s to 12 m/s range.

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anemometer and the control anemometer shall be used as correction factor for the measurement of the control anemometer.

K.4 Evaluation criteria

~~A recalibration in the wind tunnel of the primary anemometer after the measurement period is not necessary, if the following two criteria are met (only data which are recorded after the linear regression is performed have to be analysed):~~

~~a) there are at least 30 min of sampled data per bin;~~

~~b) the averages of differences in wind speed data (systematic deviation) of the corrected control anemometer ($v_{control_corr}$) and the primary anemometer ($v_{primary}$) are calculated for each wind speed bin. Furthermore, the standard uncertainties of differences in wind speed data (statistical deviation) of the corrected control anemometer ($v_{control_corr}$) and the primary anemometer are calculated for each wind speed bin. The standard uncertainty of the wind speed differences is calculated in each wind speed bin as standard deviation of wind speed differences divided by the square root of number of data points per wind speed bin. The square sum of the systematic deviation and the statistical deviation shall be less than 0,1 m/s for each wind speed bin.~~

Apply the regression or the piecewise linear interpolations from the first database to the control anemometer measurements of the second database resulting in an estimated primary anemometer wind speed for each 10 min period.

Calculate the average of differences (systematic deviation) in the measured and estimated primary anemometer wind speed for 1 m/s wide wind speed bins centred around 1 m/s values. The systematic deviation is:

$$\gamma = \frac{\sum \left(V_{\text{primary_est}} - V_{\text{primary}}\right)}{n} \tag{K.3}$$

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:

$$\sigma = \frac{\text{stdev}(\gamma)}{\sqrt{n}} = \frac{\sqrt{\frac{\sum \left(V_{\text{primary_est}} - V_{\text{primary}}\right)^2}{n}}}{\sqrt{n}} \tag{K.4}$$

If the root-sum-square of the average of differences (systemic deviation) and the standard uncertainty of wind speed differences (statistical deviation) does not exceed 0,1 m/s in any bin between 4 m/s and 12 m/s, the in-situ test has passed.

$$\delta = \sqrt{\gamma^2 + \sigma^2} < 0{,}1 \text{ m/s} \tag{K.5}$$

If the value δ is above 0,1 m/s in at least one bin and does not exceed 0,2 m/s in all bins between 4 m/s and 12 m/s, the uncertainty of the anemometer calibration $u_{VI,I}$ shall be increased at least to the maximum value of δ in the wind speed range 4 m/s to 12 m/s. If the value δ is larger than 0,2 m/s in any bin between 4 m/s and 12 m/s, the in-situ test should be shifted to an earlier period until δ does not exceed 0,2 m/s anymore. The power curve data

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after this period shall be rejected, and the uncertainty of the anemometer calibration $u_{VI,I}$ of the remaining power curve data shall be treated as in the case of no data rejection.

NOTE The in-situ test can be repeated often during the measurement campaign to aid in the identification of intermittent anemometer degradation.

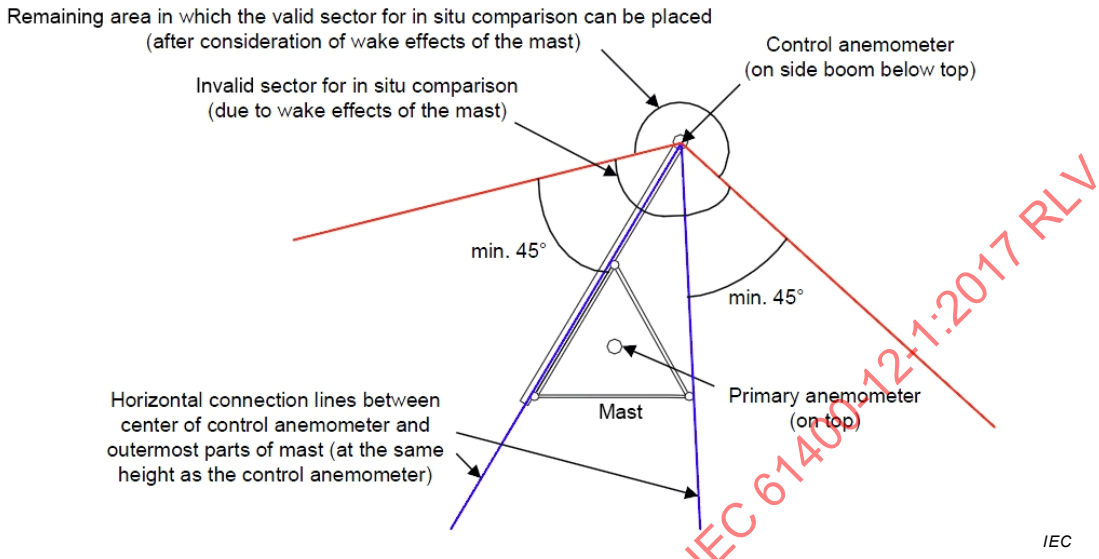

Figure K.1 – Example with triangular lattice meteorological mast

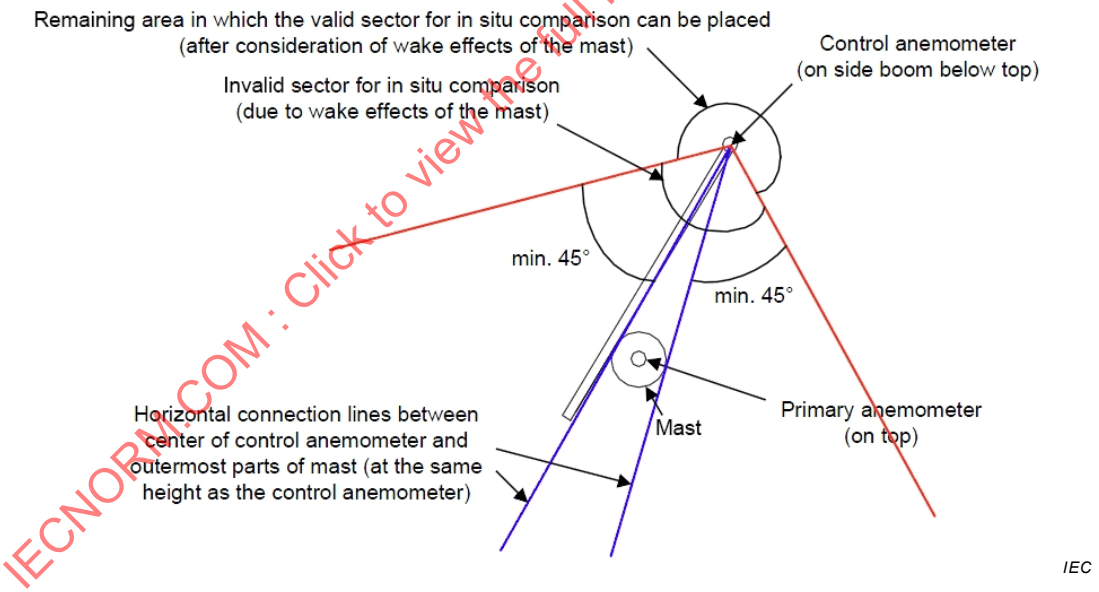

Figure K.2 – Example with tubular meteorological mast

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Annex L
(normative)

The application of remote sensing technology

L.1 General

Annex L describes the requirements for the operation of remote wind speed sensing devices such as light detection and ranging (LIDARS) and sound detection and ranging (SODARS) when deployed in relation to wind turbine power curve testing. A procedure is laid out that ensures the traceability of the measurements to international standards and presents associated uncertainty components for use in the power curve evaluation.

In the present version, the procedures pertain according to the following restrictions:

a) A meteorological mast reaching at least the minimum of 40 m or the lower tip height of the wind turbine being tested shall be used during the power curve test to monitor the performance of the remote sensing device (e.g. a lower rotor tip height of 30 m requires that a monitoring height of at least 30 m is used, while a lower rotor tip height of 50 m requires a monitoring meteorological mast at least 40 m high).

b) Only ground based remote sensing devices are used (e.g. nacelle mountings are not included).

c) The use of remote sensing for conducting power performance assessments is limited to flat terrain, that is, situations where site calibration is not required in accordance with Annex B.

When compared to measurements from a meteorological mast-mounted cup anemometer, remote sensing device measurements typically display some degree of scatter. Some of this scatter arises due to the sensitivity of the remote sensing device to various environmental conditions (e.g. temperature and wind shear). It is the task of the classification test (Clause L.2) to identify and quantify these sensitivities for a number of discrete heights covering the measuring range of interest. As for cup anemometers it is assumed that these sensitivities will be type specific and the classification test needs to be performed for each type of remote sensing device for a minimum of two instruments of each type and at a minimum of two locations.

The remaining scatter in the cup anemometer comparison is considered to be random noise. This arises from a variety of sources. For example, the turbulent de-correlation in the wind due to the distance between the meteorological masts leads to scatter. Also, the distance between the individual probe volumes of the remote sensor itself could contribute to such scatter. The random noise is assumed to be unit and site specific, i.e. it can vary between different evaluations of the same remote sensing device.

Before being used in a power curve test, a particular unit of a remote sensing device shall first undergo a verification test (Clause L.3). As an alternative, the verification test can also be performed during the power curve test. This test is a comparison of the remote sensing device measurements to those from calibrated cup anemometers mounted on a meteorological mast spanning a significant portion of the height range of interest. The purpose of this test is to convey traceability to international standards to this particular device, in the form of an uncertainty. Usually the power curve test will take place at a different location and at a different time and therefore with a different distribution of environmental conditions than for the verification test. Depending on the sensitivities identified during the classification test, the different environmental conditions will alter the performance of the remote sensing device, increasing the uncertainty in relation to that determined in the verification test. Expressions for the uncertainty of the remote sensing device and how these should be used in the evaluation of the power curve uncertainty are given in Clause L.4.

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Clause L.5 describes how the cup anemometer measurements from the short meteorological mast can be used to monitor the performance of the remote sensing device. By ensuring at least one common measuring height, it is possible to assess whether the uncertainty obtained in the classification and the verification test is consistent with the performance of the remote sensing device during the power curve test. If inconsistencies are identified from this monitoring, the corresponding uncertainties used in the power curve test are increased. This provides a useful 'safety net' for the methodology and a feedback mechanism that should promote realistic uncertainty assessments.

Specific details of how to use the remote sensing device in the power curve test are given in Clause L.6. Of particular relevance are the position and dimensions of the remote sensing device's probe volumes in relation to the wind turbine being tested.

Reporting requirements for the complete methodology are given in Clause L.7.

L.2 Classification of remote sensing devices

L.2.1 General

The accuracy of the RSD may be influenced by meteorological variables. As the meteorological conditions during the power curve test may be different from those prevailing during the RSD performance verification test, such influences are linked to additional uncertainty. It is therefore necessary to investigate the sensitivity of the performance of the remote sensing device to meteorological variables. The results of such tests shall identify the variables that influence the performance of the remote sensing device and determine the classification of the instrument.

The simplest of these evaluations entails considering the difference between the remote sensing device measurement and a reference measurement as function of one meteorological variable at a time. An accuracy class of the remote sensing device shall be evaluated for certain ranges of various environmental variables similar to the classification of cup anemometers according to Annex I based on the empirical analysis of the sensitivities observed during classification tests. Care should be taken to allow for the possible interdependency of environmental variables (e.g. wind shear and turbulence intensity) so that sensitivities are not inadvertently double counted. The uncertainties arising due to remote sensing device classification can then be evaluated.

A case-specific accuracy class may also be evaluated based on the sensitivities of the remote sensing system and the variation of the environmental variables observed during the performance verification and power curve tests. It should be clearly stated whether a classification result has been derived generically on multiple units or whether it is based on a case-specific evaluation.

L.2.2 Data acquisition

The classification test is based on concurrent measurements obtained by the remote sensing device and a high reference meteorological mast with which it is compared. The measurements will be co-located, such that they characterise flow within the same volume of air. The degrees of concurrency and co-location that shall apply to the measurements are those that enable the determination of the most precise and well understood relationship between them. In particular:

a) The same averaging intervals shall be used for the remote sensing device and reference sensor being compared: 10 min averages shall be recorded. In addition to 10 min averages, the standard deviations and extreme values of the measured variables within the 10 min periods shall be recorded.

b) The number of samples acquired by each instrument during each averaging interval to obtain an average shall be recorded.

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c) It shall be noted whether the individual samples acquired within the averaging interval by the remote sensing device are cumulative values, representing, for example, a spectrum integrated from the beginning of the averaging interval to the moment at which the sample is acquired. This will have a bearing on statistics that require successive samples to be independent, such as standard deviation used in, for example, turbulence assessments.

d) The device is sited and analysis of the measurements conducted in a manner that minimises extraneous influences on the relationship between the remote sensing device and reference sensor measurements. These influences may include, but are not limited to: flow perturbations; fixed echoes; real variations in the flow between the remote sensing device measurement volume and the reference instrument measurement location. The distance between the meteorological mast and the remote sensing device shall be a compromise allowing good correlation between meteorological mast and remote sensing device measurements while at the same time preventing or limiting the influence of the meteorological mast on the remote sensing device.

e) The meteorological mast-mounted reference sensors shall comply to the requirements of this standard. This applies especially to the calibration, classification and mounting.

f) The reference meteorological mast should preferably have a constant cross section and solidity across its height. In this way the influence of the meteorological mast on boom-mounted anemometers remains constant with height and allows a more accurate comparison of the measured wind shear between the meteorological mast and the remote sensing device.

The remote sensing device and reference sensors will be synchronised to within 1 % of the averaging interval, and this degree of synchronisation will be verified and tested for drift at least once a week. If comparison of time stamps indicates drift has occurred, the remote sensing device system clock will be reset to synchronise with the reference sensor system clock and remote sensing data time stamps adjusted to compensate for the drift over the period during which it is evident by linear interpolation. Data will be acquired until the following data coverage requirements are fulfilled:

a) Reference sensor wind speed measurements will be binned into 0,5 m/s bins centred on integer multiples of 0,5 m/s.

b) The data will be filtered according to the recommendations of the device manufacturer and the requirements of L.2.3. The following requirements shall be fulfilled after filtering.

c) The data acquisition requirements of a classification test shall not be considered fulfilled unless at least 3 pairs of valid concurrent, co-located and filtered measurements have been recorded in each wind speed bin centred between 4 m/s and 16 m/s inclusive.

d) The amount of acquired data shall cover a minimum of 180 h.

e) The duration of the data acquisition campaign will last at least 3 months and cover a significant span of environmental conditions (e.g. winter to summer). The database shall cover at least 25 % of the bins as described in Table L.3 with a minimum number of data points as defined in Equation (L.2) for all variables which are known to influence the accuracy of the RSD.

A remote sensing device classification and verification shall be considered valid for the purposes of a power curve test of a wind turbine if the reference cup anemometers used during the classification and verification tests were mounted at a minimum of 3 heights, including the lower tip height of the wind turbine ± 25 % and the hub height of the wind turbine ± 25 %. These height requirements for the classification and verification apply if the device is used for wind measurements over the entire height range of the wind turbine rotor or only for wind measurements up to hub height.

L.2.3 Data preparation

The following data filters shall be applied:

a) The reference meteorological mast shall be free of wakes from wind turbines and obstacles as defined in Annex A.

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b) Probe volumes within which the remote sensing device acquires a radial velocity measurement shall be free of wakes and flow perturbation from wind turbines and obstacles as defined in Annex A. The influence of the wake of the reference meteorological mast on the measurements of the remote sensing device shall be inspected by plotting the ratio of the remote sensing device and reference sensor measurements as a function of wind direction. Criteria regarding the permissible values of this ratio may be developed with reference to the corresponding considerations for cup anemometry discussed in Clause G.4. Remote sensing device measurements shall be excluded if they are influenced by either the meteorological mast or its guy wires.

c) Reference cup anemometers shall be free from the influence of the wakes of the meteorological mast, its guy wires or lightning receptor as defined in this standard.

d) The reference cup anemometers shall not be influenced by icing. This may be achieved by any means deemed to be suitable subject to the requirement that the method and results are adequately documented.

e) The measurements that are recorded for each averaging interval by both the remote sensing device and reference sensors will represent a single contiguous period of operation whose duration equals the averaging interval. However, as discussed below in L.2.4, there is a possibility that the data availability requirements may be relaxed. The influence that relaxing these requirements could have on the measurement accuracy should be checked by means of a sensitivity analysis. If the remote sensing device does not record the proportion of the period in the 10 min averaging interval during which it has been available, a general quality factor shall be recorded to indicate the reliability of the measurement in a similar manner as device availability. Data may then be filtered or a sensitivity analysis may be performed with reference to the quality factor. Guidance shall be provided by the manufacturer regarding the appropriate treatment of the quality factor;

f) In general no filtering on precipitation should be undertaken. Precipitation should be treated as an environmental variable in the classification test. If a remote sensing device manufacturer's guidelines make provision for filtering with reference to precipitation, these guidelines should be followed. If filtering is undertaken with reference to precipitation, the filtered data should be considered a special dataset and classification, verification and application of the remote sensing device be conducted in a manner consistent with this.

Measurements of boom-mounted reference sensors may be corrected for meteorological mast effects (blockage effects and flow acceleration effects). It should be noted that such correction of meteorological mast effects incurs additional uncertainty in comparison with top mounted reference sensors. The correction may be achieved by any means deemed suitable for reducing the total uncertainty, subject to the requirement that the method and results are adequately documented. Uncertainty associated with the use of boom-mounted anemometers is discussed in Annex D and Clause G.4.

All filtering criteria that are used, and their respective effects on the dataset, shall be recorded and reported.

L.2.4 Principle and requirements of a sensitivity test

The deviation observed between the measurements of the remote sensing device and the reference sensors shall be analysed in terms of their sensitivity to different environmental variables. Depending on the use of the remote sensing device in the power curve test campaign, the accuracy class shall be evaluated in terms of the absolute measurement of the horizontal wind speed component.

An accuracy class of the remote sensing device for alternative applications that entail the acquisition of other wind flow parameters (e.g. turbulence intensity or wind direction) may be derived in terms of the sensitivity of measurements of those parameters to different environmental variables, using suitable reference instrumentation. This is beyond the scope of

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a simple[47] power curve test, and only the evaluation of accuracy class in terms of horizontal wind speed is treated here.

The initial sensitivity to be tested shall relate to the relaxation of the criterion described in item e) in L.2.3. The sensitivity of the deviation between the reference sensors and the remote sensing device on the availability of the remote sensing device within the averaging interval or the corresponding quality factor of the measurements (as defined by the manufacturer) shall be examined. Remote sensing data shall be deemed acceptable if characterised by a level of availability or by a quality factor that has been demonstrated to have no significant influence on the deviation between the reference sensors and the remote sensing device measurements.

The percentage deviation between 10 min averages of the output parameter under consideration acquired by the remote sensing device (RSD) and reference sensors at one height level is considered as a dependent variable which is analysed as a function of one environmental variable by means of a classification test:

$$\text{Dependent variable:} \quad \frac{(v_{\text{RSD}} - v_{\text{reference}})}{v_{\text{reference}}} \times 100\,\% \tag{L.1}$$

All available environmental variables are considered to be potentially within the scope of the sensitivity analysis. A non-exhaustive list of variables to consider can be: wind shear exponent, turbulence intensity, rain, wind direction, air temperature, air density, temperature difference at two different heights, upflow angle, wind veer, and cloud cover. Some relevant parameters may be instrument-specific, for example data availability or quality factor, and may be specified by the manufacturer.

Sensitivity to an environmental parameter can be an artefact of an easily remedied error in the configuration of the remote sensing device. For example, a marked sensitivity to wind shear can arise when there is a systematic error in the heights associated with the remote sensing device wind speed measurements. If a strong sensitivity is observed with a remote sensing device, or a significant variation in sensitivity between tests is observed, the device should be checked for such errors. If errors are detected and corrected, the sensitivity tests should be repeated.

Where the reference cup anemometer exhibits a known sensitivity to an environmental variable, an attempt should be made to remove the influence of this sensitivity from the sensitivity test. This may be done by any means deemed to be suitable with the requirement that the method and results are adequately documented. As an example, Figure J.1 shows the effect of upflow angle on wind speeds measured by a commonly used class 1,7A cup anemometer as determined from industry standard wind tunnel tests.

Figure L.1 a) shows the response of a remote sensing device to upflow angle determined with respect to data from a cup anemometer of the type represented by Figure J.1. In Figure L.1 b) a linear model has been fitted to the data in Figure J.1 in the region between ± 3º and used to adjust the data points to remove the effect of the cup anemometer response. It can be seen from the figure that the sensitivity recorded for the remote sensing device in Figure L.1 a) in this case is at least partially attributable to the reference cup anemometer.

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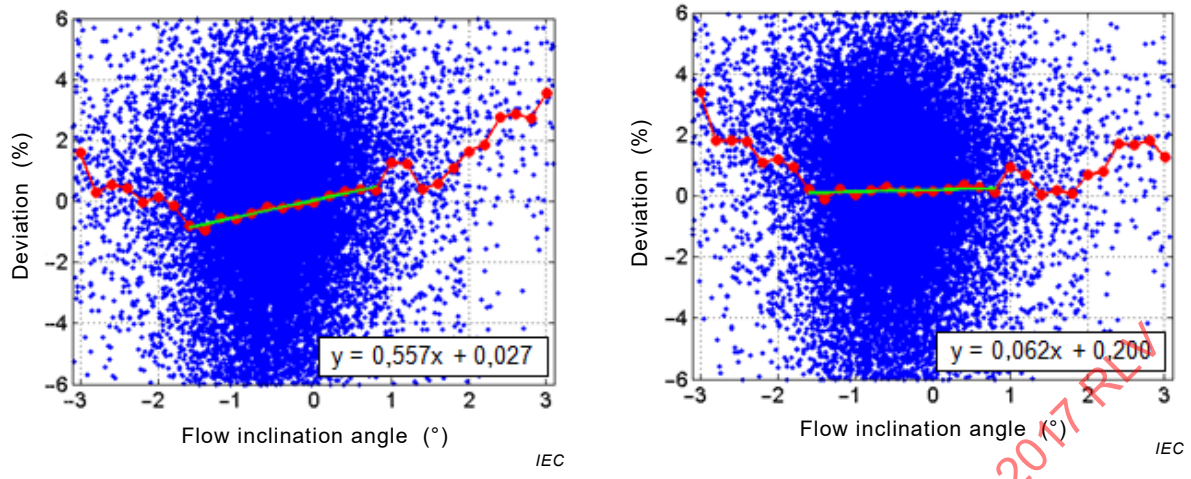
47 For example, a test that does not incorporate wind veer correction or turbulence normalisation.



a) before adjustment for cup anemometer response **b) after adjustment for cup anemometer response**

Figure L.1 – Deviation vs upflow angle determined for a remote sensing device with respect to the cup anemometer in Figure L.1

Environmental variables shall be analysed to identify any interdependency. Where this exists, further analysis shall be undertaken to identify which of the environmental variables influences measurement deviation. This may be done by any means deemed to be suitable with the requirement that the method and results are adequately documented. Documentation should include sufficient detail for the replication of results from the data acquired during the classification test. Suggested methodologies for achieving this are detailed in L.2.6. Only environmental variables found to have a direct influence on measurement deviation are to be included in the sensitivity analysis. These variables are then considered to be independent.

If any environmental variables that are known to directly influence measurement deviation are omitted from the sensitivity test, this is likely to result in additional uncertainty at the application stage, as defined in Clause L.5. If subsequent monitoring of the remote sensing device with a short anemometer meteorological mast during the power curve test shows the results of the sensitivity test have been unduly conservative, revision of the environmental variables included in the sensitivity test may be required.

A one-dimensional, two-parametric ordinary least squares (OLS) linear regression analysis shall be performed for each pair of dependent and independent variables. The following parameters are calculated from the regression analysis:

a) slope: m;

b) offset: c;

c) coefficient of determination, which in the case of OLS linear regression is the correlation coefficient: r^2;

d) standard deviation of the independent variable: std;

e) mean value of the independent variable: avg.

The estimation of the slope m and the offset c shall be performed on bin-averaged data for the measured environmental variable, where the size of the bin to be used is given in Table L.1.

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Table L.1 – Bin width example for a list of environmental variables

Independent variable	Bin width	Unit
Wind shear exponent	0,05	Dimensionless
Turbulence intensity	0,01	Dimensionless
Rain	0,1	mm
Remote sensing device availability	1	%
Wind direction	5	°
Air temperature	2	°C
Air density	0,05	kgm^{-3}
Temperature gradient	0,002	K/m
Upflow	0,2	°
Wind veer gradient	0,04	°/m

For variables to be included in the sensitivity analysis that are not listed in Table L.1, suitable bin widths should be chosen with respect to range and distribution of the data.

For a specific environmental variable, bins should only be included in the sensitivity test where they meet the criteria listed in Equations (L.2) and (L.3):

$$n_i > \frac{N}{2n_b} \tag{L.2}$$

where

n_b is the number of bins according to the ranges of variables given in Table L.3;

N is the total number of data points;

n_i is the number of data points in bin i.

Equations (L.3) is to be applied only when sensitivities on the wind speed measurement are analysed:

$$\frac{\sigma(d_i)}{\sqrt{n_i}} \frac{v_{\text{ref},i}}{100} < 0{,}03\,\text{m/s} \tag{L.3}$$

where

d_i is the data in bin i;

$\sigma(d_i)$ is the standard deviation of the percentage wind speed deviations of the ten minute data in bin i;

$V_{\text{ref},i}$ is the mean value of the reference wind speed in bin i.

The correlation coefficient (r^2), standard deviation of the independent variables (std) *and* mean value of the independent variables (avg) shall be estimated using the 10 min data in the bins included in the sensitivity test.

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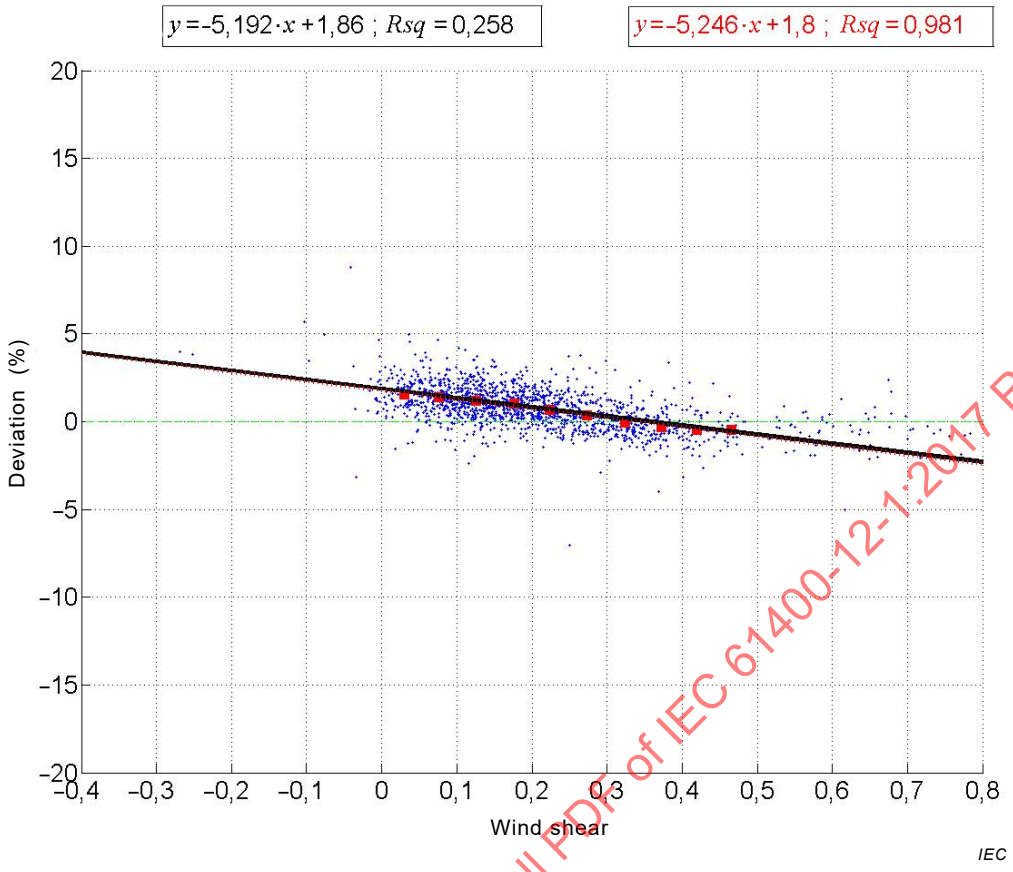

Linear regressions are plotted for 10 min data (black) and for bin-averaged data (red).

Figure L.2 – Example of sensitivity analysis against wind shear

Sensitivity is defined as the slope multiplied by the standard deviation of the independent variable: $m \cdot std$. The sensitivity indicates the extent, expressed as a percentage, that the deviation between the remote sensing device and the reference sensor measurements is changed by a change in the independent variable of one standard deviation.

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Table L.2 – Parameters derived from a sensitivity analysis of a remote sensing device

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[%]	[-]	[%]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Turbulence intensity	0,07	0,03	8,855	0,26	0,08	0,074
104		0,07	0,03	13,902	0,39	0,093	0,119
72		0,08	0,03	15,812	0,4	0,133	0,146
135	Rain (yes=1, no=0)	0,02	0,13	0,205	0,03	0,001	0,001
104		0,04	0,19	1,168	0,22	0,028	0,037
72		0,03	0,18	0,499	0,09	0,007	0,008
135	Wind direction	247,28	31,62	–0,007	–0,22	0,059	–0,053
104		252,83	34,19	0,012	0,43	0,108	0,141
72		225,14	11,39	0,003	0,03	0,001	0,001
135	Air temperature at 131 m	14,66	2,7	0,044	0,12	0,016	0,015
104		14,56	2,66	–0,042	–0,11	0,008	–0,010
72		15,16	3,43	–0,091	–0,31	0,083	–0,089
135	Air density	1,23	0,01	–16,43	–0,24	0,065	–0,061
104		1,23	0,01	1,804	0,03	0	0,000
72		1,22	0,02	5,208	0,08	0,005	0,006
135	Temperature difference between 133 m and 10 m	–0,69	1,36	–0,112	–0,15	0,027	–0,025
104		–0,69	1,36	–0,444	–0,6	0,217	–0,279
72		–0,64	1,53	–0,281	–0,43	0,158	–0,171
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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An example of a sensitivity analysis of a remote sensing device conducted with respect to a variety of environmental parameters is shown above in Figure L.2 and Table L.2. The sensitivity of the device has been analysed at three different heights. Only remote sensing data with availability within the averaging interval of 80 % or more have been considered for the test. As can be seen from Table L.2, and following significance criteria that are defined in L.2.5, the wind shear, turbulence intensity, wind direction, air temperature difference (as simple indicator for stratification), upflow angle and wind veer appear to have a significant influence on the deviation between the remote sensing and reference cup anemometer measurements of wind speed. The other independent variables appear not to be significant. However some variables that appear to influence the performance of the remote sensing device might not have an influence. If their variation is correlated with the variation of some other variables that also have an influence, this correlation may be the reason for their apparent influence. Interdependency between variables shall be analysed to identify which variables exert a genuine meaningful influence as discussed in L.2.6 before estimating the

final accuracy class of the remote sensing device. For example, multivariate regression techniques may be employed to achieve this.

The classification is analogous to the existing classification of cup and sonic anemometers according to this standard as laid out in Annex I and Annex J. The remote sensing device class can be evaluated for either pre-defined conditions or for the specific conditions prevailing during the application of the remote sensing device.

Conditions analogous to the A-classification of cup and sonic anemometry according to this standard as laid out in Annex I and Annex J are presented in Table L.3.

Table L.3 – Ranges of environmental parameters for sensitivity analysis

Independent variable		Max	Min	Range	Source
Wind shear exponent	[-]	0,80	–0,40	1,20	N/A
Turbulence intensity	[-]	0,24	0,03	0,21	This standard
Rain (yes=1, no=0)	[-]	1	0	1	Definition of sensor
Availability	[%]	100	80	20	Definition of filter
Wind direction	[°]	360	0	180	Deviation of 2 directions has a maximum of 180°
Air temperature	[°C]	40	0	40	This standard
Air density	[kg/m^3]	1,35	0,90	0,45	This standard
Temperature gradient From 133 m to 10 m height	[K/m]	0,06	–0,02	0,08	N/A
Upflow angle	[°]	3	–3	6	This standard
Wind veer from 133 m to 35 m height	[°/m]	0,2	–0,2	0,4	N/A

The availability range of the remote sensing device shall be consistent with the range to be applied during deployment in the field. Unless otherwise determined by the configuration of the reference sensors, the limits of the air temperature difference observed between the two height levels indicated shall be 10 times the standard lapse rate between the considered height levels (the standard lapse rate is 0,65 K/100 m) and the wind veer range shall be 4 times the standard deviation of the difference between the 10 minute average wind directions at the heights indicated.

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L.2.5 Assessment of environmental variable significance

The significance of a variable is assessed by measuring its degree of influence on the remote sensing device measurement. The sensitivity tests may indicate that no significant relationship exists between the dependent variable and some of the independent variables. Therefore only relevant independent variables shall be considered. Relevance is determined where:

a) a sensitivity of at least 0,5 is demonstrated or a product of correlation coefficient r and sensitivity of at least 0,1 is found;

b) the sensitivity analysis of an independent variable shall be relevant for all measurement heights if one of the above conditions is fulfilled for a single height.

For a sensitivity of 0,5 or more a significant influence of the independent variable on the accuracy of the remote sensing device is directly measured during the classification test. The correlation coefficient may modify this criterion as it indicates the significance of the relationship between the dependent and independent variables. The correlation coefficient and the sensitivity both indicate the relevance of an independent variable. Thus the product of both measures defines the second, alternative condition in the first item above.

Environmental variables for which the measured range does not cover at least 25 % of the bins as described in Table L.3 with a minimum number of data points as defined by Equation (L.2) should be excluded from the sensitivity analysis. Sensitivity results derived for these variables would be unrepresentative of any relationship with measurement deviation. Although a variable may be eliminated from the sensitivity analysis due to insufficient variation for the reliable establishment of a relationship with measurement deviation, it may be the case that a wider range of variation is observed during application of the device in the course of the power performance test. If the variable in question is found to have an influence on measurement deviation through the monitoring process during application, the device may be rejected. Alternatively, the additional uncertainty will be applied to the results to adequately reflect this, following Clause L.4. Environmental variables that are determined to influence measurement deviation only through their correlation with other environmental variables, as discussed in L.2.6, should be excluded from the sensitivity analysis.

The selection of relevant independent variables for a remote sensing device is illustrated in Table L.4.

Table L.4 – Example selection of environmental variables found to have a significant influence

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[%]	[-]	[%]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Turbulence intensity	0,07	0,03	8,855	0,26	0,08	0,074
104		0,07	0,03	13,902	0,39	0,093	0,119
72		0,08	0,03	15,812	0,4	0,133	0,146
135	Wind direction	247,28	31,62	–0,007	–0,22	0,059	–0,053
104		252,83	34,19	0,012	0,43	0,108	0,141
72		225,14	11,39	0,003	0,03	0,001	0,001
135	Temperature difference between 133 m and 10 m	–0,69	1,36	–0,112	–0,15	0,027	–0,025
104		–0,69	1,36	–0,444	–0,6	0,217	–0,279
72		–0,64	1,53	–0,281	–0,43	0,158	–0,171
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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L.2.6 Assessment of interdependency between environmental variables

The sensitivity analysis in L.2.4 makes the assumption that the environmental variables under consideration are independent, i.e. uncorrelated. In practice this may not be the case. This can lead to entries being registered in the accuracy class for specific variables due to their correlation with other variables rather than through any direct relationship with measurement deviation. An illustration of the effect of correlation between environmental variables can be seen in Figure L.3 and Figure L.4 for wind shear and turbulence intensity. Figure L.3 shows

the relationship between wind shear and turbulence intensity during a classification test. It can be seen that wind shear and turbulence intensity at this test site are not entirely uncorrelated during the measurement period in question. This manifests itself in Figure L.4 as a clustering of the data points within the scatter plot of measurement deviation against turbulence intensity according to the magnitude of the wind shear. This clustering may skew the line fit from which the sensitivity of the device with respect to turbulence intensity is determined. Through this mechanism a relationship in the sensitivity test can be transferred from an environmental variable that is directly correlated to measurement deviation to one that is not if the environmental variables are not mutually independent.

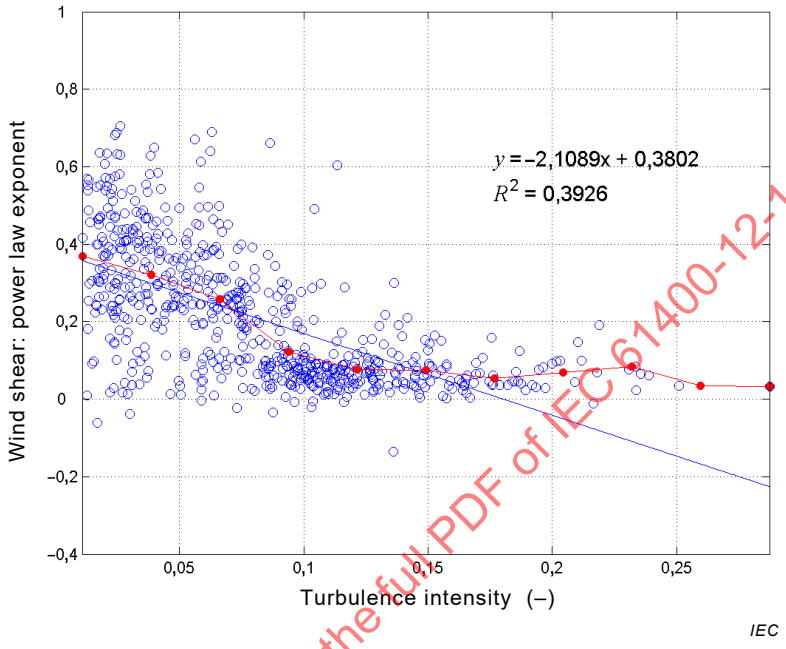
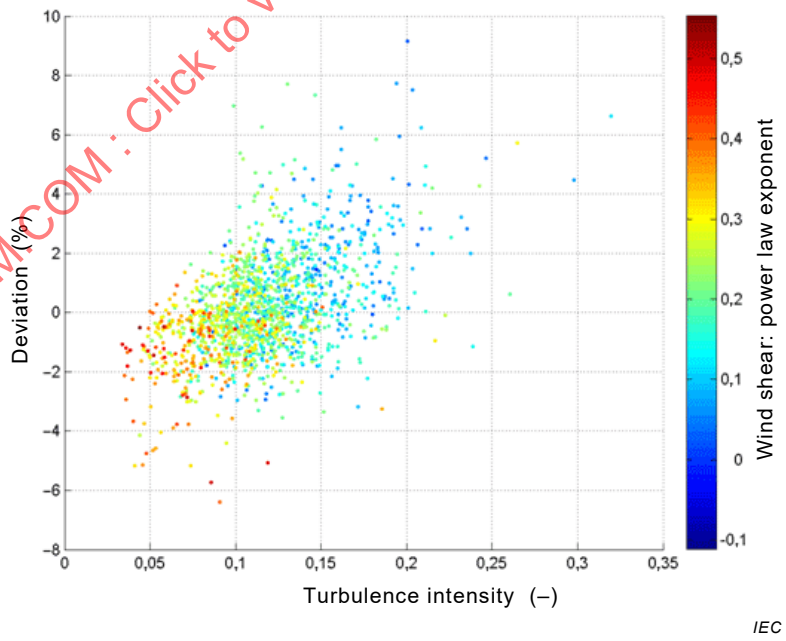


Figure L.3 – Example of wind shear versus turbulence intensity



The colour indicates the wind shear.

Figure L.4 – Example of percentage deviation of remote sensing device and reference sensor measurements versus turbulence intensity

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In order to mitigate over estimation of uncertainty, it is necessary to eliminate from the sensitivity analysis any correlated environmental variables that can be demonstrated not to directly influence measurement deviation. An example is shown in Figure L.4, where it is clear the inclusion of both turbulence intensity and wind shear in the calculation of the uncertainty estimate would result in "double counting" of uncertainty contributions due to the relationship evident between them. The elimination of correlated environmental variables may be done by any means deemed suitable with the requirement that the method and results are adequately documented, as discussed in L.2.4. Documentation should include sufficient detail for the replication of results from the data acquired during the classification test.

Dependencies between environmental variables have been analysed for the data used in Table L.4. Variables that do not have a direct influence on the measurement deviation that are correlated with one or more variables that do have a direct influence on measurement deviation have been eliminated from the sensitivity test. After removing the effect of the wind shear from the dataset, the remaining influence of the turbulence intensity was not relevant. The remaining variables are shown in Table L.5. Only wind shear, upflow angle and wind veer appear to have a significant influence on the deviation between the remote sensing and reference cup anemometer wind speed measurements.

Table L.5 – Sensitivity analysis parameters remaining after analysis of interdependency of variables

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[-]	[-]	[-]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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L.2.7 Calculation of accuracy class

The general principle of the calculation of accuracy classes is as follows:

a) define ranges of all remaining variables having significant influence as described in the example of Table L.5;

b) calculate the maximum deviation of each independent variable on the accuracy of the remote sensing device by multiplication of the regression slope m and the range of the independent variable, as taken from Table L.3. An illustrative example is given in Table L.6;

c) calculate the accumulated maximum influence of all independent variables on the accuracy of the remote sensing device by considering the different variables as fully independent from each other, such that the maximum measurement errors caused by each individual variable are added in quadrature.

In relation to item c), it is acknowledged that the environmental variables under consideration are not fully independent from each other. However, with respect to uncertainty assessments, the differences between environmental conditions prevailing during the application of the remote sensing device for the purposes of the power curve test and during performance

verification is a key consideration. These differences are highly dependent on the power curve test site and on the RSD performance verification test site. This site dependency decouples the variables from each other with respect to uncertainty calculations. Therefore to estimate the accumulated maximum influence, independence between variables is a necessary assumption, despite the efforts undertaken in L.2.6 for addressing the interdependency of variables.

The preliminary accuracy classes resulting from this scheme are presented in Table L.7. These have been calculated as the sum in quadrature of the maximum deviations of both all and only the individual significant environmental variables according to Table L.6 and Table L.4. The values do not represent the final classification result.

Table L.6 – Example scheme for calculating maximum influence of environmental variables

Height above ground level	Independent variable	Range variable	*m*	*m* × range
[m]	[-]	[unit variable]	[%/unit variable]	[-]
135	Wind shear exponent	1,20	–2,324	2,79
104		1,20	–1,918	2,30
72		1,20	0,607	0,73
135	Turbulence intensity	0,21	8,855	1,86
104		0,21	13,902	2,92
72		0,21	15,812	3,32
135	Rain (yes=1, no=0)	1,00	0,205	0,21
104		1,00	1,168	1,17
72		1,00	0,499	0,50
135	Remote sensing device availability	20,00	0,017	0,34
104		20,00	–0,068	1,36
72		20,00	–0,318	6,37
135	Wind direction	180,00	–0,007	1,28
104		180,00	0,012	2,24
72		180,00	0,003	0,51
135	Air temperature at 131 m	40,00	0,044	1,76
104		40,00	–0,042	1,69
72		40,00	–0,091	3,65
135	Air density	0,45	–16,430	7,39
104		0,45	1,804	0,81
72		0,45	5,208	2,34
135	Temperature difference between 133 m and10 m	8,00	–0,112	0,90
104		8,00	–0,444	3,55
72		8,00	–0,281	2,25
135	Upflow angle	6,00	–0,085	0,51
72		6,00	0,665	3,99
135	Wind veer between 133 m and 35 m	40,00	–0,036	1,45
104		40,00	–0,070	2,81
72		40,00	–0,036	1,42

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Table L.7 – Preliminary accuracy classes of a remote sensing device considering both all and only the most significant influential variables

Height	Accuracy classes	
	Considering all variables	Considering only significant influential variables
[m]	[-]	[-]
135	8,6	3,2
104	7,1	3,6
72	9,7	4,3

To calculate the final accuracy class, the preliminary accuracy class shall be divided by √2. The maximum influences as calculated in Table L.6 are valid under the assumption that the performance verification test of the remote sensing device has been conducted at the one extreme of the ranges of all environmental variables while the power curve test is conducted at the opposite extreme, which is considered to be an unlikely scenario. A more likely assumption is that the variables x during both measurements lie close to the centre of the maximum range with a maximum deviation of half of the range:

$$x_{\text{application}} \in \left[x_{\text{centre}} - \frac{x_{\text{range}}}{2}; x_{\text{centre}} + \frac{x_{\text{range}}}{2} \right]$$

$$x_{\text{verification_test}} \in \left[x_{\text{centre}} - \frac{x_{\text{range}}}{2}; x_{\text{centre}} + \frac{x_{\text{range}}}{2} \right] \quad \text{(L.4)}$$

If the conditions during performance verification and the power curve test are considered independent of each other, the deviations of the environmental variables have the maximum ranges:

$$\mathrm{d}\left(x_{\text{application}} - x_{\text{verification_test}}\right) = \sqrt{\left(\frac{x_{\text{range}}}{2}\right)^2 + \left(\frac{x_{\text{range}}}{2}\right)^2} = \frac{x_{\text{range}}}{\sqrt{2}} \quad \text{(L.5)}$$

The resulting accuracy classes for the influences of variables given as examples in Table L.6 are shown in Table L.8.

Table L.8 – Example final accuracy classes of a remote sensing device

Height	Final accuracy class
[m]	[-]
135	2,3
104	2,5
72	3,0

L.2.8 Acceptance criteria

The classification test shall be performed for a minimum of two devices of the specific type of remote sensing device at a minimum of two different sites. This will enable type-specific classification, provided the results of these tests converge sufficiently. At least one of the test

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devices shall be tested at two different sites, resulting in a minimum of three tests required to achieve type classification.

If the results are too divergent an individual unit may be withdrawn on the assumption that it is malfunctioning and is therefore not representative of the instrument type. A withdrawal of a unit on these grounds is subject to the requirements stated above regarding the minimum number of individual units tested to derive a type-specific classification. A type-specific classification is not possible if the withdrawal of units on the grounds that they are malfunctioning results in an insufficient number of tested units. If units are withdrawn, consideration should be given to the number of units withdrawn compared to the number accepted as representative. The reason for withdrawal of a unit from the sensitivity test shall be well justified and reported.

Results of these classifications are considered to converge sufficiently if the order of magnitude of the influence of the environmental variables considered is coherent among the different classification tests (e.g. for each significant independent variable, the magnitude of the sensitivity derived from each individual test differs by no more than 50 % from the mean value).

L.2.9 Classification of RSD

The class is determined from a minimum of three classification tests (2 units at the same location and one unit at 2 different locations).

The final sensitivity slope should be used in Equation (L7) to calculate the uncertainty. The final slopes result from the combination of the slopes from the various classification tests as follow:

a) every significant independent variable resulting from every classification test should be considered (i.e. if a variable is found to be significant and independent in one test out of three, it should be considered in the final class).

b) for every significant independent variable:

   1) interpolate the slope to the height of interest for every classification test,

   2) combine the slopes from the various classification test using Equation (I.3).

L.3 Verification of the performance of remote sensing devices

Measurements acquired by the remote sensing device shall be calibrated against concurrent and co-located measurements of the same wind flow parameters acquired by meteorological mast-mounted reference sensors which would have been deemed compliant for conducting a power curve test. Depending on the use of the remote sensing device in the power curve test campaign, the accuracy shall be evaluated in relation to those same remote sensing device output parameters considered during the classification test and which are relevant to the power curve test.

The calibration shall be conducted not earlier than one year prior to the start of the power curve test (or during the power performance test) for its results still to be considered valid in relation to the power curve test in which the remote sensing device is being deployed.

Regarding data acquisition and data preparation, the calibration test is conducted in the same way as the sensitivity analysis as described in L.2.2 and L.2.3, with the exception that criterion L.2.2 e) is relaxed, such that it is sufficient to acquire 180 h of data. The requirements on the heights of the reference sensors described in L.2.2 in relation to classification tests also apply to verification tests.

A bin average procedure shall be used to compare the measurements acquired using the remote sensing device and the reference sensors. The bin-wise deviation between the remote

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sensing device measurement and the measurement of the reference sensor is considered the key result. The width and centre of the bins shall be as follows[48]:

a) 0,5 m/s wide reference wind speed bins centred on multiple integers of 0,5 m/s shall be applied for the comparison of horizontal wind speeds and the comparison of standard deviation values of the horizontal wind speed;

b) 5° wide wind direction bins shall be applied for comparison of wind directions, centred on multiple integers of 5°.

The raw data, expressed as 10 min averages, shall be presented as a scatter plot of the measurements acquired by the remote sensing device against the measurements acquired by the reference sensor. In addition, the deviations between the remote sensing device measurements and reference measurements shall be plotted against the reference measurements. These shall be shown on the same plot, an example of which is shown in Figure L.5. For the first scatter plot, the correlation coefficient shall be computed. For the second scatter plot, the mean value and standard deviation of the deviations shall be computed. For both scatter plots, mean values and standard deviations per bin of the dependent variable shall be calculated (Table L.9).

The bin averages of the remote sensing measurements shall be plotted as a function of the bin averages of the reference sensor measurements (Figure L.6). A two-parameter ordinary least squares (OLS) linear regression shall be plotted through the data points that lie within the reference wind speed range 4 m/s to 16 m/s inclusive.

The total uncertainty of the remote sensing device remaining from its calibration test shall be assessed as described in L.4.3 (Figure L.6, Table L.9). The bin-averaged deviations of the RSD measurements and reference measurements shall be compared to the standard uncertainty of the calibration test reduced by the bin averaged deviations as given by the following expression where all components have consistent units:

$$\sqrt{u_{\mathrm{ver},i}^2 - \left(\overline{V}_{\mathrm{RSD},i} - \overline{V}_{\mathrm{Ref},i}\right)^2}$$

where

$\overline{V}_{\mathrm{RSD},i}$ bin average of RSD at calibration test in bin i;

$\overline{V}_{\mathrm{Ref},i}$ bin average of reference measurement at calibration test in bin i;

$u_{\mathrm{ver},i}$ standard uncertainty of calibration test in bin i according to L.4.3.

The wind speed measurements of the RSD may be corrected based on the calibration test results in order to remove a bias. Such a correction is recommended if the bin-averaged deviations exceed the above expression (at least in one bin). The wind speed correction may consist of a linear regression of the bin averaged reference sensor measurements versus the RSD measurements.

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48 Comparisons of parameters other than those listed may be desirable in the context of alternative applications of remote sensing. For example, 0,1 m/s wide bins may be used for the comparison of vertical wind speeds and the comparison of standard deviations of the horizontal wind speed, centred on multiple integers of 0,1 m/s, while 1 % (0,01) wide bins may be used for comparison of turbulence intensities, centred on multiple integers of 1 % (0,01).

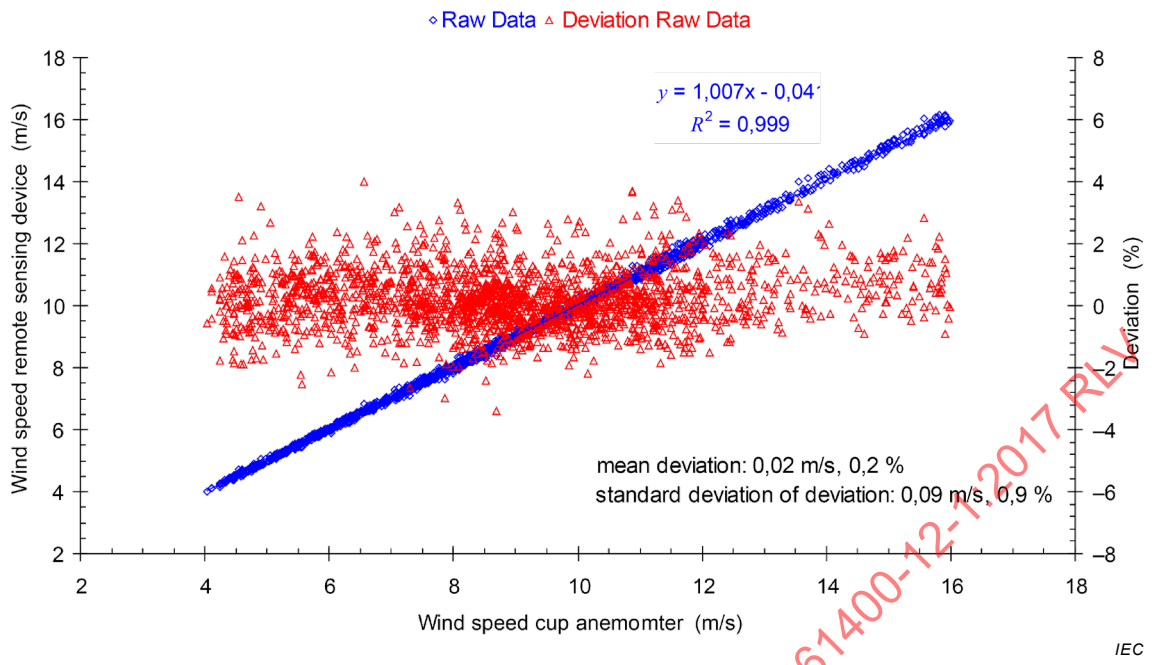

Figure L.5 – Comparison of 10 minute averages of the horizontal wind speed component as measured by a remote sensing device and a cup anemometer

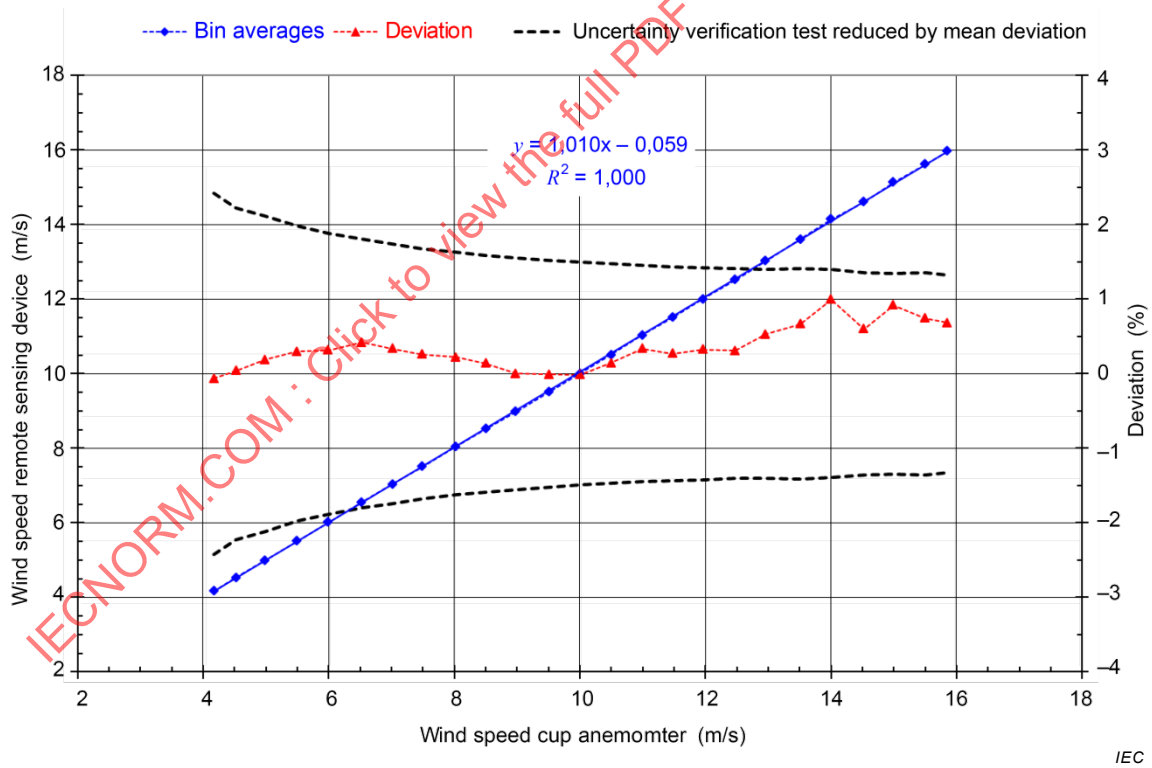

Figure L.6 – Bin-wise comparison of measurement of the horizontal wind speed component of a remote sensing device and a cup anemometer

The considerations discussed in L.2.4 in relation to errors and sensitivities detected during classification tests that are artefacts of incorrect remote sensing device configuration, in particular, the introduction of errors and sensitivities to wind shear as a result of incorrect assignment of measurement heights, should also be considered in the context of calibration tests, see reference [10].

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L.4 Evaluation of uncertainty of measurements of remote sensing devices

L.4.1 General

The following components shall be taken into account for the evaluation of the uncertainty of the measurements with remote sensing devices:

a) uncertainty resulting from the RSD calibration test according to L.4.3;

b) uncertainty resulting from the classification of the remote sensing device according to L.4.4;

c) uncertainty due to non-homogenous flow within the measurement volume of the remote sensing device according to L.4.5;

d) uncertainty due to mounting effects of the remote sensing device according to L.4.6;

e) uncertainty due to variation in flow across the power curve test site according to L.4.7;

f) a possible uncertainty due to unexpected results of the monitoring of the remote sensing device's accuracy on the application site according to Clause L.5.

The different uncertainty components shall be assumed to be independent from each other and shall be added in quadrature.

L.4.2 Reference uncertainty

The following uncertainty components are considered for the evaluation of the standard uncertainty of the reference sensor (in case of a cup anemometer) and shall be considered to be independent from each other and thus shall be added in quadrature:

a) wind tunnel calibration;

b) cup anemometer effects according to the anemometer classification;

c) cup anemometer mounting effects;

d) uncertainty of any applied meteorological mast correction to the reference cup anemometer measurements;

e) uncertainty in the data acquisition system of the reference instrument for the wind speed in bin i.

L.4.3 Uncertainty resulting from the RSD calibration test

The measurements of the remote sensing device are linked to the following systematic uncertainties (category B uncertainties) resulting from the calibration test, which shall be calculated for each bin of the measurement of the remote sensing device:

a) the standard uncertainty of the reference sensor according to L.4.2;

b) the mean deviation of the remote sensing device measurements and the reference sensor measurements. If a correction of the measurement of the remote sensing device is performed, the average deviation between the corrected measurements of the remote sensing device and the reference sensor measurements are evaluated;

c) the standard uncertainty of the measurement of the remote sensing device calculated as the standard deviation of the measurements divided by the square root of the number of data records per bin (category A uncertainty of calibration test);

d) uncertainty of the remote sensing device due to mounting effects during the calibration test;

e) uncertainty of the remote sensing device due to non-homogenous flow within the measurement volume during the calibration test according to L.4.5.

Site effects may be considered as an additional uncertainty if the remote sensing device and the reference sensor meteorological mast are separated from each other by a significant distance that compromises compliance with item L.2.2 d). In particular, an additional

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uncertainty in wind speed of 1 % times the separation distance divided by the measurement height shall be applied. The separation distance is the distance between the centroid of the measurement volume and the reference sensor being used for the test. The measurement height is the height at which the comparison between the reference sensor and the remote sensing device is being performed. This is not referred to the hub height or rotor diameter of the test wind turbine as these may not be known at the time the classification or calibration tests are being conducted. The additional uncertainties associated with similar issues arising during the power curve test due to the distance of the remote sensing device from the test wind turbine are discussed in L.4.7.

Uncertainties of the data acquisition system of the remote sensing device are automatically integrated in the calibration test results and shall not be considered additionally.

The different uncertainty components shall be assumed to be independent from each other and shall be added in quadrature for each wind speed bin. An example calculation is shown in Table L.9. The total category B uncertainty of the measurements of the remote sensing device resulting from the calibration test shall be taken into account as category B uncertainty of the power curve test in any case.

Table L.9 – Example of uncertainty calculations arising from calibration of a remote sensing device (RSD) in terms of systematic uncertainties

V_{cup}	V_{RSD}	Number of data sets	V_{RSD} max	V_{RSD} min	V_{RSD} std	V_{RSD} std/$\sqrt{n}$	Mean deviation	V_{cup} uncertainty	Mounting uncertainty RSD	V_{RSD} uncertainty
[m/s]	[m/s]	[-]	[m/s]	[m/s]	[m/s]	[m/s]	[%]	[%]	[%]	[%]
4,133	4,148	15	4,30	4,00	0,090	0,023	0,4	2,3	0,5	2,4
4,528	4,525	33	4,85	4,28	0,139	0,024	0,0	2,2	0,5	2,3
5,064	5,086	26	5,31	4,74	0,141	0,028	0,4	2,0	0,5	2,2
5,538	5,593	47	5,92	5,28	0,166	0,024	1,0	1,9	0,5	2,2
5,985	6,025	44	6,27	5,72	0,141	0,021	0,7	1,9	0,5	2,0
6,513	6,546	45	6,80	6,26	0,158	0,024	0,5	1,8	0,5	1,9
6,995	7,019	87	7,33	6,73	0,151	0,016	0,3	1,7	0,5	1,8
7,500	7,501	109	7,83	7,14	0,156	0,015	0,0	1,7	0,5	1,7
8,010	8,013	118	8,41	7,69	0,160	0,015	0,0	1,6	0,5	1,6
8,512	8,537	145	8,97	8,22	0,183	0,015	0,3	1,6	0,5	1,6
8,993	9,033	146	9,45	8,71	0,176	0,015	0,4	1,5	0,5	1,6
9,498	9,554	121	9,97	9,16	0,171	0,016	0,6	1,5	0,5	1,6
10,008	10,059	166	10,57	9,63	0,181	0,014	0,5	1,5	0,5	1,6
10,506	10,536	106	10,91	10,25	0,141	0,014	0,3	1,5	0,5	1,5
11,003	11,037	78	11,52	10,68	0,185	0,021	0,3	1,4	0,5	1,5
11,502	11,510	59	11,92	11,13	0,188	0,025	0,1	1,4	0,5	1,4
12,000	12,035	63	12,62	11,68	0,217	0,027	0,3	1,4	0,5	1,5
12,519	12,521	68	12,97	12,15	0,182	0,022	0,0	1,4	0,5	1,4
12,957	12,998	64	13,40	12,64	0,186	0,023	0,3	1,4	0,5	1,4
13,469	13,470	40	13,87	13,17	0,177	0,028	0,0	1,4	0,5	1,4
14,011	14,014	25	14,36	13,67	0,192	0,038	0,0	1,3	0,5	1,4
14,444	14,490	30	14,83	14,21	0,172	0,031	0,3	1,3	0,5	1,4
14,983	14,951	14	15,48	14,62	0,246	0,066	–0,2	1,3	0,5	1,4
15,509	15,585	17	15,92	15,38	0,135	0,033	0,5	1,3	0,5	1,4
15,990	16,038	16	16,24	15,77	0,130	0,032	0,3	1,3	0,5	1,4

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V_{cup}	V_{RSD}	Number of data sets	V_{RSD} max	V_{RSD} min	V_{RSD} std	V_{RSD} std/$\sqrt{n}$	Mean deviation	V_{cup} uncertainty	Mounting uncertainty RSD	V_{RSD} uncertainty
16,475	16,479	10	16,69	16,22	0,149	0,047	0,0	1,3	0,5	1,3
17,066	17,140	12	17,50	16,75	0,227	0,065	0,4	1,3	0,5	1,4
17,515	17,682	13	17,91	17,44	0,153	0,042	1,0	1,3	0,5	1,6
18,001	18,020	8	18,32	17,82	0,157	0,056	0,1	1,3	0,5	1,3
18,430	18,549	13	18,82	18,25	0,173	0,048	0,6	1,3	0,5	1,5
18,849	18,980	4	19,16	18,80	0,149	0,075	0,7	1,3	0,5	1,5
19,415	19,430	3	19,67	19,23	0,223	0,129	0,1	1,3	0,5	1,4
The uncertainty due to non-homogenous flow within the measurement volume is assumed to be zero.										

It is pointed out that the statistical standard uncertainty of the measurement of a remote sensing device related to single 10-minute averages of a measured variable as resulting from the calibration test is given by the standard deviation of the deviations of the measurements of the remote sensing device and the reference sensor. This uncertainty is significantly higher than the statistical uncertainty of the bin averages of the calibration test described in above bullet point c). However, the statistical uncertainty of single 10-minute averages is automatically included in the category A uncertainty of the bin averages of the evaluated power curve and shall therefore not be accounted for by additional means.

L.4.4 Uncertainty due to remote sensing device classification

Sensitivity of the device due to varying conditions introduces uncertainty due to the fact that the meteorological conditions during the application of the remote sensor may deviate from the meteorological conditions present during the calibration test. The standard uncertainty arising from the accuracy class as determined following L.2.7 will be the final accuracy class number divided by $\sqrt{3}$.

The accuracy class according to L.2.7 represents the maximum measurement error of the remote sensing device due to the influence of environmental conditions within each 10 min period (after the associated calibration test). This uncertainty includes uncertainties due to a variation of the environmental variables around its mean values as present at the power curve test in each wind speed bin. However, the uncertainty due to this variation of the environmental variables at the power curve test is of statistical nature and is fully reflected in the category A uncertainty of the bin averages of the power curve (category A uncertainty of the power curve) and should therefore not be accounted for as category B uncertainty of the wind speed measurement. The category B uncertainty of the wind speed measurement due to the influence of environmental variables on the performance of the remote sensing device should rather take into account only the deviations of the mean values of the environmental variables during the calibration test and the power curve test and should be calculated for each wind speed bin as:

$$u_{VR,\mathrm{class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \left| \bar{x}_{PC,j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)^2} \qquad \text{(L.6)}$$

where

$u_{VR,\mathrm{class},i}$ is category B standard uncertainty of wind speed measurement in wind speed bin i due to the influence of the environmental variables on the performance of the remote sensing device;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

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m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of the results from a minimum of 3 classification tests;

$\bar{x}_{PC,j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the power curve test;

$\bar{x}_{\text{ver},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the calibration test of the remote sensing device.

For relevant environmental variables not measured during the power curve test, the maximum range of that variable as present at the power curve test shall be estimated, and the deviation of the mean values of the environmental variables during the power curve test and during the calibration test in the above equation shall be replaced by the expected maximum absolute deviation of that variable as present during the power curve test from its mean value present during the calibration test divided by $\sqrt{3}$. However, as the classification derivation is based on the assumption of a linear response to perturbations in the independent variables, where the maximum and minimum values of the independent variables during the power curve or calibration test exceed the ranges obtained during the classification sensitivity tests, care should be taken when interpreting the classification uncertainty result. If the calibration test includes the same data as the power curve test, the uncertainty according to L.4.4, becomes equal to zero.

L.4.5 Uncertainty due to non-homogenous flow within the measurement volume

Many remote wind sensing devices assume equivalent wind conditions in regions within the measurement volume that have significant spatial separation. This assumption can be violated in complex terrain. Even in terrain not classified as complex according to this standard, significant errors can occur due to the non-homogeneity of the flow. The uncertainty linked to the assumption of equivalent wind conditions in spatially separated probe volumes shall be assessed. Remote sensing devices should be subject to a rigorous and thorough analysis of the influence of non-uniform flow on measurement bias with reference to their particular configuration.

For example, the combination of a suitable flow model and a model reproducing the remote sensing device horizontal wind speed extraction algorithm might be used to assess the uncertainty due to non-homogeneous flow.

A simplified alternative to estimate this uncertainty applicable to many monostatic systems implemented by observations of the Doppler effect is given by the method used by Bingöl et al., reference [11], with extensions by Albers *et al.*, reference [12].

The user should consult with the remote sensing device manufacturer for the best method for evaluating the uncertainty for their specific device at the test site.

L.4.6 Uncertainty due to mounting effects

The uncertainty of the remote sensing device due to non-ideal levelling of the device shall be estimated. The uncertainty is highly dependent on the type of instrument being used.

L.4.7 Uncertainty due to variation in flow across the site

The same uncertainty as in the application of a mast shall be assumed for this uncertainty, i.e. a standard uncertainty of 2 % in terms of the horizontal wind speed component for a distance range of 2 to 3 rotor diameters and a standard uncertainty of 3 % for a distance range above 3 rotor diameters. When an RSD is used, it is the horizontal distance between the centre of the probe volume of the remote sensing device and the position of the test turbine that shall be considered.

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L.5 Additional checks

L.5.1 Monitoring the performance of the remote sensing device at the application site

A meteorological mast reaching at least the minimum of 40 m or the lower tip height of the tested wind turbine shall be applied at the power curve test for monitoring the performance of the remote sensing device. The set-up of the meteorological mast and the remote sensing device and the data preparation shall comply with the requirements described in L.2.2 and L.2.3 with the exception that the meteorological mast has only a relatively small height and may be equipped with reference sensors only at the top of the meteorological mast. The data analysis described in L.5.1 to L.5.3 shall be undertaken.

L.5.2 Identification of malfunctioning of the remote sensing device

Time series plots of the wind measurements (wind speed and wind direction) performed with the meteorological mast shall be compared to time series plots of the measurements of the respective wind measurements of the remote sensing device. In addition scatter plots of the measurements of the wind speed and wind direction of the remote sensing device versus the respective measurements with the meteorological mast shall be inspected. Periods with obvious outlier data or other anomalies shall be excluded from the power curve test.

L.5.3 Consistency check of the assessment of the remote sensing device systematic uncertainties

Note that this subclause does not apply if the RSD calibration is done simultaneously with the power performance measurement. The comparison and analysis of the measurements of the remote sensing device and the reference sensors at common measurement heights as performed for a calibration test according to Clause L.3 shall be repeated with the meteorological mast at the power curve test site for the full duration of the power curve measurement period. It is expected that the absolute value of the mean deviation of the measurements of the remote sensing device and the reference sensor per wind speed bin at the power curve test does not exceed the square root of the sum of the squares of the following uncertainty components:

a) the category B standard uncertainty of the measurement of the remote sensing device resulting from the calibration test performed prior to the power curve test assessed in full accordance with L.4.3;

b) systematic effects of environmental variables on the performance of the remote sensing device at the power curve test as assessed according to the equation given in L.4.4, taking into account only mean deviations of the influential environmental variables at the power curve test and the calibration measurement prior to the power curve test.

If the absolute value of the mean deviation of the measurements of the remote sensing device and the reference sensor exceeds this expectation in a certain wind speed bin, the difference of the true and expected deviation is considered an additional category B uncertainty component of the measurement of the remote sensing device at the power curve test in that wind speed bin. For the measurement heights of the remote sensing device not captured by the meteorological mast at the power curve test site, this additional uncertainty shall be calculated as follows:

$$u_{\text{added_systematic},j,i} = u_{\text{added_systematic},1,i} \frac{u_{\text{systematic},j,i}}{u_{\text{systematic},1,i}} \quad \text{(L.7)}$$

where

$u_{\text{added_systematic},j,i}$ is added category B standard uncertainty at measurement height j (not covered by the meteorological mast);

$u_{\text{added_systematic},1,i}$ is added category B uncertainty at the height of the top of the meteorological mast;

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$u_{\text{systematic},j,i}$ is cumulated other category B uncertainties of the remote sensing device at height j;

$u_{\text{systematic},1,i}$ is cumulated other category B uncertainties of the remote sensing device at the height of the top of the meteorological mast.

The added category B uncertainty shall be cumulated with the other category B uncertainties of the remote sensing device measurements in quadrature.

L.5.4 In-situ test of the remote sensing device

In order to check the consistency of the accuracy of the measurements of the remote sensing device throughout the power curve measurement campaign, the meteorological mast present at the test site may be used to perform an in-situ test of the remote sensing device similar to the in-situ test defined in Annex K. If in-situ testing is performed, it shall be done for all common measurement heights covered by the meteorological mast and the remote sensing device.

A successful in-situ test can replace a repetition of the calibration test after the power curve test.

L.6 Other requirements specific to power curve testing

Before using the remote sensing device for power curve measurements, a classification test according to Clause L.2 and a calibration test according to Clause L.3 shall be performed. Alternatively, the calibration test can be performed during the power curve test. If the calibration test is not performed at the power curve test site, the remote sensing device shall either be stored or shall be directly transported to the location where the power curve campaign shall take place at the end of the calibration test. A repetition of the calibration test shall be performed after the power curve test. As an alternative, an in-situ test of the remote sensing device against the meteorological mast present at the power curve test site can be performed. Deviations of the calibration test methodology or of such deviations implied by the in-situ test shall be treated like deviations of cup anemometer calibrations as defined in this standard.

If a measurement height required for the power curve test is between two measurement heights available from the calibration test or the classification test, linear interpolation of the results of the calibration test or of the classification test according to the height shall be performed. Linear extrapolation[49] of the results of the calibration test or of the classification test should not be performed. If the measurements required for the calculation of the rotor equivalent wind speed extend beyond the height range covered by the calibration test or the classification test, a higher uncertainty than the uncertainty pertaining to the nearest height covered by the calibration test or the classification test shall be considered.

In some cases it is helpful to carry out a site calibration in terrain which is sufficiently non-complex to satisfy the requirements of Annex B. If the remote sensing device is used in conjunction with a site calibration measurement, the measurement volume shall be centred horizontally within 10 m or 10 % of the hub height H of the reference meteorological mast, whichever is larger. Where a site calibration is not required, the remote sensing device may be situated consistent with the requirements of 6.3.2. In both cases, when acquiring hub height wind speed measurements, the extremes of the measurement volume at hub height H shall not lie closer to the test wind turbine than $2D$, where D is the rotor diameter, and the centroid of the measurement volume shall not lie further than $4D$ from the test wind turbine. This is illustrated in Figure L.7, where an inverted conical scan geometry is used for illustrative purposes only: this guidance is not limited to this particular scan geometry. The extremes of the measurement volume at all heights evaluated for the power curve test shall

49 Other types of extrapolation are permitted as long as they are conservative.

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lie outside a sphere centred at the position and hub height of any wind turbine with a radius of 2 rotor diameters of the respective wind turbine.

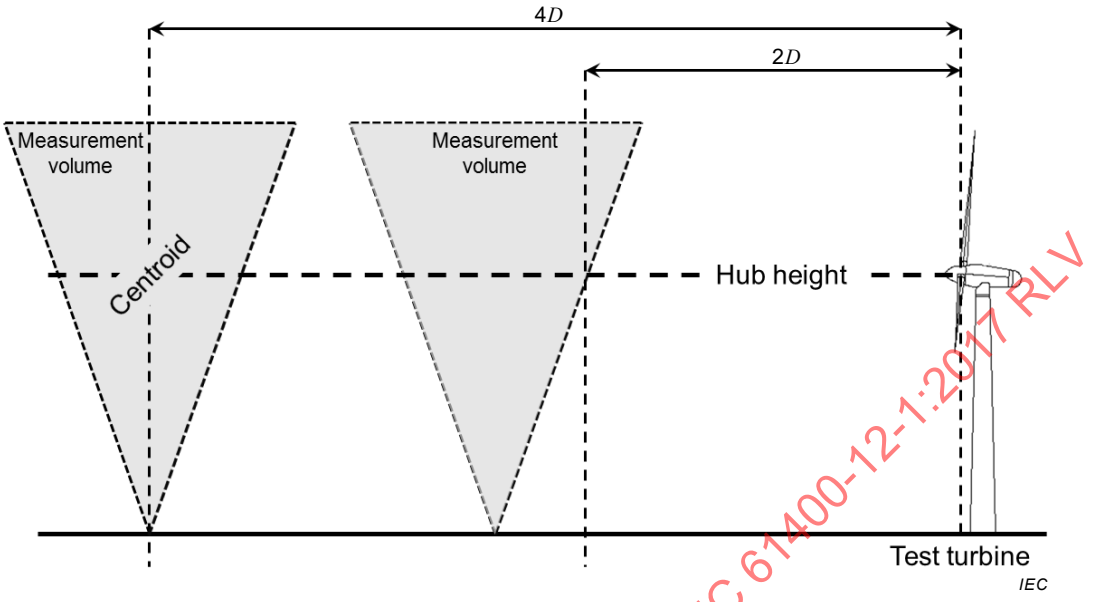

Figure L.7 – Example of permitted range of locations for measurement volume

Probe volumes within which the remote sensing device acquires a radial velocity measurement shall be free of wakes and flow perturbation from wind turbines and obstacles as defined in Annex A. For clarity:

a) the measurement volume is the region within which wind flow characteristics can influence a wind speed measurement and is defined by the scan geometry, device configuration or arrangement of the multiple beams penetrating the volume in order to acquire that measurement;

b) the probe volume is the region from which a single constituent physical measurement of, for example, Doppler shift, radial or line of sight velocity, is acquired, several of which are typically required to derive a wind speed measurement. The probe volume is a characteristic of the basic physical interaction of the remote sensing device with the atmosphere, rather than the wind speed measurement derived from these interactions, which is determined by the flow within the measurement volume.

Device-specific measures should be undertaken according to the advice and guidance of the manufacturers of the remote sensing device employed. The aim is to comply with the general requirements in measurement height.

The same remote sensing device configuration, operating parameters, software/firmware and performance related hardware components shall be used during the power curve test as were used during device classification and during the calibration test. No major changes shall be implemented that might affect performance between calibration, classification and power curve test.

If the meteorological mast available for the power curve test does not reach hub height, the atmospheric pressure measured by the meteorological mast instruments shall be adjusted to hub height following this standard. Furthermore, the air temperature will be adjusted to hub height assuming that the atmosphere varies according to ISO 2533:1975. An alternative method is to mount a temperature sensor on the wind turbine nacelle. The sensor shall be mounted at least one meter (1 m) above the nacelle and upwind of any existing ventilation systems. The effects of the nacelle on the sensor shall be mitigated in accordance with the international standard IEC 61400-12-2.

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The following measurements are required for the power curve test, the calibration test and for the classification test if the remote sensing device requires respective data filtering for the provision of accurate measurements:

a) measurement of precipitation;

b) measurement of cloud height;

c) measurement of ambient acoustic noise level.

The need for such measurements shall be reasonably assessed during the classification test.

L.7 Reporting

L.7.1 Common reporting on classification test, calibration test, and monitoring of the remote sensing device during application

The reports on the classification test, on the calibration test and on the monitoring of the remote sensing device during the application shall include the following common contents:

a) all details of the set-up of the reference measurement and all details of the test site as required for a power curve test;

b) all details of the set-up of the remote sensing device, including exact position of the remote sensing device, relative position to reference meteorological mast, orientation, version and set-up of operating software, pitch and roll angle and its monitoring;

c) serial number and type of the remote sensing device;

d) measurement period;

e) description of data analysis including filtering;

f) presentation of raw data as described in Clause L.3;

g) bin-wise analysis of measurement of remote sensing device versus reference measurement including graphical and tabular documentation as described in Clause L.3 and L.4.3;

h) analysis of uncertainty of reference measurements, where applicable in accordance to L.4.2;

i) environmental conditions during the test remaining after all data filtering: At least all variables having a significant influence on the accuracy of the remote sensing device as resulting from the classification test shall be documented. Each of these variables shall be plotted as a function of the wind speed at the evaluation height and shall be bin-averaged against this wind speed using bins with a width of 0,5 m/s centred on multiple integers of 0,5 m/s. In addition, the distribution of these variables shall be shown. For the performance monitoring at the power curve test, this documentation is limited to the available measurements of environmental conditions;

j) all calibration certificates of all reference sensors and of the data acquisition system.

L.7.2 Additional reporting on classification test

The report about the classification test shall contain in addition to the items given in L.7.1:

a) scatter plots of 10 min data and bin averages related to the sensitivity analysis for all considered variables as detailed in L.2.4;

b) description and reasoning of the selection of considered environmental variables;

c) complete documentation of the process of the identification and elimination of insignificant environmental variables;

d) complete documentation of the process of the investigation of inter-correlations of the considered environmental variables;

e) sensitivity parameters, sensitivities, correlation coefficients, mean values and standard deviations of all variables considered according to Clause L.2;

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f) ranges of environmental variables considered for the classification;

g) choice of the classification method;

h) classification results for the parameter ranges defined in Table L.3.

L.7.3 Additional reporting on calibration test

The report about the calibration test shall contain in addition to the items given in L.7.1:

a) standard uncertainty of the remote sensing device resulting from the calibration test according to L.4.3;

b) if the calibration test is repeated after the power curve test: comparison of results of calibration tests and consequences of the comparison;

c) additional reporting on monitoring of remote sensing device during application;

d) any anomalies of the measurements according to L.5.2;

e) amount and periods of data filtered out based on data check according to L.5.2;

f) uncertainty analysis according to L.4.3 and L.4.4;

g) bin-wise representation of evaluation criteria according to L.5.3 and added uncertainty;

h) training and test period, results and consequences of in-situ test so far performed.

L.7.4 Additional reporting on application

The report about the application shall contain in addition to the items given in L.7.1:

a) full uncertainty assessment of measurements of the remote sensing device according to Clause L.4;

b) realisation of air density measurements and description of associated data corrections to hub height.

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Annex M
(informative)

Normalisation of power curve data according to the turbulence intensity

M.1 General

Wind turbine power curves are influenced by turbulence intensity. A significant part of the turbulence intensity effect is caused by the averaging of the measured power output and the measured wind speed over 10 min periods. This can be understood from the non-linear relationship between the power output and the wind speed: In the wind speed range where the power output increases proportionally with the wind speed (ankle of the power curve), the 10 min averaging leads to an increase of the power output with increasing turbulence intensity. This is typically the case at low wind speeds and at wind speeds around the maximum power coefficient. In the wind speed range where the power output increases less than proportional with the wind speed (knee of the power curve), the 10 min averaging leads to a decrease of the power output with increasing turbulence intensity. This is typically the case at the knee of the power curve at wind speeds just below rated wind speed.

Annex M describes a procedure for normalising power curve data to a reference turbulence intensity (see references [13] and [14]). The reference turbulence intensity can be defined as a function of the wind speed. The given procedure considers only the effect of 10 min averaging of the measurement data. Other turbulence effects on the wind turbine power output are not covered by the method. It is recommended to apply the turbulence normalisation procedure to make power curves measured at different turbulence intensities more comparable to each other.

The turbulence normalisation procedure outlined here makes simplifying assumptions such as the wind turbine follows, at each instant, a certain power curve, which is independent of the turbulence intensity, and the assumption that the wind speed fluctuations relevant for the entire rotor area within a 10 min period are adequately characterised by the turbulence intensity at hub height. Despite the simplicity of these assumptions, the method enables the adjustment of the effect of 10 min averaging for a large variety of wind turbine types, rotor sizes and turbulence ranges.

A procedure for the estimation of uncertainties linked to the effects of turbulence on power curves both for the case of turbulence normalisation and for the case that no turbulence normalisation is performed is given in Clause M.5. The suggested uncertainty calculation is also intended to cover contributions to power curve test uncertainties due to turbulence effects not related to the 10 min averaging.

M.2 Turbulence normalisation procedure

It is assumed for the turbulence normalisation that at each instant the wind turbine follows a certain power curve, here defined as zero turbulence power curve. The determination of the zero turbulence power curve is described in Clause M.3. Figure M.1 illustrates the turbulence normalisation process.

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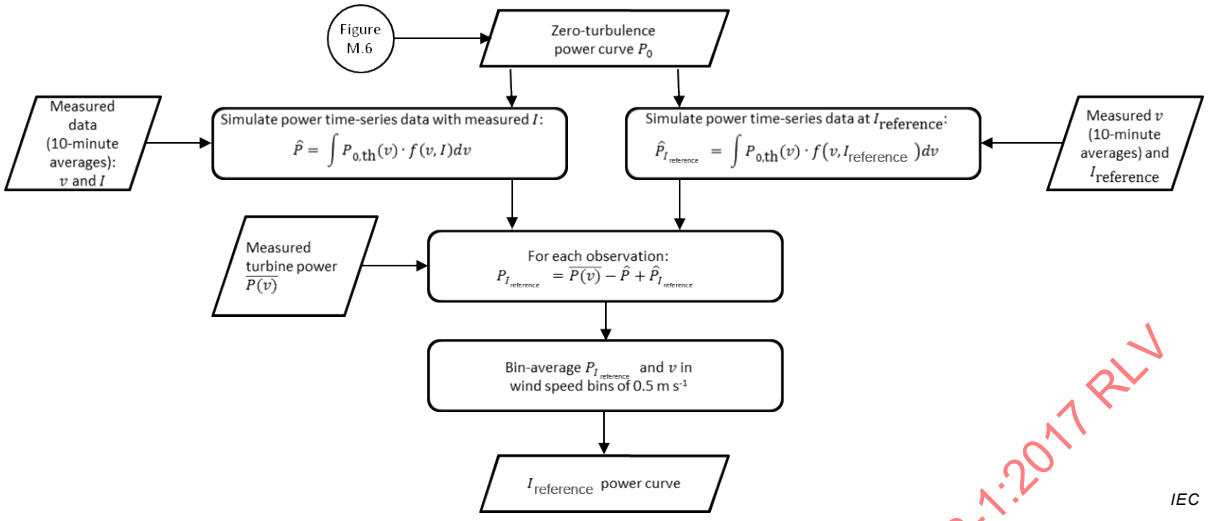

Figure M.1 – Process for obtaining a power curve for a specific turbulence intensity ($I_{\mathrm{reference}}$)

Based on the zero turbulence power curve and wind speed distribution within a 10 min period, the 10 min average of the wind turbine power output can be simulated by the following equation:

$$\overline{P_{\mathrm{sim}}(v)} = \int_{v=0}^{\infty} P_{I=0}(v) \cdot f(v) dv \qquad \text{(M.1)}$$

where

$f(v)$ is the wind speed distribution within 10-minute period;

$P_{I=0}(v)$ is the zero turbulence power curve;

$P_{\mathrm{sim}}(v)$ is a simulated 10 min average of measured power output.

Equation (M.1) shall be applied to power curve data (every 10 min period) to calculate two simulated power outputs for the following conditions:

1) The wind speed distribution as measured in the 10 min period at hub height. A Gaussian distribution $f(v)$ may be assumed, which is fully determined by the average wind speed and the standard deviation of the wind speed as recorded within the 10 min period. In case of a wind turbine with active power control, Equation (M.1) shall be evaluated for the air density normalised hub height wind speed. The standard deviation to be applied is calculated as the product of the measured turbulence intensity (standard deviation of wind speed divided by the average wind speed at hub height) and the air density normalised average wind speed (at hub height);
2) A Gaussian wind speed distribution with the 10 min average of the wind speed measured at hub height and a standard deviation equal to the product of the 10 min average of the wind speed measured at hub height and the reference turbulence intensity. In case of a wind turbine with active power control, Equation (M.1) shall be evaluated for the air density normalised wind speed (at hub height).

The measured power output is then normalised to the reference turbulence intensity by the following equation:

$$\overline{P_{I_{\mathrm{ref}}}(v)} = \overline{P(v)} - \overline{P_{\mathrm{sim},I}(v)} + \overline{P_{\mathrm{sim},I_{\mathrm{ref}}}(v)} \qquad \text{(M.2)}$$

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where

$\overline{P(v)}$ is the 10 min average of measured power output;

$\overline{P_{\mathrm{sim},I}(v)}$ is the simulated 10 min average of measured power output according to the above condition 1: Equation (M.1) applied for the measured wind speed distribution (measured average wind speed and measured turbulence intensity);

$\overline{P_{\mathrm{sim},I_{\mathrm{ref}}}(v)}$ is the simulated 10 min average of measured power output according to the above condition 2: Equation (M.1) applied for the measured average wind speed and for the reference turbulence intensity I_{ref} by assuming a Gaussian wind speed distribution.

In case of a stall-regulated wind turbine, Equation (M.2) shall be applied with the air density normalised measured power output.

The power coefficient data (as applied only for graphical demonstration of the measurements) shall be calculated on the basis of the power output normalised to the reference turbulence intensity. In case of a stall-regulated wind turbine, the power coefficient data shall be calculated on the basis of the power output normalised to the reference turbulence intensity and on the basis of the reference air density (not on basis of the measured air density).

M.3 Determination of the zero turbulence power curve

An initial zero turbulence power curve is calculated on the bin-averaged power curve normalised according to the air density, but not normalised according to the turbulence intensity and not corrected according to the wind shear. The initial zero turbulence power curve is determined as a first approach as follows (see also Figure M.2 and Figure M.3):

a) assumption of zero power output below cut-in wind speed. As a first approach, the cut-in wind speed is set to the average wind speed of the wind speed bin, where the measured power output reaches at least 0,1 % of the rated power;

b) assumption of constant power coefficient c_{P} equal to the maximum power coefficient $c_{\mathrm{P,max}}$ between cut-in wind speed and rated wind speed. This assumption is equal to an increase of the power output with the third power of the wind speed. The initial zero turbulence power curve shall be calculated with this assumption and on the basis of the reference air density between the cut-in wind speed and the rated wind speed in increments not larger than 0,1 m/s. As a first approach, the maximum power coefficient $c_{\mathrm{P,max}}$ shall be set to the maximum power coefficient of the measured bin-averaged power curve;

c) calculation of rated wind speed v_{rated} from rated power P_{rated}, rotor swept area A, maximum power coefficient $c_{\mathrm{P,max}}$ and reference air density ρ by: $v_{\mathrm{rated}} = \left(\frac{2 \cdot P_{\mathrm{rated}}}{\rho \cdot c_{\mathrm{P,max}} \cdot A} \right)^{\frac{1}{3}}$. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins;

d) power output equal to rated power for wind speeds above rated wind speed v_{rated}. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins of the measured power curve. This rated power output shall be assumed for wind speeds far above cut-out wind speeds (e.g. 100 m/s) for the definition of the initial zero turbulence power curve.

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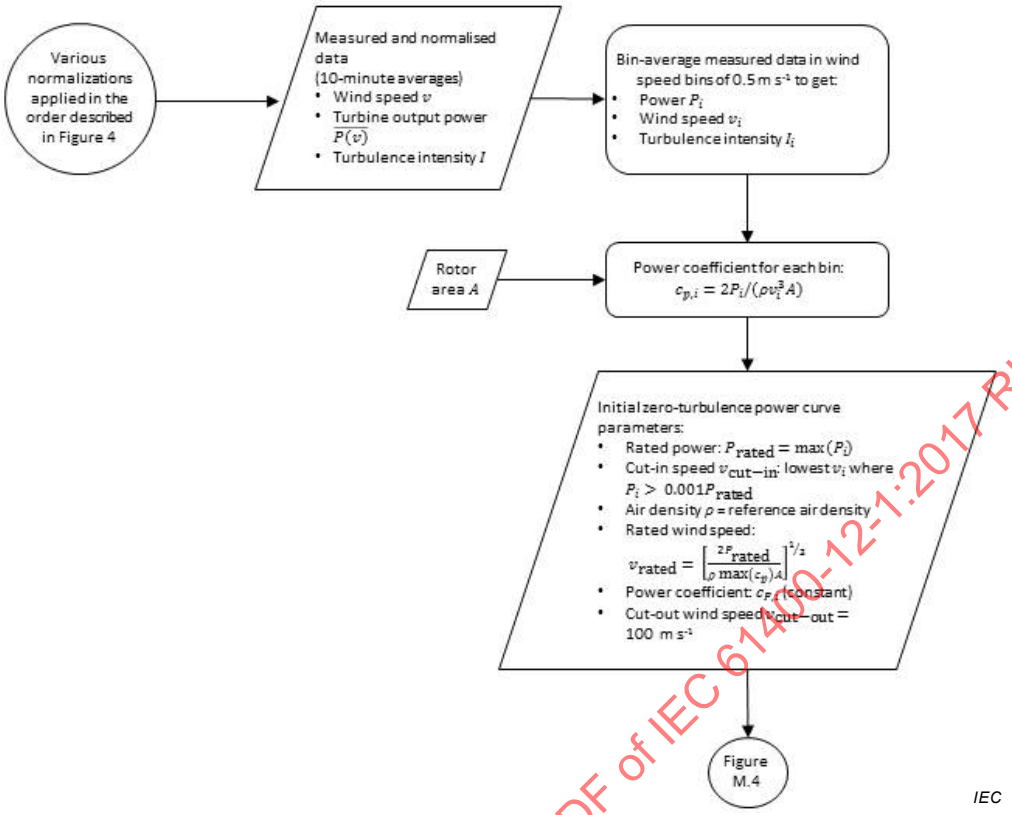

Figure M.2 – Process for obtaining the initial zero turbulence power curve parameters from the measured data

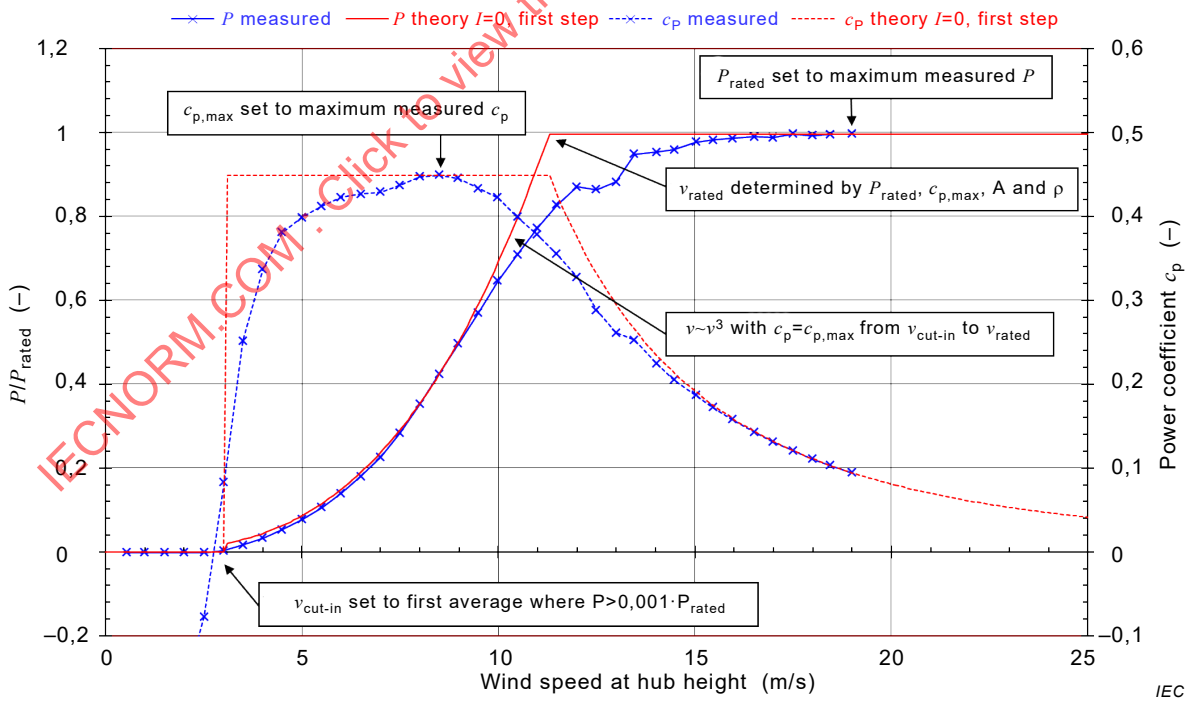

Figure M.3 – First approach for initial zero turbulence power curve

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In the next step, the rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall be adjusted because these three parameters are dependent on the turbulence intensity and because values for these parameters have been applied in the previous step instead the values corresponding to the turbulence intensity of zero. A bin-average of the measured turbulence intensity as a function of the wind speed measured at hub height shall be performed. In case of a wind turbine with active power control, the turbulence intensity shall be bin averaged according to the air density normalised wind speed at hub height.

The initial zero turbulence power curve shall be integrated over a Gaussian wind speed distribution according to Equation (M.1) with the average wind speed equal to the bin average of the measured power curve and with the standard deviation calculated as product of the bin-averaged wind speed and the bin averaged turbulence intensity. The air density normalised wind speed at hub height shall be applied in case of a wind turbine with active power control. By this procedure, the power curve is simulated for each wind speed bin for the measured turbulence intensity, while the simulated power curve refers to exactly the same wind speed bins than the measured power curve. The rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall then be adjusted as follows (see Figure M.4):

a) the rated power shall be adjusted such that the maximum power of the simulated power curve fits the maximum bin averaged power of the measured power curve;

b) the cut-in wind speed shall be adjusted such that the cut-in wind speed of the simulated power curve fits the cut-in wind speed of the bin averaged measured power curve. Cut-in wind speed is for both power curves defined as lowest wind speed bin where the power output reaches at least 0,1 % of the rated power;

c) the maximum power coefficient shall be adjusted such that the maximum power coefficient of the simulated power curve fits the maximum power coefficient of the measured power curve.

Steps a) to c) above shall be all three repeated at every iteration, in the given order, until the three parameters converge at least as follows:

a) the maximum power of the simulated power curve deviates from the maximum bin averaged power of the measured power curve by no more than 0,1 %;

b) the cut-in wind speed of the simulated power curve deviates from the cut-in wind speed of the bin averaged measured power curve by no more than 0,5 m/s;

c) the maximum power coefficient of the simulated power curve deviates from the maximum power coefficient of the measured power curve by no more than 0,01.

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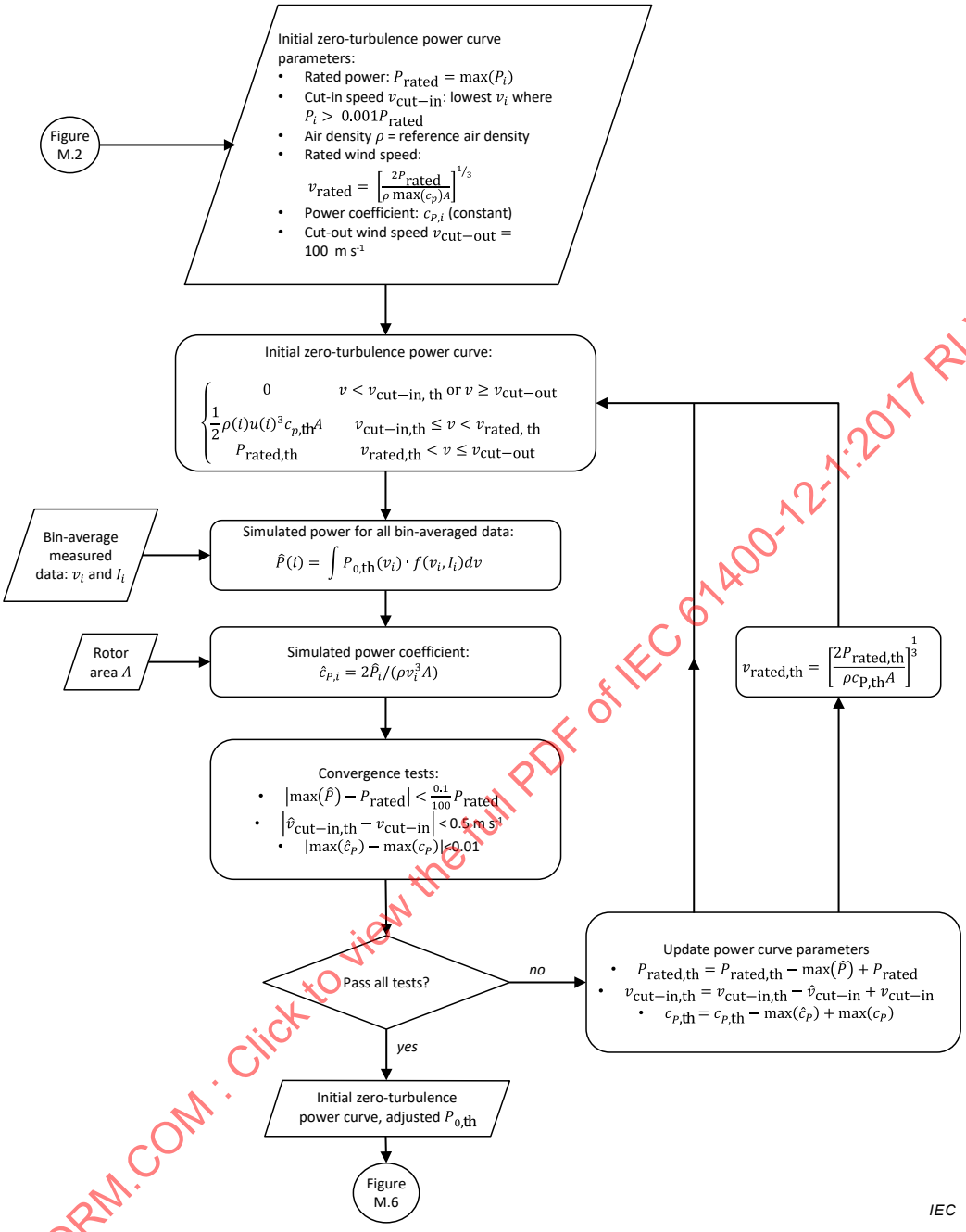

Figure M.4 – Process for obtaining the theoretical zero-turbulence power curve from the measured data

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Sufficient convergence is normally reached after the first or second iteration. Figure M.5 illustrates how the adjustments normally change the initial zero turbulence power curve from the first step.

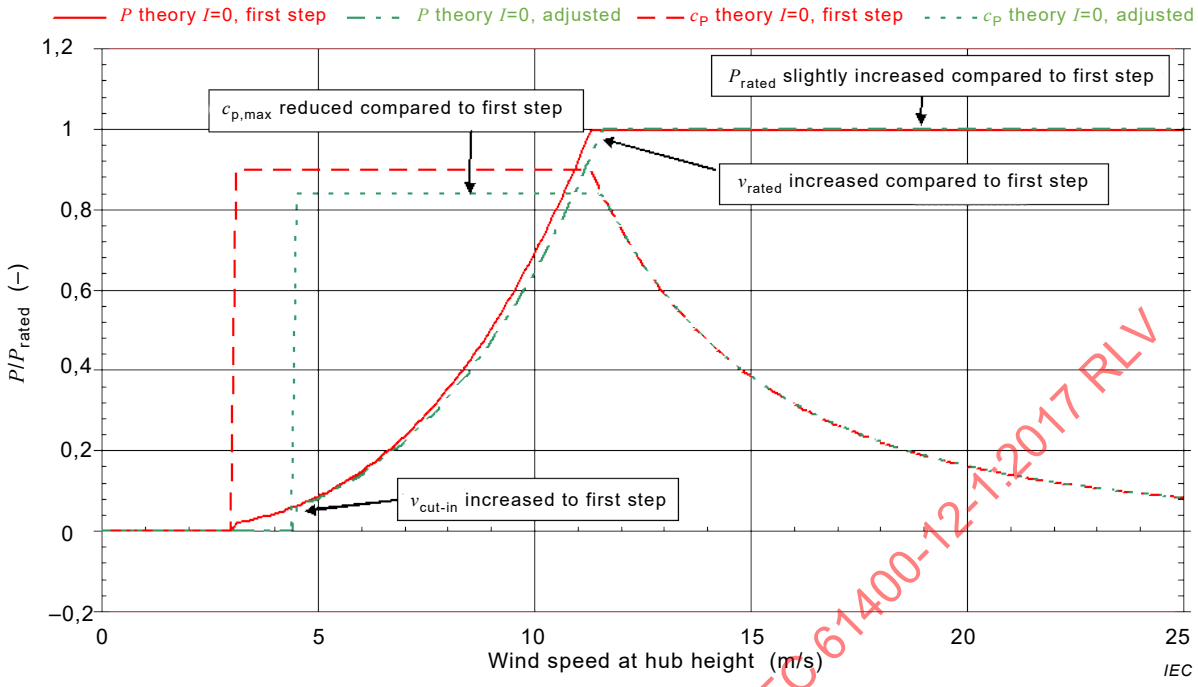

Figure M.5 – Adjusted initial zero turbulence power curve (green) compared to first approach (red)

The zero turbulence power curve shall then be determined by applying the data normalisation process described in Clause M.2 with the zero turbulence power curve set to the initial zero turbulence power curve in Equation (M.1) and by assuming a turbulence intensity of zero (constant wind speed during 10 min period). The final zero turbulence power curve is gained by bin-averaging the so normalised power curve raw data as illustrated in Figure M.6. This bin-averaged power curve shall be extended with the power output of the highest bin to wind speeds far above cut-out wind speeds (e.g. 100 m/s) when applying Equations (M.1) and (M.2) for turbulence normalisations.

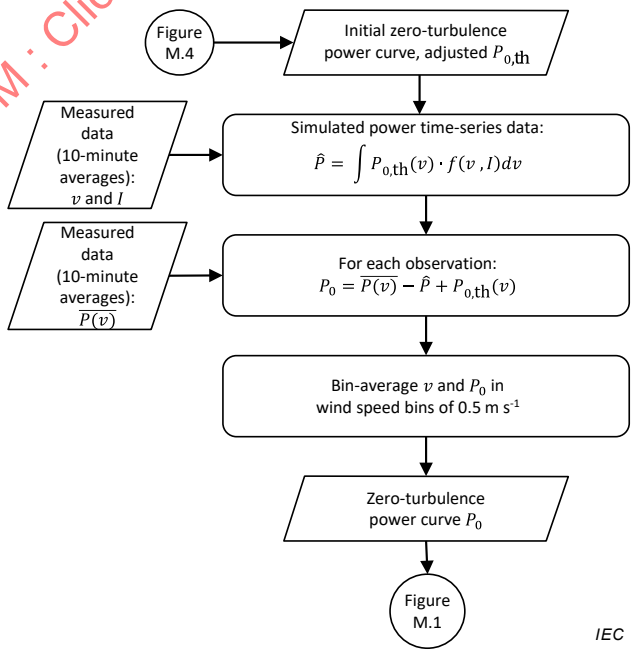

Figure M.6 – Process for obtaining the final zero-turbulence power curve from the measured data

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Figure M.7 illustrates how the final zero turbulence power curve typically compares to the initial zero turbulence power curve.

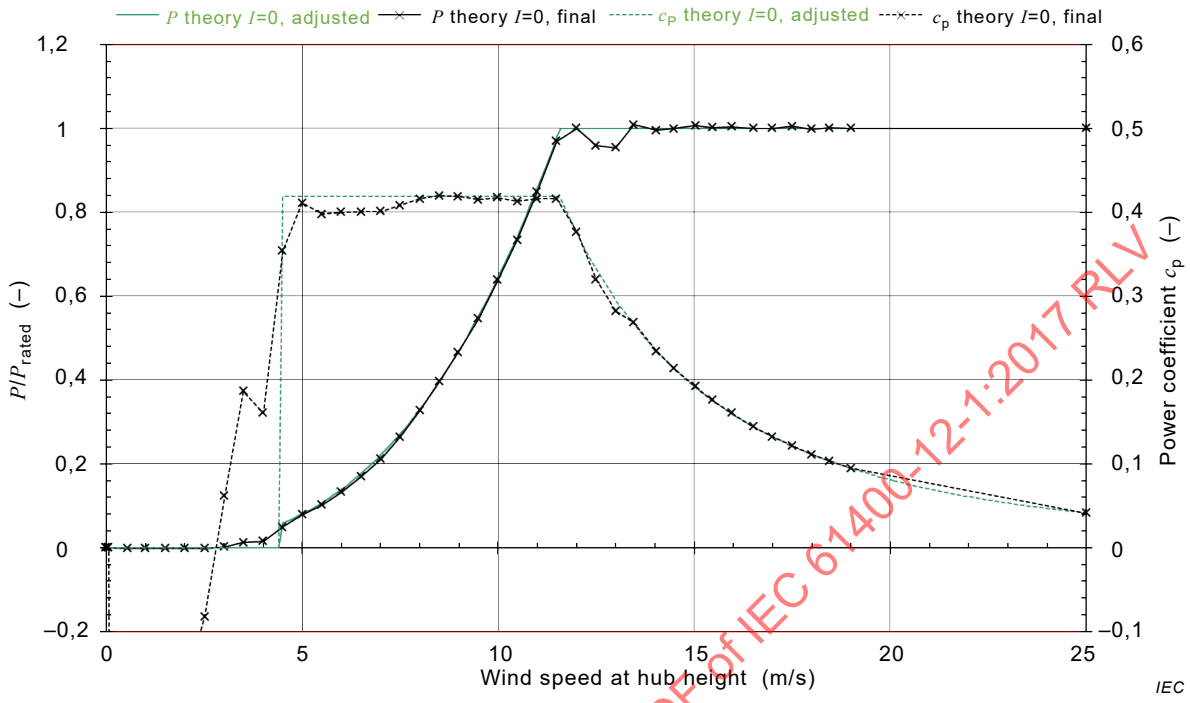

Figure M.7 – Adjusted initial zero turbulence power curve (green) compared to final zero turbulence power curve (black)

M.4 Order of wind shear correction (normalisation) and turbulence normalisation

The order of the application of the wind shear or wind veer correction (or normalisation) and the turbulence normalisation normally has no major influence on the final power curve. It is more convenient to apply the turbulence normalisation only on the basis of the hub height wind speed, as it is described in Clause M.2 and M.3, although it could also be applied on the basis of the wind shear- or wind veer-corrected (or-normalised) wind speed when wind speed measurements over the entire rotor height allow applying the wind shear correction. At the end, the final power shall be calculated by bin-averaging the turbulence-normalised power output against the wind shear- or wind veer-corrected (or-normalised) wind speed. In case of a wind turbine with active power control, the wind shear corrected (wind shear normalised) wind speed shall be normalised according to the air density prior to the bin-averaging. In case of a stall-regulated wind turbine, the turbulence-normalised power output according to Clause M.2 is already corrected for the air density.

M.5 Uncertainty of turbulence normalisation or of power curves due to turbulence effects

The turbulence normalisation given in Clause M.2 and M.3 is designed to handle effects of the 10 min data averaging on the evaluated power curve. There are further effects of the turbulence intensity on wind turbine power curves, which could, for instance, be due to direct impact of the turbulence intensity on the aerodynamics or due to the 3-dimensional character of turbulence. In the end, the turbulence intensity normalisation is a strongly simplified approach for characterising short term wind speed fluctuations. Thus, there is a remaining uncertainty of the evaluated power curve due to possible turbulence effects, even if the turbulence normalisation procedure is applied. The turbulence normalisation often removes about half of the observed effect of the turbulence intensity on measured wind turbine power

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curves. Thus, the following steps should be performed in order to calculate the uncertainty of the turbulence normalisation:

a) the final bin-averaged power curve shall be evaluated on the basis of the turbulence normalised power output and on the basis of the non-turbulence normalised power output;

b) the deviation of these two power curves shall be assumed to be the maximum uncertainty of the turbulence-normalised power curve per wind speed bin resulting from the turbulence normalisation. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the power curves divided by $\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties of the power performance measurement for the determination of the total standard uncertainty according to Annex D.

The uncertainty of turbulence effects on the measurement shall also be taken into account if no turbulence normalisation is performed, the uncertainty is higher, as the power curve is valid only for the turbulence conditions present during the power performance test and not for a reference turbulence intensity deviating from the test conditions. Thus, if no turbulence normalisation is applied, the following estimation of uncertainty due to turbulence effects is recommended:

1) two turbulence normalised power curves shall be evaluated according to Clause M.2 and M.3 just for the determination of the uncertainty. First, the power curve shall be normalised to an extremely low turbulence intensity, second, the power curve shall be normalised to an extremely high turbulence intensity. If the user does not have pre-defined extreme turbulence intensity limits, the turbulence intensities 0,05 and 0,15 shall be considered as the extreme turbulence intensities for the two power curve normalisations;

2) the deviation of the two normalised power curves shall be assumed to be half of the maximum uncertainty due to turbulence effects. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the two normalised power curves multiplied by the factor $2/\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties for the determination of the total uncertainty of the power curve according to Annex D;

3) if the measured power curve shall be compared with a power curve that refers to a certain (possibly wind speed dependent) turbulence intensity (e.g. a warranted power curve) and no power curve normalisation is performed, the two extreme turbulence intensities applied in step 1) shall be replaced by the bin-averaged measured turbulence intensity and by the reference turbulence intensity of the to be compared power curve for the uncertainty calculation.

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Annex N
(informative)

Wind tunnel calibration procedure for wind direction sensors

N.1 General

This procedure describes the calibration method of wind direction sensing devices including wind vanes and sonic anemometers operating as wind direction sensing devices.

N.2 General requirements

The general requirements for the calibration of wind direction sensors are summarized as follows:

a) the calibration of the wind direction sensor shall be carried out in an operating wind tunnel that is suitable for the calibration of wind direction sensors;

b) the calibration facility shall be accredited in accordance with ISO/IEC 17025, the standard for testing and calibration laboratories;

c) all transducers and measuring equipment relevant for the calibration of wind direction sensors shall have traceable calibrations. Calibration certificates and reports shall contain all relevant traceability information. All reference standards used during the calibration of the wind direction sensor shall be stated within the test report of the calibration campaign;

d) prior to every calibration campaign (when a batch of wind direction sensors is being calibrated) the integrity of the experimental set-up shall be verified by means of a comparative calibration of the calibration facility's "quality control wind direction sensor";

e) flow quality measurements shall be carried out according to Clause N.3;

f) the repeatability of the calibration shall be verified according to Clause N.3;

g) wind direction sensor calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM 1995).

N.3 Requirements of the wind tunnel

The wind tunnel shall meet the requirements of Clause F.2.

The presence of the wind direction sensor shall not substantially affect the direction of the flow (field) in the wind tunnel. The presence of the wind direction sensor during its calibration may cause a flow diversion that is not encountered by the wind direction sensor when operated in the open field. To keep these effects at an acceptable level, the blockage ratio – defined as the ratio of the wind direction sensor frontal area with the fin oriented in line with the flow plus its mounting system to the total test section area – shall not exceed 0, for an open test section and 0,05 for a closed test section.

Special focus shall additionally be applied to verify that the horizontal direction of the wind tunnel flow is aligned parallel in relation to the test section centreline. The uniformity of the flow field (as required in Annex F) and the direction of flow shall be assessed prior to the calibration of the wind direction sensor. The flow direction shall be surveyed relative to the test section centreline at the representative location of the wind direction sensor by utilizing direction-sensitive flow measuring devices (i.e. two-hole conical yaw meter). The measured horizontal direction of flow shall be parallel to the test section centreline within 0,2°, the deviation shall be considered in the data evaluation.

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The facility shall undergo a detailed examination of the repeatability of wind direction sensor calibrations. The facility shall designate at least one reference wind direction sensor for use in these tests. The reference wind direction sensor(s) shall be used only for checking performance of this and other wind direction sensor calibration facilities. The repeatability examination shall include at least 10 calibrations of the quality control wind direction sensor. The repeatability test shall not be conducted in succession. It is more representative if the calibrations are conducted over a longer time span. This will provoke a greater range of atmospheric conditions during the tests. The maximum difference between calibrations of the same reference sensor should be less than 0,5° at 8 m/s wind speed throughout the measuring range of the wind direction sensor excluding the north band (wind vanes) where usually undefined conditions exist. This process shall be repeated after any modification or recalibration of the facility. The facility shall prove, through proficiency testing, that its results are comparable with other anemometer calibration facilities, according to ISO 17043.

The facility's average reference wind direction sensor calibration (as determined from repeatability tests described above) should agree with the average result of other calibration facilities within a deviation of the indicated equivalent flow direction of less than 1° throughout the measuring range, excluding the north band, at a wind speed of 8 m/s.

N.4 Instrumentation and calibration set-up requirements

Dedicated external signal conditioning equipment such as instrument amplifiers etc. shall be calibrated in isolation from the wind direction sensor, so that the wind direction sensor's calibration can be derived and reported in isolation from the signal conditioning equipment. The resolution of the data acquisition system used shall be at least 12 bits. Care shall also be exercised in the case of an analogue voltage instrument to ensure that the signal is adequately buffered to prevent its attenuation by low impedance logging equipment. Such effects are easily overlooked since 'believable' signals are still registered. The reference angle measurement system shall be the direct type (direct angle encoding, counting of increments, measuring proportional quantity such as magnetic, inductive or potentiometric methods). The shaft of the reference angle measurement system shall be connected to the shaft of the wind direction sensor rotation mechanism by means of a backlash-free coupling. The coupling shall be resistant to torsion and flexible to bending (flexion-elastic) in order to achieve the maximum possible elimination of assembly-influencing quantities (tolerances of concentricity and angles of both axes of rotation). The axes of rotation shall be oriented concentric and coaxial. The housing of the reference angle measurement system shall be securely fixed in a backlash-free manner. The reference angle measurement sensor shall be positioned in the tunnel as accurate as possible, and it may not disturb the wind direction sensor under test. The maximum deviation allowed is 0,1°. Figure N.1 illustrates an example of a calibration setup in a wind tunnel.

During calibration, the wind direction sensor shall be mounted on top of a tube in order to minimize flow distortion. This tube shall be of the same dimensions as the one on which the wind direction sensor will be mounted in service in the free atmosphere. It is important to ensure that the flow field around the wind direction sensor is not influenced by the presence of any reference wind speed measurement equipment. Conversely the presence of the wind direction sensor shall not affect the direction of the flow in a significant way.

The wind direction sensor shall be mounted at the test section perpendicular to the flow field of the wind tunnel as accurately as possible. The maximum deviation allowed is 0,2°. The fin shall also be aligned relative to the datum line/north mark and held there in position by an adjustable support until the calibration process begins. An accurate alignment of the wind direction sensor and its fin may be achieved by an appropriate device such as a mechanical jig or the employment of an optical instrument (i.e. 2D laser level). The wind direction sensor output signal shall be examined during calibration to ensure that it is not subject to interference or noise. The determination of the wind tunnel flow speed shall be in accordance with Annex F.

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Great care shall be taken when aligning the wind direction sensor relative to the datum line (centreline) of the wind tunnel. The mechanical reference indicator (usually the north mark) of the wind direction sensor has to be properly aligned in relation to the datum line of the wind tunnel. It is not acceptable to perform the angular alignment of the wind direction sensor just by utilizing its electrical output signal. This would provoke an angular deviation between the external reference mark and the indicated value from the internal angular transducer of the wind direction sensor. This deviation would later be difficult to identify since the alignment of the vane at the meteorological mast is usually realized by means of the north mark. The proper angular alignment for the calibration shall be assured using an adequate method to measure the external reference mark.

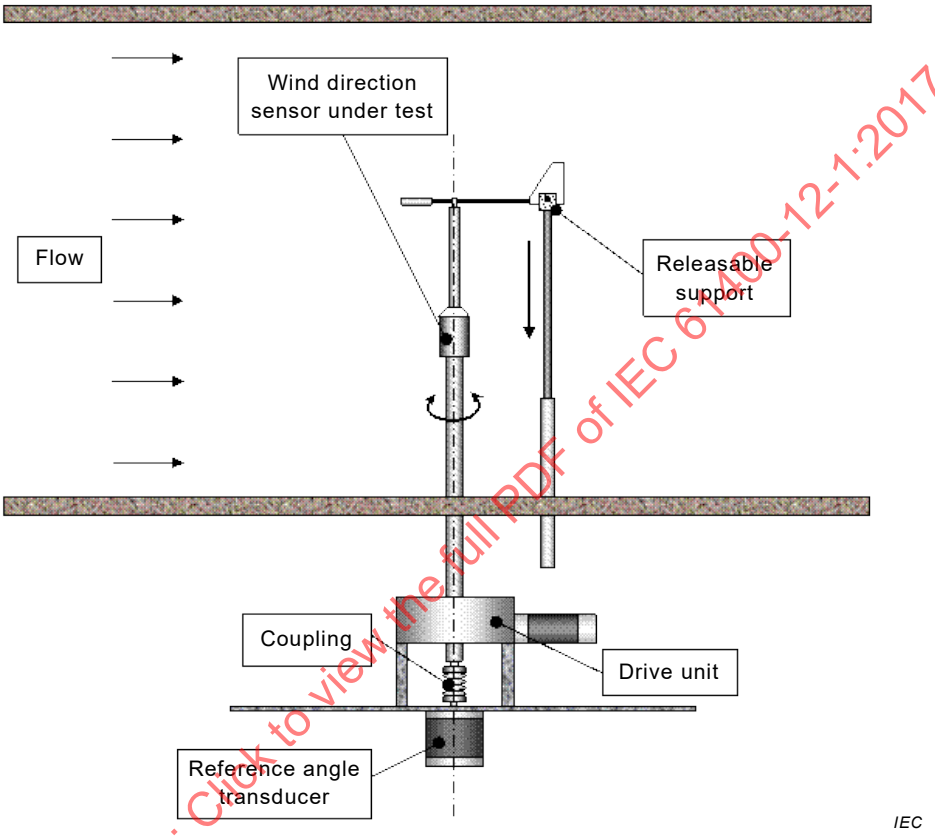

Figure N.1 – Example of calibration setup of a wind direction sensor in a wind tunnel

N.5 Calibration procedure

Generally the wind direction sensor shall be directionally positioned by means of an adequate rotation mechanism (i.e. rotary table) while the direction and the speed of the flow remains unchanged. The output signal of the wind direction sensor is then assessed in relation to the reference angle measurement system installed at the rotation mechanism.

The procedure for the calibration of wind direction sensors is as follows:

The wind direction sensor is rotated at a constant yaw rate or stepwise. The indicated yaw angle (measured value of the wind direction sensor) is simultaneously recorded together with the reference yaw angle (measured value of the rotation mechanism). The selected rate of rotation is a compromise between adequate measurement precision and feasible measurement time. The recommended rate is 0,5 °/s. For a stepwise procedure, it is important to have an adequately fine increment of less than 3° in order not to miss erroneous direction data. The sampling frequency shall be high enough (usually 1 Hz or faster) to have a sampling bias within acceptable limits. The temperature of the wind direction sensor shall not vary significantly during its calibration to minimize an additional uncertainty due to

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temperature-induced effects upon the indicated direction. A run in time of > 1 min shall be included to minimize temperature deviation between the wind direction sensor and the flow in the wind tunnel prior to the calibration run.

The calibration process shall consist of at least two complete yaw sweeps (including the north jump) for each of the above procedure. Each sweep shall be of opposite directions to account for possible hysteresis effects. There shall be an angular overlap of the data points of at least 10° at the beginning and the end of each sweep. A possible sequence may cover a clockwise sweep from –10° to 370° and a counter clockwise run from 370° to –10° for the subsequent sweep.

The calibration shall be performed at a constant wind speed of (8 ± 10 %) m/s. The average wind speed should not vary throughout the duration of the wind direction sensor calibration.

N.6 Data analysis

Only the horizontal wind vector shall be considered during the wind direction sensor data assessment. The evaluation of the wind direction signal shall, for both wind vanes and sonic anemometers, be performed using the method of vector averaging as described in ISO 16622 [4] and 7.3.

All relevant data shall be evaluated as bin-averaged data. Data of the reference yaw sensor is hereby used as a basis to define the bin interval for the remaining data base. The bin-width shall have at least a resolution of 10°, centred at 5°, 15° .etc. of the yawing device. The bin-width shall be reduced to adequately assess the behaviour of certain sensor types (i.e. sonic anemometer) or to better represent sensor characteristics (i.e. excessive non-linearity).

N.7 Uncertainty analysis

It is important to identify the uncertainty of the horizontal flow direction measurement in conjunction with the wind direction sensor.

It is required that an uncertainty analysis shall be carried out in accordance with the ISO guide 98-3 to the expression of uncertainty comprising both category A and category B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall account for:

a) measurement uncertainty of the reference angle measuring system (reference angle transducer, coupling, mounting, electrical transducers, digital conversion, etc.);

b) uncertainty of the flow direction sensed by the wind direction sensor, including an assessment of possible flow diversion due to the presence of the wind direction sensor;

c) mounting uncertainty of the wind direction sensor (alignment of north mark and fin relative to the wind tunnel centreline);

d) category A uncertainty due to short-term scatter (signal of wind direction sensor may vary over time due to unsteady flow conditions);

e) category A uncertainty due to long-term scatter (scatter/drift of calibration results of the reference wind direction sensor over time for a number of calibrations);

f) uncertainty when measuring the electrical signal of the wind direction sensor (electrical transducer, digital conversion, etc.).

N.8 Reporting format

The relevant documentation shall provide information on the procedure followed and the facility used for calibrating the wind direction sensor (test report on the calibration campaign) and on the individual wind direction sensor calibration (wind direction sensor calibration

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report). The test report on the calibration facility setup shall contain the following information as a minimum:

a) description of the wind tunnel (including test section, settling chamber, flow straighteners, fan arrangement);
b) sketch of the wind tunnel showing the exact positions of the wind direction sensor and pitot tube(s) in the test section;
c) flow quality measurements;
d) turbulence measurements;
e) instrumentation certificates;
f) measurement procedure;
g) data evaluation procedure;
h) repeatability documentation of wind direction sensor calibration;
i) uncertainty analysis;
j) deviations from these requirements.

The calibration report of a wind direction sensor shall as a minimum contain the following information:

a) make, type and serial number of the tested wind direction sensor and fin serial number if the item can be separated;
b) tube diameter of the mounting system;
c) make, type and serial number of external converters, if taken (i.e. frequency-to-voltage converters);
d) name and address of the customer;
e) signatures from the persons who carried out the calibration, checked the results and approved their issue;
f) name of the wind tunnel;
g) environmental conditions during calibration (air temperature, barometric air pressure and humidity);
h) regression parameters (offset and slope), in tabular and graphical presentation of all calibration points;
i) information of measured north dead-band width;
j) The table shall contain the following information:
    1) bin number;
    2) average reference (flow) direction per bin;
    3) average indicated direction signal of the wind direction sensor per bin;
    4) uncertainty per bin;
    5) wind tunnel flow speed per bin.
k) The graphical presentation shall include:
    1) indicated wind direction sensor signal as a function of reference yaw angle per bin;
    2) scatter plot of wind direction sensor signal vs. reference yaw angle if sweep is used;
    3) scatter plot of residuals of sensor signal vs. reference yaw angle;
    4) residuals per bin (deviation between indicated wind direction sensor signal and result of wind direction sensor calibration function);
    5) uncertainty associated with each measuring point.
l) reference to the corresponding calibration campaign report and date of the calibration;
m) photo showing the wind direction sensor and the mounting in the wind tunnel;

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n) rate of angular velocity, data bin-width and number of acquired data points per bin.

N.9 Example of uncertainty calculation

N.9.1 General

The determination of the measurement uncertainty is based on the assumption that the following three main sources contribute to the total uncertainty:

a) determination of flow direction in the wind tunnel (type B);

b) uncertainty due to the wind direction sensor to be calibrated (wind vane, sonic anemometer) (category B);

c) repeatability (category A).

In the following only category B uncertainties are considered. To determine the total uncertainty, the category A component shall be included as well.

N.9.2 Measurement uncertainties generated by determination of the flow direction in the wind tunnel

N.9.2.1 General

To evaluate the measurement uncertainty in the determination of the flow direction, the following individual uncertainties have to be considered:

N.9.2.2 Uncertainty contribution by uncertainties in the determination of the geometrical centreline α_{CL} (wind tunnel centreline)

Assuming that the centreline is defined with simple geometrical methods and the lines are accurate to 2 mm for a test section of 1,00 m by 2,00 m, the uncertainty of the geometrical centreline is 0,1°. Accepting a rectangular distribution, the contribution to the total standard uncertainty is 0,06°.

N.9.2.3 Contribution by uncertainties in the determination of flow direction α_{dir}

Calibration of flow direction occurs by means of a wedge type probe. A well designed wind tunnel shows practically no deviation of the flow direction from the geometrical centreline of the wind tunnel. The contribution to uncertainty is deemed to be 0,1°. Accepting a rectangular distribution the contribution to the total standard uncertainty is 0,06°.

N.9.2.4 Contribution by uncertainties in the calibration of the reference yawing sensor α_{sensor}

The reference angle is defined by using an electronic yawing sensor. Contribution to uncertainty resulting from the calibration of this sensor is assumed to be 0,35°. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,2°.

N.9.2.5 Contribution by aligning the centreline with the north marking of the wind direction sensor α_{set}

Using a laser, the sensor (north marking, fin, wind tunnel centreline) can be aligned. Assuming that the laser beam has a maximum deviation of 1 mm from the centreline, the uncertainty contribution is less than 0,1°. A contribution to total uncertainty of 0,1° is assumed. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,06°.

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N.9.2.6 Contribution due to influence of the angle between the axes of rotation $\alpha_{\text{incl.1}}$

When mounting the reference unit on the turning drive, errors can occur in the angle between the rotary axes of the turning drive and the reference unit (inclination of the calibrated object relative to the calibration device inclination). The rotary axes do not align, but a coupling between the shafts of the reference and of the calibrated object compensates within certain limits for the effect of the position of the angle measurement planes. The angle error can be calculated using the following equation:

$$\delta\alpha_{\text{incl.1}} = 0{,}125 \cdot (2 \cdot p / r)^2 \cdot \sin\alpha \quad \text{(N.1)}$$

where, according to VDI/VDE 2648, reference [5]:

α is the angle to be measured (calibration value);

p is the axial run-out deviation;

r is the effective radius of angle measurement.

With an assumed deviation of the levels of 1 mm and a radius of 50 mm for the yaw sensor, the extreme case of α = 90° results in an uncertainty of 0,01°.

N.9.2.7 Contribution to uncertainty by potential eccentricity between wind direction sensor and reference unit α_{Exz}

By mounting the wind direction sensor on the turning drive of the reference unit, eccentricities can occur, referring to the parallel misalignment between the respective rotary axes. The rotary axes do not align. The angle error that may occur because of the parallel misalignment can be calculated using the following equation:

$$\delta\alpha_{\text{Exz}} = 2 \cdot (e / r) \cdot \sin(\alpha / 2) \quad \text{(N.2)}$$

where, according to VDI/VDE 2648, reference [5]:

α is the angle to be measured (calibration value);

e is the eccentricity;

R is the effective radius of angle measurement.

Based on an assumed eccentricity of the rotary axes of 0,2 mm and a radius of 50 mm, the uncertainty of the extreme case of α = 180° is 0,2°.

N.9.3 Contribution to measurement uncertainty by the wind direction sensor

N.9.3.1 General

Wind direction sensors may have different output signals. There are also digital sensors indicating directly the azimuth direction angle in degree. Usually the specimen is a wind direction sensor with an analogue output signal (current or voltage) or a potentiometric sensor.

N.9.3.2 Contribution to uncertainty by digital output signal α_{Digital}

Half of the digital resolution is assumed to contribute to the measurement uncertainty.

N.9.3.3 Contribution to measurement uncertainty by analogue output signal α_{Analog}

Sensors with an analogue signal (typically 10 V or 20 mA) are supposed to contribute to uncertainty with the resolution of the analogue-to-digital conversion. Assuming a measurement system with a resolution of 12 bit, the contribution to uncertainty is

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360°/4 096=0,1°. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,06°.

N.9.3.4 Contribution to uncertainty by the determination of the ohmic resistance of a wind direction sensor α_{Ω}

The resistance of a potentiometric wind-vane can only be determined by means of a known voltage/current measurement. When determining the resistance of a potentiometric wind-vane (typically several kΩ) by means of indirect resistance measurement of voltage and constant current, the following uncertainties can occur:

- percent error of instrument shunt 0,030 %;
- error current through measurement system 0,020 %;
- resolution of analogue-to-digital conversion 0,025 %;
- assumed measurement uncertainty 0,05 % ~ 0,16 °.

Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,1°.

N.9.3.5 Contribution to uncertainty by mounting the wind direction sensor α_{item}

Typical wind direction sensors have a diameter of approximately 50 mm. The north marking often has a breadth of 1 mm and is therefore typically 2°. For the alignment of the north marking with a laser beam an uncertainty of 0,25 mm is assumed, thus resulting in a contribution to uncertainty of 0,25°. Assuming a rectangular distribution, the contribution to total standard uncertainty is 0,15°.

N.9.3.6 Contribution to uncertainty by possible malposition of the wind direction sensor $\alpha_{Incl.2}$

When mounting the wind direction sensor on the turning drive and the reference unit, angle errors in the alignment angle between the rotary axes can occur. The angle error is assumed to be 0,05°.

N.9.4 Result of the uncertainty calculation

To determine the total standard uncertainty, the following individual uncertainties have been considered (see Table N.1 and Table N.2):

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Table N.1 – Uncertainty contributions in wind directions sensor calibration

Factor	Uncertainty category	Uncertainty distribution	Sensitivity coefficient	Measurement uncertainty	Standard deviation	Contribution to uncertainty	Unit
Reproducibility	A	1	1	-		0,1	°
Determination of geometrical centreline	B	2	1	0,1	$u_{CL} = \frac{1}{\sqrt{3}} \cdot CL$	0,06	°
Determination of flow direction	B	2	1	0,1	$u_{DIR} = \frac{1}{\sqrt{3}} \cdot DIR$	0,06	°
Reference yaw sensor	B	1	1	0,35	$u_{REF} = \frac{1}{2} \cdot REF$	0,2	°
Inclination angle	B	2	1	0,01	$u_{Incl.1} = \frac{1}{\sqrt{3}} \cdot INCL.1$	0,01	°
Eccentricity	B	2	1	0,2	$u_{EXZ} = \frac{1}{\sqrt{3}} \cdot EXZ1$	0,12	°
1 = normal distribution; 2 = rectangular distribution							

The calculation of the standard measurement uncertainty in the determination of the flow direction is carried out by means of quadratic accumulation:

$$u_{Flow_dir} = (u_{CL}^{\ 2} + u_{DIR}^{\ 2} + u_{REF}^{\ 2} + u_{Incl.1}^{\ 2} + u_{EXZ1}^{\ 2})^{0,5} \quad \text{(N.3)}$$

$$u_{Flow_dir} = (0,06^2 + 0,06^2 + 0,2^2 + 0,01^2 + 0,12^2)^{0,5} = 0,25° \quad \text{(N.4)}$$

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Table N.2 – Uncertainty contributions and total standard uncertainty in wind direction sensor calibration

Factor	Uncertainty category	Uncertainty distribution	Sensitivity coefficient	Measurement uncertainty	Standard deviation	Contribution to uncertainty	Unit
Digital output signal	B	2	1	half of digital resolution	$u_{Digital} = \frac{1}{2} \cdot LSB$	-	°
Or analogue output signal	B	2	1	0,1	$u_{Analog} = \frac{1}{\sqrt{3}} \cdot ANALOG$	0,06	°
Or potentiometric sensor	B	1	1	0,2	$u_{\Omega} = \frac{1}{\sqrt{3}} \cdot \Omega$	0,12	°
Mounting of sensor	B	1	1	0,25	$u_{Mounting} = \frac{1}{\sqrt{3}} \cdot Mounting$	0,15	°
Inclination angle	B	2	1	0,01	$u_{INCL.2} = \frac{1}{\sqrt{3}} \cdot INCL.2$	0,01	°
Eccentricity	B	2	1	0,2	$u_{EXZ2} = \frac{1}{\sqrt{3}} \cdot EXZ2$	0,12	°
1 = normal distribution; 2 = rectangular distribution							

The total standard uncertainty for e.g. a potentiometric wind vane is:

$$u_{Total} = (u_{Flow_dir}{}^2 + u_{\Omega}{}^2 + u_{Mounting}{}^2 + u_{Incl.2}{}^2 + u_{Exz2}{}^2)^{0,5} \quad \text{(N.5)}$$

$$u_{Total} = (0,25^2 + 0,12^2 + 0,15^2 + 0,01^2 + 0,12^2)^{0,5} = 0,34° \quad \text{(N.6)}$$

The contribution to total standard uncertainty by the individual uncertainty sources therefore result in a total standard uncertainty of 0,34 °for k =1 for a potentiometric wind vane. Usually this value is multiplied with the coverage factor k =2.

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Annex O
(informative)

Power performance testing in cold climate

O.1 General

Power performance testing at temperatures below 0 °C may be desirable for different reasons. For example, low temperatures may be frequent or there could be a need to determine the power performance degradation due to iced blades.

Annex O gives guidance on what is important to consider when carrying out power performance tests in cold climates and to provide recommendations.

O.2 Recommendations

O.2.1 General

It is recommended to use wind speed measurement sensors that are not susceptible to ice, such as heated cup anemometers, heated ultra-sonic anemometers, and remote sensing devices or to use suitable icing detectors to reliably monitor the presence of ice and filter the data accordingly.

Equipment for power performance testing in cold climate should include reliable icing detection. There are several possibilities to detect ice, including ice detectors for atmospheric icing, ice detectors for instrumental icing, visual observation or similar. Ice accretion occurs at temperatures below, or around zero. Power performance testing at temperatures far below 0 °C could therefore be performed without any significant difficulties, provided that suitable instruments and methods are used.

Ice accretion on supports and mounting structures can have a significant effect on the flow conditions for the anemometer. It is essential that such situations are avoided. A thorough assessment or monitoring of the conditions is required. It is recommended to use sufficiently heated structures in the vicinity of the instruments to prevent ice accretion.

O.2.2 Sonic anemometers

Sonic anemometers are allowed for power performance testing provided that suitable calibration procedures and classification procedures according to Annex F and in Annex I and Clause J.4 are adhered to.

Sonic anemometers that have sufficient heating capabilities may be used because they have no moving parts and are therefore suitable to be used in cold conditions.

O.2.3 Cup anemometers

The lower temperature limit for class A anemometers may be extended from 0 °C to –30 °C in the case of proper shaft (bearing) heating. This does not remove the need for ice detection.

Extension of the temperature range below the lower limit for the class can be carried out provided that sufficient evidence can be provided that the frictional effects can be assessed and accounted for.

The classification of the anemometer with an extended temperature range can be accomplished by extending the temperature range in Annex J provided that measurements of bearing friction cover the whole temperature range.

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O.3 Uncertainties

Extended temperature range: Given by the class S.

O.4 Reporting

In addition to the normal reporting requirements, the precautions that have been adopted to ensure that the instruments that are used to measure the wind speed are not affected by ice and that low temperature effects on the measurement of the wind speed are accounted for.

The filtering for ice conditions should be individually documented. The results of the power performance test with and without the temperature extension taken into account shall be reported.

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Annex P
(informative)

Wind shear normalisation procedure

P.1 General

For deriving a climate specific power curve, the influence of the wind shear and wind veer on the power curve shall be accounted for by normalising the hub height wind speed to a pre-defined reference wind shear and wind veer. The reference wind shear and wind veer profile can have any shape and may be defined as function of the wind speed at hub height. The reference wind shear and wind veer could for instance reflect the conditions expected at the power curve test site if the purpose of the power curve test is to verify a warranted power curve that is specified for the same reference conditions. If not defined otherwise, a power law wind shear profile with shear exponent of 0,2 and a wind veer of 0° throughout the entire height range of the turbine rotor shall be applied.

The normalisation of the wind speed at hub height to the reference wind shear and wind veer shall be performed by means of the rotor equivalent wind speed concept. The kinetic energy in the wind across the rotor height range is:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho(V\cos(\varphi - \varphi_{\text{hub}}))^3 \,\mathrm{d}A \tag{P.1}$$

and the rotor equivalent wind speed that corresponds to the kinetic energy is:

$$V_{\text{eq}} = \left(\frac{1}{A}\int_i (V_i \cos(\varphi_i - \varphi_{\text{hub}}))^3 \,\mathrm{d}A_i\right)^{1/3} \tag{P.2}$$

The ratio of the rotor equivalent wind and the hub height wind speed characterises the shape of the wind shear profile and wind veer profile that is relevant for the description of the available kinetic energy at a certain wind speed at hub height. This ratio is called wind shear correction factor:

$$f_r = \frac{V_{\text{eq}}}{V_h} \tag{P.3}$$

The same rotor equivalent wind speed can be reached by different combinations of hub height wind speeds and wind shear/veer conditions, e.g. by the wind shear/veer and hub height wind speed present within a 10-minute period at the power curve test as well as by the reference wind shear / veer and a corresponding hub height wind speed (here called normalised wind speed):

$$V_{\text{eq}} = f_{r,\text{measured}} \cdot V_{h,\text{measured}} = f_{r,\text{reference}} \cdot V_{h,\text{normalised}} \tag{P.4}$$

Consequently, the wind shear/veer normalised hub height wind speed shall be calculated for each 10-minute period as:

$$V_{h,\text{normalised}} = \frac{V_{\text{eq}}}{f_{r,\text{reference}}} \tag{P.5}$$

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or as

$$V_{h,\text{normalised}} = \frac{f_{r,\text{measured}}}{f_{r,\text{reference}}} \cdot V_{h,\text{measured}} \tag{P.6}$$

For a reference wind shear correction factor of 1 ($f_{r,\text{reference}}$ = 1), i.e. in case of zero shear and veer, the normalised hub height wind speed equals the rotor equivalent wind speed. The uncertainty of the measurement of the wind shear and wind veer normalised wind speed shall be assessed according to Clause E.8, E.11.2.2 and E.11.2.3. It is pointed out that the rotor equivalent wind speed may overestimate the wind energy effectively usable by large wind turbines in case of the presence of high wind shear. Thus, a method uncertainty of one third of the correction of the hub height wind speed shall be applied as additional uncertainty to the uncertainty of the measurement of the wind shear and wind veer normalised wind speed.

Under certain conditions, the evaluation of the wind shear and wind veer over the height range of the turbine rotor may not be possible, because no measurements of the wind speed or wind direction over the height range of the turbine rotor are available or because a site calibration of the wind speed and wind direction at other heights than hub height is not possible. In this case, the lack of the integration of the wind shear/veer in the power curve evaluation shall be accounted for according to E.11.2.2.2 and E.11.2.3.2 for the desired reference wind shear/veer conditions. In addition, a method uncertainty of one third of a virtual wind speed correction from the assumed wind shear/veer conditions at the power curve test to the desired reference wind shear/veer conditions shall be taken into account.

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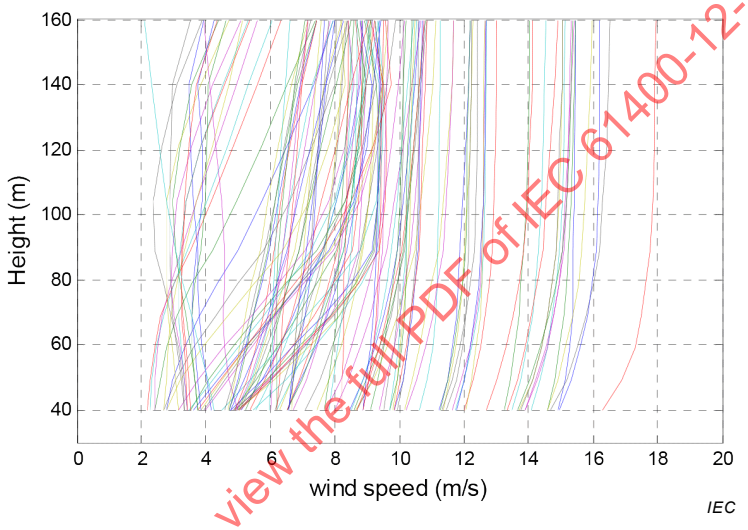
Annex Q
(informative)

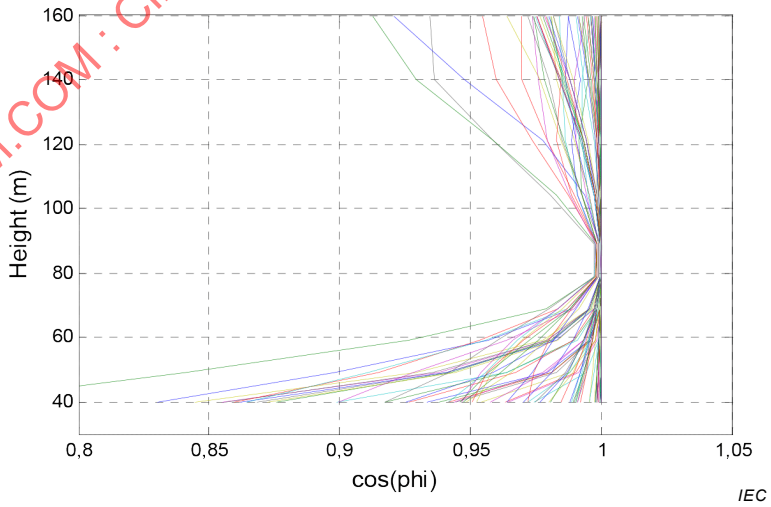
Definition of the rotor equivalent wind speed under consideration of wind veer

Q.1 General

The wind speed at hub height is not always representative of the wind over the whole rotor. Large wind speed and direction variations may be present as a result of either the atmospheric stability and/or terrain influence. Figure Q.1 shows LIDAR wind profiles over flat terrain as well as the cosine of wind direction changes relative to an assumed hub height. It is seen that the wind speed component perpendicular to the wind turbine rotor at a specific height will occasionally be much less than the wind speed at the specific height.



a) Lidar wind profiles



b) Cosine of wind direction variation angle relative to a height

Figure Q.1 – Wind profiles measured with LIDAR over flat terrain

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Therefore, the energy yield through the wind turbine rotor will depend on both the wind shear and wind veer of the specific profile. Using the power curve based on the wind speed at hub height ignores both wind shear and wind veer. The power curve obtained with the rotor equivalent wind speed depends less on the wind shear and wind veer than the power curve obtained with the wind speed at hub height.

Q.2 Definition of rotor equivalent wind speed under consideration of wind veer

The rotor equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the wind shear and wind veer. For the case that at least three measurement heights are available (see 7.2.6) the rotor equivalent wind speed is defined as

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n} \left(v_i \cos(\varphi_i) \right)^3 \frac{A_i}{A} \right)^{1/3} \qquad \text{(Q.1)}$$

where

n is the number of available measurement heights ($n \geq 3$);

v_i is the wind speed measured at height i;

φ_i is the angle difference between the wind direction at hub height and segment i;

A is the area swept by the rotor (i.e. πR^2 with radius R);

A_i is the area of the i^{th} segment, i.e. the segment the wind speed v_i represents (refer to 9.1.3.2, Equation (6).

Q.3 Measurement of wind veer

The rotor equivalent wind speed as defined in Equation (Q.1) is influenced by the difference of wind direction measurements at various heights relative to hub height. In order to provide accurate measurements of the difference of wind directions, it is important to measure the wind directions at the different height levels with the same type of sensor, i.e. one remote sensing device measuring all heights, or same sensors on the meteorological mast at all heights.

Q.4 Combined wind shear and wind veer normalisation

The procedures described in Annex P may be extended to referencing back the measured power curve to reference wind veer conditions by considering also a reference wind veer profile in addition to a reference wind shear profile. The integration of the reference profiles over the rotor area shall be done according to Equation (Q.1).

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Annex R
(informative)

Uncertainty considerations for tests on multiple turbines

R.1 General

Annex R addresses the uncertainty considerations that arise when compiling test results from multiple turbines. When testing multiple turbines, the quantities of interest are typically the mean AEP of the sample and the uncertainty in that mean. The mean AEP can most simply be determined by taking a simple average of the individual turbine AEPs.

The determination of the uncertainty in the average AEP is not as straightforward. As this is a frequently encountered situations, this standard provides an informative approach as to how this uncertainty may be estimated. The mathematical framework for this approach is exactly the same as explained in IEC 61400-12-2:2013 Annex I and J and will not be repeated here. What is different for this standard is Table R.1 of estimated correlations between tests on different turbines and the results as represented in Figures J.1 and J.2 of IEC 61400-12-2:2013, which will be repeated here. As an introduction, a short discussion of the problem at hand will be repeated.

One approach to combining uncertainties is a simple average of the individual test uncertainties. However, the simple average fails to account for the chief benefit of multiple tests, i.e. a reduction in the combined test uncertainty. A second approach is to calculate the standard uncertainty of the mean of the uncertainties:

$$u_{AEP_{\mathrm{AVG}}} = \frac{1}{L}\sqrt{\sum_{i=1}^{L} u_{AEP,i}^2} \tag{R.1}$$

where

$u_{AEP_{\mathrm{AVG}}}$ [50] is the uncertainty in the average AEP;

$u_{AEP,i}$ is the uncertainty in AEP for turbine i;

L is the number of turbines tested.

Equation (R.1) assumes full independence among the individual turbine test results, meaning there is no correlation in the individual test results from one unit to the next. As a consequence application of Equation (R.1) would lead to an underestimation of the uncertainty in the average AEP. Therefore, in order to accurately assess the uncertainty in the average AEP, it is necessary to identify a practical method for handling correlated uncertainty components. An approach is suggested based on the ISO information publication '*Guide to the expression of uncertainty in measurement*' with minor adjustments in the handling of correlation.

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50 Please note that the equation here is slightly different from the equation in IEC 61400-12-2. As this is the uncertainty of an average and division by $1/L$ is a linear transformation, we get a $1/L^2$ under the square root or a $1/L$ in front of the square root.

Table R.1 – List of correlated uncertainty components

Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
Electric power	Current transformers	$\rho_{up1,m,n}$	Same instrument make Different instrument make	0,9 0,1	C_{Ts} of the same make tend to have similar cat B error values relative to the true value.
	Voltage transformers	$\rho_{up2,m,n}$	Same instrument make Different instrument make	0,9 0,1	V_{Ts} of the same make tend to have similar cat B error. Direct measurement of voltage eliminates this uncertainty.
	Power transducer or power measurement device	$\rho_{up3,m,n}$	Same instrument make Different instrument make	0,9 0,1	Power measurement devices of the same make tend to have similar cat B error.
	Dynamic power measurement	$\rho_{up4,m,n}$	Same instrument make Different instrument make	0,9 0,1	Power measurement devices of the same make tend to have similar cat B error.
	Data acquisition	$\rho_{udp,m,n}$	Same instrument make Different instrument make	0,9 0,1	Data acquisition devices of the same make tend to have similar cat B errors relative to the true value.
Wind speed	Anemometer calibration	$\rho_{uv1,m,n}$	Shared instrument (same met mast) Different masts, same make/model, same calibration lab Different masts, different make/model, same calibration lab Different masts, same make/model, different calibration labs Different masts, different make/model, different calibration labs	1,0 0,9 0,7 0,4 0,1	Calibration reference and method produces similar cat B error.
	PostCal / In-situ cal	$\rho_{uv2,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,7	Anemometers of the same make tend to have similar cat B errors relative to the true value.
	Operational uncertainty	$\rho_{uv3,m,n}$	Shared Instrument (same masts) Same instrument make Different instrument make	1,0 0,9 0,8	Anemometers of the same make tend to have similar cat B errors relative to the true value.
	Mounting effects	$\rho_{uv4,m,n}$	Per specification in this standard	0,9	Similar mounting required for use of a given transfer function drives a correlated uncertainty.
	DAQ	$\rho_{uv5,m,n}$	Shared DAQ Different DAQ of same make, same design Different DAQ of different make, same design Different DAQ of same make, different design Different DAQ of different make, different design	1,0 0,9 0,7 0,5 0,2	DAQ will be correlated the more similar the setup is.

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Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
	Flow distortion due to terrain without site cal	$\rho_{uv6,m,n}$	Both turbines $2D$ to $3D$ (or $3D$ to $4D$) from met mast	0,9	Increased terrain complexity and variation in terrain amongst test units will tend to have dis-similar cat B errors on the wind speed relative to the true value, distance plays an important role.
			One turbine $2D$ to $3D$ and one turbine $3D$ to $4D$	0,6	
	Flow distortion due to terrain amongst test units with site cal, anemometer calibration	$\rho_{uv7,m,n}$	Shared instrument (same met mast)	1,0	
			Different masts, same make/model, same calibration lab	0,9	
			Different masts, different make/model, same calibration lab	0,7	
			Different masts, same make/model, different calibration labs	0,4	
			Different masts, different make/model, different calibration labs	0,1	
	Flow distortion due to terrain amongst test units with site cal, operational uncertainty	$\rho_{uv7,m,n}$	Shared instruments (same masts)	1,0	
			Different masts, same make/model)	0,9	
			Different masts, different make/model	0,7	
	Data acquisition for site calibration	$\rho_{udv,m,n}$	Shared DAQ	1,0	Data acquisition devices of the same make tend to have similar cat B error.
			Different DAQ of same make, same design	0,9	
			Different DAQ of different make, same design	0,7	
			Different DAQ of same make, different design	0,5	
			Different DAQ of different make, different design	0,2	
Tempera-ture	Temperature sensor	$\rho_{ut1,m,n}$	Shared instruments(same met mast)	1,0	Temperature measurement devices of the same make tend to have similar cat B error.
			Same instrument make	0,9	
			Different instrument make	0,1	
	Radiation shielding	$\rho_{ut2,m,n}$	Shared instruments(same met mast)	1,0	Radiation shields tend to have the same method errors relative to the true value.
			Same instrument make	0,9	
			Different instrument make	0,6	
	Mounting effects	$\rho_{ut3,m,n}$	Shared instruments(same met mast)	1,0	
			Same location and mounting	0,9	
			Different location or mounting	0,1	
	Data acquisition	$\rho_{udt,m,n}$	Shared instruments(same met mast)	0,9	Data acquisition devices of the same make tend to have similar cat B error.
			Same instrument make	0,1	
			Different instrument make		

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Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
Pressure	Pressure sensor	$\rho_{ub1,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	Pressure measurement devices of the same make tend to have similar cat B error.
	Mounting effects	$\rho_{ub2,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	If using multiple instruments, mounting will likely be similar.
	Data acquisition	$\rho_{udb,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	Data acquisition devices of the same make tend to have similar cat B error.
Method	Air density correction	$\rho_{um1,m,n}$	Same correction methodology for all turbines	1,0	
	Wind Conditions	$\rho_{um2,m,n}$	Same conditions for different turbines	1,0	
	Seasonal variation	$\rho_{um3,m,n}$	Testing occurs during the same time of year Testing occurs during different time of year	1,0 0,6	
Statistical	Variance in electrical power	$\rho_{sp,m,n}$		0,0	Inherently random and independent.

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Annex S
(informative)

Mast flow distortion correction for lattice masts

Annex S gives guidance regarding a possible method to determine a correction for flow distortion of side mounted anemometers. Such a correction is already discussed in 7.2.4 as well as 9.1.2. In this annex, a more detailed approach is presented for a lattice mast.

A similar method may work for other types of mast configuration but it is likely that specific changes need to be made to allow for the differences in the configuration. Other methods to determine a correction may be applied but shall be documented in sufficient detail to allow the results to be reproduced by a third party based on the reported information.

The starting point is to do a linear regression between two anemometers installed on different booms at the same measurement height. The residuals of the regression can be determined and plotted against wind direction for the full 0° to 360° sector. Other filters may be applied to ensure data quality. This plot will normally show two things:

a) for specific directions large flow distortions will be visible, indicated wakes operation from mast, guy wires or other sensors;

b) a slowly changing sine wave is normally visible with a period of 360°.

An example is given in Figure S.1 below. This example is for a goal-post design for the top of the mast but it illustrates the expected signal behaviour. As shown in the graph, it may be beneficial to also plot the expected wakes as determined from the geometric set-up as this will help to correctly interpret the plot. Care should be taken when there are too many and/or too strong wakes, from masts, guys and other sensors as the wakes may overshadow the sine-wave we are interested in and thereby make this method impractical or impossible to apply.

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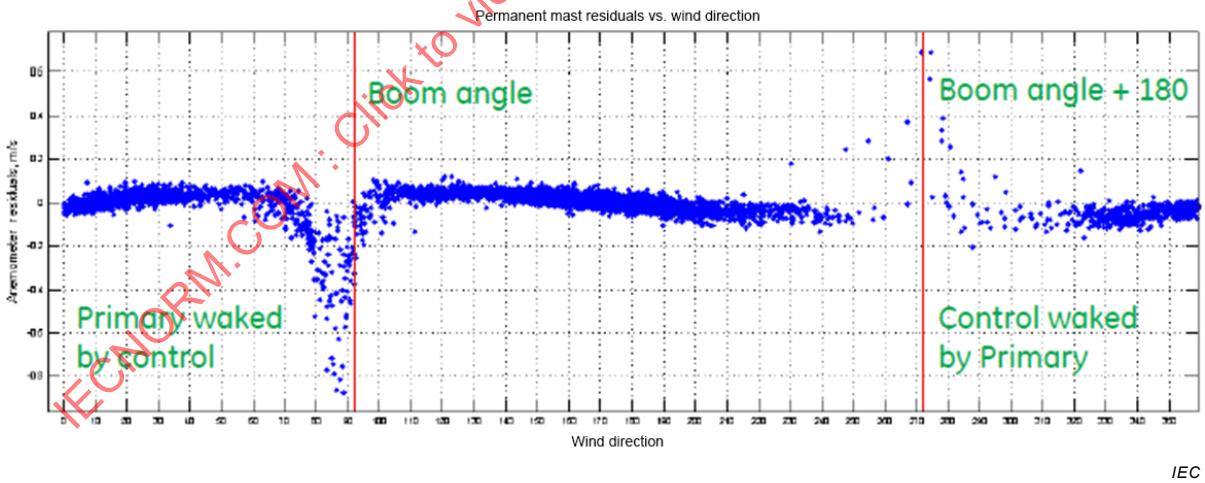

Figure S.1 – Example of mast flow distortion

The sine wave is the flow distortion from the mast and other hardware at the same measurement height that we aim at correcting. This is done by finding suitable values for the parameters in this equation:

$$V_1 = m \cdot V_2 + B + A\sin(\mathrm{WD} + Centre) \quad \text{(S.1)}$$

where

V_1 is the wind speed from sensor one;

V_2 is the wind speed from the second sensor;

m is the slope of the regression between V_1 and V_2;

B is the offset of the regression between V_1 and V_2;

A is a scaling parameter;

WD is the wind direction.

Centre is the wind direction where the residuals are expected to be zero; In the above examples where the boom angles are 92° and 272°, *Centre* = 182°. Figure G.3, Figure G.6 and Figure G.8 may be useful in assessing the directions where flow distortion is equal at both sensor locations. Solutions within the measurement sector (or closest to) are most useful.

A is a scaling parameter that we need to solve for. A can be found by iteration; by first setting A to zero and picking another point in the data (keeping away from the wakes data), we can determine the current value for the residuals. In the graph above we see a residual value of 0,03 at 150° and a residual value of 0 at 182°. Now we define *Centre* = 182° and require a value of zero for V_1 at 150°. This determines value for A of 0,06 (note the negative sign for the sine at an angle of 150°+180° = 330°). Further checking of other points is recommended to make sure we have the right value for A and that this is not based on accidental outlier data.

A reflects the magnitude of the sum effect of the flow distortion on both anemometers. Therefore, each anemometer wind speed must be corrected by half of amplitude A according to Equations (S.2) and (S.3) below:

$$V_{1\text{corr}} = V_1 + \frac{A}{2}\sin(\text{WD} + Centre) \tag{S.2}$$

$$V_{2\text{corr}} = V_2 - \frac{A}{2}\sin(\text{WD} + Centre) \tag{S.3}$$

The flow distortion correction shown here does not correct to zero flow distortion but only normalizes to the direction where the flow distortion effect is the same at both anemometers. The direction at which the flow distortion is zero may be estimated from the flow speed graphs in Clause G.4, and the final flow correction can be adjusted accordingly.

The corrected wind speeds can now be used to recalculate residuals, which can be plotted in the same graph to show the improvement. The residuals of the corrected signal (in red) are clearly less depending on wind direction than the original (in blue), as shown in Figure S.2.

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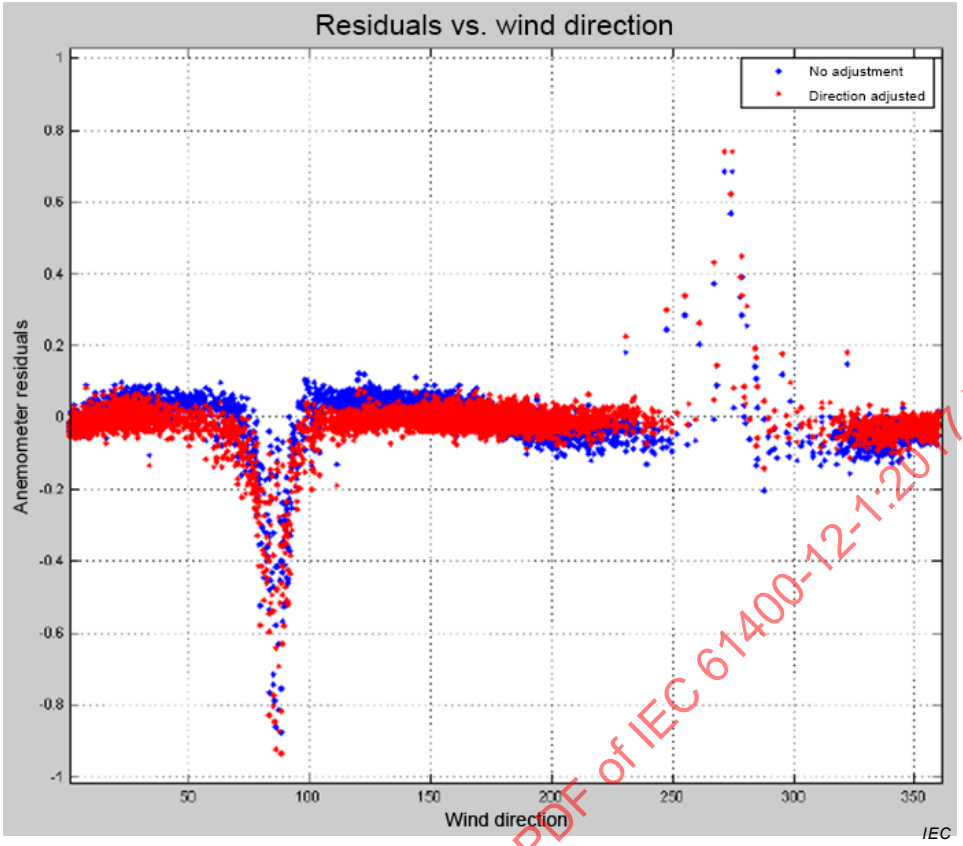

Figure S.2 – Flow distortion residuals versus direction

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Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines

Systèmes de génération d'énergie éolienne – Partie 12-1: Mesures de performance de puissance des éoliennes de production d'électricité

IEC 61400-12-1:2017-03(en-fr)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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WIND ENERGY GENERATION SYSTEMS –

Part 12-1: Power performance measurements of electricity producing wind turbines

FOREWORD

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International Standard IEC 61400-12-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This second edition cancels and replaces the first edition published in 2005. This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

a) new definition of wind speed,
b) inclusion of wind shear and wind veer,
c) revision of air density correction,
d) revision of site calibration,
e) revision to definition of power curve,
f) interpolation to bin centre method,
g) revision of obstacle model,

h) clarification of topography requirements,
i) new annex on mast induced flow distortion,
j) revision to anemometer classifications,
k) inclusion of ultrasonic anemometers,
l) cold climate annex added,
m) database A changed to special database,
n) revision of uncertainty annex,
o) inclusion of remote sensing.

IEC 61400-12-2 is an addition to IEC 61400-12-1.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/610/FDIS	88/617/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

A list of all parts in the IEC 61400, published under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee recognizes that this revision represents a significant increase in complexity and perhaps greater difficulty to implement. However, it represents the committee's best attempt to address issues introduced by larger wind turbines operating in significant wind shear and complex terrain. The committee recommends that the new techniques introduced be validated immediately by test laboratories through inter-lab proficiency testing. The committee recommends a Review Report be written within three years of the release of this document which includes recommendations, clarifications and simplifications that will improve the practical implementation of this standard. If necessary a revision should be proposed at the same time to incorporate these recommendations, clarifications and simplifications.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigenda of September 2019 and March 2020 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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INTRODUCTION

The purpose of this part of IEC 61400 is to provide a uniform methodology that will ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. The standard has been prepared with the anticipation that it would be applied by:

a) a wind turbine manufacturer striving to meet well-defined power performance requirements and/or a possible declaration system;

b) a wind turbine purchaser in specifying such performance requirements;

c) a wind turbine operator who may be required to verify that stated, or required, power performance specifications are met for new or refurbished units;

d) a wind turbine planner or regulator who shall be able to accurately and fairly define power performance characteristics of wind turbines in response to regulations or permit requirements for new or modified installations.

This document provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines. The document will benefit those parties involved in the manufacture, installation planning and permitting, operation, utilization, and regulation of wind turbines. The technically accurate measurement and analysis techniques recommended in this standard should be applied by all parties to ensure that continuing development and operation of wind turbines is carried out in an atmosphere of consistent and accurate communication relative to wind turbine performance. This document presents measurement and reporting procedures expected to provide accurate results that can be replicated by others. Meanwhile, a user of the standard should be aware of differences that arise from large variations in wind shear and turbulence. Therefore, a user should consider the influence of these differences and the data selection criteria in relation to the purpose of the test before contracting the power performance measurements.

A key element of power performance testing is the measurement of wind speed. This document prescribes the use of cup or sonic anemometers or remote sensing devices (RSD) in conjunction with anemometers to measure wind. Even though suitable procedures for calibration/validation and classification are adhered to, the nature of the measurement principle of these devices may potentially cause them to perform differently. These instruments are robust and have been regarded as suitable for this kind of test with the limitation of some of them to certain classes of terrain.

Recognising that, as wind turbines become ever larger, a wind speed measured at a single height is increasingly unlikely to accurately represent the wind speed through the entire turbine rotor, this standard introduces an additional definition of wind speed. Whereas previously wind speed was defined as that measured at hub height only, this may now be supplemented with a so called Rotor Equivalent Wind Speed (REWS) defined by an arithmetic combination of simultaneous measurements of wind speed at a number of heights spanning the complete rotor diameter between lower tip and upper tip. The power curves defined by hub height wind speed and REWS are not the same and so the hub height wind speed power curve is always presented for comparison whenever a REWS power curve is measured. As a consequence of this difference in wind speed definition, the annual energy production (AEP) derived from the combination of a measured power curve with a wind speed distribution uses an identical definition of wind speed in both the power curve and the wind speed distribution.

Procedures to classify cup anemometers and ultrasonic anemometers are given in Annexes I and J. Procedures to classify remote sensing devices are given in Annex L. Special care should be taken in the selection of the instruments chosen to measure the wind speed because it can influence the result of the test.

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WIND ENERGY GENERATION SYSTEMS –

Part 12-1: Power performance measurements of electricity producing wind turbines

1 Scope

This part of IEC 61400 specifies a procedure for measuring the power performance characteristics of a single wind turbine and applies to the testing of wind turbines of all types and sizes connected to the electrical power network. In addition, this standard describes a procedure to be used to determine the power performance characteristics of small wind turbines (as defined in IEC 61400-2) when connected to either the electric power network or a battery bank. The procedure can be used for performance evaluation of specific wind turbines at specific locations, but equally the methodology can be used to make generic comparisons between different wind turbine models or different wind turbine settings when site-specific conditions and data filtering influences are taken into account.

The wind turbine power performance characteristics are determined by the measured power curve and the estimated annual energy production (AEP). The measured power curve, defined as the relationship between the wind speed and the wind turbine power output, is determined by collecting simultaneous measurements of meteorological variables (including wind speed), as well as wind turbine signals (including power output) at the test site for a period that is long enough to establish a statistically significant database over a range of wind speeds and under varying wind and atmospheric conditions. The AEP is calculated by applying the measured power curve to reference wind speed frequency distributions, assuming 100 % availability.

This document describes a measurement methodology that requires the measured power curve and derived energy production figures to be supplemented by an assessment of uncertainty sources and their combined effects.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60688:2012, *Electrical measuring transducers for converting A.C. and D.C. electrical quantities to analogue or digital signals*

IEC 61400-12-2:2013, *Wind turbines – Part 12-2: Power performance of electricity-producing wind turbines based on nacelle anemometry*

IEC 61869-1:2007, *Instrument transformers – Part 1: General requirements*

IEC 61869-2:2012, *Instrument transformers – Part 2: Additional requirements for current transformers*

IEC 61869-3:2011, *Instrument transformers – Part 3: Additional requirements for inductive voltage transformers*

ISO/IEC GUIDE 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

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ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

ISO/IEC 17043:2010, *Conformity assessment – General requirements for proficiency testing*

ISO 2533:1975, *Standard atmosphere*

ISO 3966:2008, *Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accuracy
closeness of the agreement between the result of a measurement and a true value of the measurand

3.2
annual energy production
AEP
estimate of the total energy production of a wind turbine during a one-year period by applying the measured power curve to different reference wind speed frequency distributions at hub height, assuming 100 % availability

3.3
atmospheric stability
a measure of tendency of the wind to encourage or suppress vertical mixing

Note 1 to entry: Stable atmosphere is characterized by a high temperature gradient with altitude, high wind shear, possible wind veer and low turbulence relative to unstable conditions. Neutral and unstable atmosphere generally result in lower temperature gradients and low wind shear.

3.4
complex terrain
terrain surrounding the test site that features significant variations in topography and terrain obstacles (refer to 3.18) that may cause flow distortion

3.5
cut-in wind speed
the lowest wind speed at which a wind turbine will begin to produce power

3.6
cut-out wind speed
the wind speed at which a wind turbine cuts out from the grid due to high wind speed

3.7
data set
a collection of data sampled over a continuous period

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3.8
distance constant
indication of the response time of an anemometer, defined as the length of air that shall pass the instrument for it to indicate 63 % of the final value for a step input in wind speed

3.9
extrapolated power curve
extension of the measured power curve by estimating power output from the maximum measured wind speed to cut-out wind speed

3.10
flow distortion
change in air flow caused by obstacles, topographical variations, or other wind turbines that results in the wind speed at the measurement location to be different from the wind speed at the wind turbine location

3.11
hub height (of wind turbines)
height of the centre of the swept area of the wind turbine rotor above the ground at the tower

Note 1 to entry: For a vertical axis wind turbine the hub height is defined as the height of the centroid of the swept area of the rotor above the ground at the tower.

3.12
measured power curve
table and graph that represents the measured, corrected and normalized net power output of a wind turbine as a function of measured wind speed, measured under a well-defined measurement procedure

3.13
measurement period
period during which a statistically significant database has been collected for the power performance test

3.14
measurement sector
a sector of wind directions from which data are selected for the measured power curve

3.15
method of bins
data reduction procedure that groups test data for a certain parameter into intervals (bins)

Note 1 to entry: For each bin, the number of data sets or samples and their sum are recorded, and the average parameter value within each bin is calculated.

3.16
net active electric power
measure of the wind turbine electric power output that is delivered to the electrical power network

3.17
normal maintenance
any intervention which is done according to a defined regular maintenance program, independent from the fact that a power performance test is being done, e.g. oil change, blade washing (if due anyway, i.e. independent from the power performance test) and any intervention which is out of the scope of the regular maintenance program (e.g. repair of a failed component) and which is not a machine configuration change

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3.18
obstacles
obstructions that block the wind and create distortion of the flow, such as buildings and trees

3.19
pitch angle
angle between the chord line at a defined blade radial location (usually 100 % of the blade radius) and the rotor plane of rotation

3.20
power coefficient
ratio of the net electric power output of a wind turbine to the power available in the free stream wind over the rotor swept area

3.21
power performance
measure of the capability of a wind turbine to produce electric power and energy

3.22
rated power
quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

3.23
rotor equivalent wind speed
wind speed corresponding to the kinetic energy flux through the swept rotor area when accounting for the variation of the wind speed with height, as represented in Equation (5)

3.24
special maintenance
any intervention which is out of the scope of the regular maintenance program and which is not a machine configuration change, i.e. any intervention which is done in order to improve the power performance during a test period, e.g. an unscheduled blade washing, any replacement of an essential component

3.25
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

3.26
swept area
for a horizontal axis wind turbine, the projected area of the moving rotor upon a plane normal to axis of rotation

Note 1 to entry: For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft. For a vertical axis wind turbine, the projected area of the moving rotor upon a vertical plane.

3.27
test site
location of the wind turbine under test and its surroundings

3.28
uncertainty in measurement
parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to the measurand

3.29
wind measurement equipment
meteorological mast or remote sensing device

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3.30
wind shear
change of wind speed with height across the wind turbine rotor

3.31
wind shear exponent
exponent α of the power law defining the variation of wind speed with height

Note 1 to entry: This parameter is used as a measure of the magnitude of wind shear for site calibration in Annex C and may be otherwise useful. The power law equation is

$$v_{zi} = v_h \left(\frac{z_i}{H} \right)^{\alpha} \quad (1)$$

where

v_h is the hub height wind speed;

H is the hub height (m);

v_{zi} is the wind speed at height z_i;

α is the wind shear exponent.

3.32
wind veer
change of wind direction with height across the wind turbine rotor

4 Symbols and units

A	swept area of the wind turbine rotor	[m^2]
A_i	area of the i^{th} wind turbine rotor segment	[m^2]
A_w	Weibull scale factor	[m/s]
AEP	annual energy production	[Wh]
B	barometric pressure	[Pa]
B_{10min}	measured air pressure averaged over 10 min	[Pa]
Ch	pitot tube head coefficient	
$C_{P,i}$	power coefficient in bin i	
C_{QA}	generalized aerodynamic torque coefficient	
C_T	thrust coefficient	
c	sensitivity factor of a parameter (the partial differential)	
$c_{B,i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{d,i}$	sensitivity factor of data acquisition system in bin i	
c_{index}	sensitivity factor of index parameter	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{T,i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{V,i}$	sensitivity factor of wind speed in bin i	[Ws/m]
$c_{\rho,i}$	sensitivity factor of air density correction in bin i	[Wm^3/kg]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
Dn	rotor diameter of neighbouring and operating wind turbine	[m]
d	meteorological mast diameter	[m]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
f_i	the relative occurrence of wind speed in a wind speed interval	

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$f_{r,MM}$	wind shear correction factor, measured using meteorological mast mounted instruments	
$f_{r,RSD}$	wind shear correction factor, measured using a remote sensing device	
H	hub height of wind turbine	[m]
h	height of obstacle	[m]
I	inertia of cup anemometer rotor	[kgm^2]
k	class number	
k	Weibull shape factor	
k_b	blockage correction factor	
k_c	wind tunnel calibration factor	
k_f	wind tunnel correction factor to other tunnels (only used in uncertainty estimate)	
k_ρ	humidity correction to density	
$K_{B,t}$	barometer sensitivity	[N/m^{2}V]
$K_{B,s}$	barometer gain	
$K_{B,d}$	barometer sampling conversion	
$K_{T,t}$	temperature transducer sensitivity	[K/A]
$K_{T,s}$	temperature transducer gain	[A/V]
$K_{T,d}$	temperature transducer sampling conversion	
$K_{p,t}$	pressure transducer sensitivity	
$K_{p,s}$	pressure transducer gain	
$K_{p,d}$	pressure transducer sampling conversion	
L_m	distance between adjacent legs of lattice meteorological mast	[m]
L	distance between the wind turbine and the wind measurement equipment	[m]
L_e	distance between the wind turbine or the wind measurement equipment and an obstacle	[m]
L_n	distance between the wind turbine or the wind measurement equipment and a neighbouring and operating wind turbine	[m]
l_h	height of obstacle	[m]
l_w	width of obstacle	[m]
M	number of uncertainty components in each bin	
M_A	number of category A uncertainty components	
M_B	number of category B uncertainty components	
N	number of bins	
N_h	number of hours in one year ≈ 8 760	[h]
N_i	number of 10 min data sets in wind speed bin i	
N_j	number of 10 min data sets in wind direction bin j	
n	number of samples within sampling interval	
n_h	number of available measurement heights	
P_o	porosity of obstacle (0: solid, 1: no obstacle)	
P_i	normalized and averaged power output in bin i	[W]
P_n	normalized power output	[W]
$P_{n,i,j}$	normalized power output of data set j in bin i	[W]
P_{10min}	measured power averaged over 10 min	[W]
P_w	vapour pressure	[Pa]
Q_A	aerodynamic torque	[Nm]

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Q_f	friction torque	[Nm]
R	rotor radius	[m]
R_0	gas constant of dry air (287,05)	[J/kgK]
R_d	distance to meteorological mast centre	[m]
R_w	gas constant of water vapour (461,5)	[J/kgK]
RSD	remote sensing device	
r	correlation coefficient	
s	category A standard uncertainty component	
s_A	category A standard uncertainty of tunnel wind speed time series	
$s_{k,i}$	category A standard uncertainty of component k in bin i	
s_i	combined category A uncertainties in bin i	
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
s_{sc}	category A standard uncertainty of site calibration	[m/s]
$s_{w,i}$	category A standard uncertainty of climatic variations	[Wh]
$s_{\alpha,j}$	category A standard uncertainty of wind speed ratios in bin j	
S	meteorological mast solidity	
T	absolute temperature	[K]
TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	[K]
t	time	[s]
U	wind speed	[m/s]
U_d	centreline wind speed deficit	[m/s]
U_{eq}	equivalent horizontal wind speed	[m/s]
U_i	wind speed in bin i	[m/s]
U_t	threshold wind speed	[m/s]
U	wind speed vector	
u	category B standard uncertainty component	
u_{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	[Pa]
$u_{c,i}$	combined standard uncertainty of the power in bin i	[W]
u_i	combined category B uncertainties in bin i	
u_{index}	category B standard uncertainty of index parameter	
$u_{k,i}$	category B standard uncertainty of component k in bin i	
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[m/s]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
$u_{\alpha,i,j}$	combined standard uncertainty of site calibration in wind speed bin i and wind direction bin j	[m/s]
$u_{\rho,i}$	category B standard uncertainty of air density correction in bin i	[kg/m^3]
V	wind speed	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_i	normalized and averaged wind speed in bin i	[m/s]
V_n	normalized wind speed	[m/s]
$V_{n,i,j}$	normalized wind speed of data set j in bin i	[m/s]
V_{10min}	measured wind speed averaged over 10 min	[m/s]

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v	transversal wind speed component	[m/s]
$\bar{v}$	mean flow air speed	[m/s]
v_{eq}	measured equivalent wind speed	[m/s]
$v_{eq,final}$	final rotor equivalent wind speed	[m/s]
$v_{eq,MM}$	equivalent wind speed based on meteorological mast measurements	[m/s]
$v_{eq,RSD}$	equivalent wind speed based on remote sensing device measurements	[m/s]
v_h	hub height wind speed	[m/s]
$v_{h,MM}$	wind speed measured at hub height with meteorological mast	[m/s]
v_{hn}	hub height wind speed normalised for a specific wind shear profile	[m/s]
$v_{h,RSD}$	wind speed measured at hub height by the remote sensing device	[m/s]
v_i	wind speed measured at height i	[m/s]
v_{zi}	wind speed at height z_i	[m/s]
WME	wind measurement equipment	
w	vertical wind speed component	[m/s]
w_i	weighting function to define deviation envelope	
X_k	parameter averaged over pre-processing time period	
X_{10min}	parameter averaged over 10 min	
x	distance downstream from obstacle to wind measurement equipment or wind turbine	[m]
z	height above ground	[m]
z_i	height of the i^{th} wind turbine rotor segment	[m]
α	wind shear exponent from power law	[°]
$\varepsilon_{max,i}$	maximum deviation for any wind speed bin i in the wind speed range	[m/s]
θ	disturbed sector	[°]
κ	von Karman constant 0,4	
λ	speed ratio	
ρ	air density	[kg/m^3]
ρ_0	reference air density	[kg/m^3]
ρ_{10min}	derived air density averaged over 10 min	[kg/m^3]
$\sigma_{P,i}$	standard deviation of the normalized power data in bin i	[W]
σ_{10min}	standard deviation of parameter averaged over 10 min	
$\sigma_u/\sigma_v/\sigma_w$	standard deviations of longitudinal/transversal/vertical wind speeds	
Φ	relative humidity (range 0 % to 100 %)	
ω	angular speed	[s^{-1}]

5 Power performance method overview

The wind shear and wind veer may vary significantly over the rotor height of large wind turbines for atmospheric stability conditions and it is also dependent on topography at the site. The occurrence of extreme atmospheric stability conditions is a site specific issue, and if occurring during a power performance test, the power curve may vary significantly.

The power performance measurement method used in this standard is based on a definition of the power curve that expresses power produced versus the wind speed that represents effectively the kinetic energy flux in the wind flowing across the swept area of the rotor.

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The kinetic energy flux (referring to a certain point in time or period of time, typically 10 min, assuming that the wind speed does not change within this time[1]) across the vertical capture area is in general terms expressed as:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho V^3 \,\mathrm{d}A \tag{2}$$

Here the wind speed V, measured at a point in space over the rotor area, is the horizontal wind speed[2]. The horizontal wind speed is defined as the average magnitude of the horizontal component of the instantaneous wind velocity vector, including only the longitudinal and lateral (but not the vertical) components. When we consider a horizontal axis wind turbine the wind veer is also taken into account and the kinetic energy in the wind is corrected according to the wind direction at hub height:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho \left(V\cos\left(\varphi - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A \tag{3}$$

Here φ_{hub} is the wind direction at hub height. The wind veer may vary significantly over the rotor height of large wind turbines for extreme atmospheric stability conditions and it is also dependent on topography at the site.

In this standard we do not consider wind shear and wind veer in the horizontal plane. Thus the energy equivalent wind speed that corresponds to the kinetic energy in the wind as derived from the expression of kinetic energy in Equation (3) in general is described as:

$$V_{\text{eq}} = \left(\frac{1}{A}\int_i \left(V_i\cos\left(\varphi_i - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A_i\right)^{1/3} \tag{4}$$

Here the index i refers to the height within the rotor area[3].

Although horizontal wind speed is considered to be the influential wind speed parameter, on sites with significant non-horizontal flow (up or down-flow), there is additional uncertainty associated with both the measurement of the horizontal wind speed and the response of the wind turbine.

At sites with low and homogeneous wind shear and wind veer over the rotor (and for turbines with small rotor diameters in possibly more complex wind flow conditions), the wind speed measured at hub height can be a good representation of the kinetic energy to be captured by the rotor. Hub height wind speed is the wind speed upon which power curves have historically been defined in all previous editions of this standard. For that reason, the wind speed measured at hub height is the default definition of wind speed and shall always be measured and reported, even when more comprehensive measurements of wind speed are available over the rotor height.

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1 If the wind speed changes (i.e. if the turbulence intensity is >0) during a certain time period, then the kinetic power (averaged over this time period) is higher than in case of a constant wind speed, whereas a wind turbine has only a limited possibility to transform this additional kinetic power into additional electric power. This issue is not taken into further consideration here. As a simplification, the Equations (2), (3) , (4) are considered valid here, even in case of a turbulence intensity >0. The impact of wind speed changes on the time averaged kinetic power and the associated impact on the wind turbine power curve is treated by the turbulence normalisation procedure as included in Annex M.

2 Wind turbine power seems to correlate better with the horizontal wind speed definition than with a vector wind speed definition for a one point hub height wind speed measurement.

3 However when wind speed is mentioned in the document, it is by default referring to the hub height wind speed definition unless specifically stated to be this energy equivalent wind speed definition.

At sites and seasons where extreme atmospheric stability conditions are expected to be frequent, it is recommended always to measure wind shear.

If wind shear and wind veer are not measured over the full height of the rotor, there is added uncertainty in the equivalent wind speed. This uncertainty decreases as more wind speed and wind direction measurement heights are used. If measurements are limited to only hub height and there is no measurement of wind shear over the most significant parts of the rotor then this implies an uncertainty in determination of the equivalent wind speed.

For small wind turbines[4], where the influence of the wind shear and wind veer are insignificant, the wind speed shall be represented by a hub height wind speed measurement alone without adding uncertainty due to lack of wind shear and wind veer measurements.

For vertical axis wind turbines, where the influence of the wind veer is not present, the wind veer shall be neglected.

As the wind conditions at the position of the test turbine and at the position of the wind measurement may differ significantly if the test turbine or the wind measurement is located in wakes of any wind turbines, such situations shall be excluded from the test.

The air density ρ also varies over the height of a large wind turbine rotor. However, this variation is small. For practical implementation of the power performance measurement method, it is sufficient to define and determine the air density only at hub height. The power curve is normalized to the average air density at the measurement site over the measurement period or to a pre-defined reference air density.

Power curves are also influenced by the turbulence at the test site, and turbulence may vary over the rotor. In this standard, only the site turbulence at hub height is considered. High turbulence increases the radius of curvature of the power curve at cut-in and at the start of power regulation at nominal power while low turbulence will make these corners of the power curve sharper. Site turbulence shall be measured and presented as a supplement to the power curve. If needed, a normalisation to a specified turbulence can be done using the method of Annex M.

In summary, the power curve according to this standard is a climate specific power curve, where:

a) the wind speed at a point in space is defined as the horizontal wind speed;

b) the wind speed of a power curve is defined as the hub height wind speed. This definition may be supplemented with the equivalent wind speed, as defined in Equation (4), taking account of vertical wind shear and wind veer[5];

c) air density is measured at hub height and the power curve is normalized to a site average air density during the measurement period or to a pre-defined reference air density;

d) turbulence is measured at hub height and the power curve is presented without a turbulence normalization;

e) the power curve can be normalized to a broader range of climatic conditions (e.g. specific air density, turbulence intensity, vertical shear and veer)[6].

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4 Small turbines, refer to IEC 61400-2.

5 For vertical axis wind turbines, the wind veer is omitted in Equation (3) (setting $\varphi_i = \varphi_{\text{hub}}$).

6 The power curve normalization is only valid for limited ranges of climatic conditions from the actual site conditions.

In this standard, all necessary procedures for measurements, calibration, classification, data correction, data normalization and determination of uncertainties are provided. However, if not all parameters are sufficiently measured, then uncertainty shall be applied due to the lack of measurement. This applies, for example, to the measurement of a power curve of a large wind turbine with only a hub height wind speed sensor. In this case, an uncertainty shall be applied for the variability of the wind shear and of the wind veer.

The best results from the use of the standard are achieved by measurement of all required parameters and use of all relevant procedures. However, if this is not possible, there are options both for the measurement setup and for the use of the procedures. These options are described in Table 1. The options refer to the use of wind measurement equipment, the applied normalizations, and additional uncertainties connected to the lack of measurements.

Table 1 – Overview of wind measurement configurations for power curve measurements that meet the requirements of this standard

Wind measurement configuration	1. Meteorology mast to hub height and remote sensing to all heights	2. Meteorology mast below hub height and remote sensing to all heights	3. Meteorology mast above hub height	4, Meteorology mast to hub height
Typical application	Large wind turbines[7] in flat terrain (see Annex B)	Large wind turbines in flat terrain (see Annex B)	Large and small wind turbines in all types of terrain	Large and small wind turbines in all types of terrain
Wind measurement sensors	7.2.3, 7.2.5	7.2.3, 7.2.5	7.2.3, 7.2.4	7.2.3
Normalisation procedures for climate specific power curve determination	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density; 9.1.5
Additional uncertainty due to lack of wind shear measurement	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	Additional gross uncertainty for large wind turbines due to lack of vertical wind shear; E.11.2.2
Optional normalization procedures[8]	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4. Meteorological mast flow distortion; 9.1.2, Site calibration; Annex C.	Turbulence and upflow angle; 9.1.6. Site calibration; Annex C.

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7 Refer to IEC 61400 -2 for definition of large and small wind turbines.

8 Upflow influences the power curve and can be measured with 3D sonic anemometers or upflow vanes. If an upflow angle normalization is applied then the method should be documented (uncertainty on upflow is considered in Annex E). However, no specific procedure is described in this standard on how to normalise for upflow angle.

6 Preparation for performance test

6.1 General

The specific test conditions related to the power performance measurement of the wind turbine shall be well-defined and documented in the test report, as detailed in Clause 10.

6.2 Wind turbine and electrical connection

As detailed in Clause 10, the wind turbine and electrical connection shall be described and documented to identify uniquely the specific machine configuration that is tested.

6.3 Test site

6.3.1 General

At the test site wind measurement equipment shall be set up in the neighbourhood of the wind turbine to determine the wind speed that drives the wind turbine.

Wind shear and atmospheric stability characteristics of the site may have significant influences on the wind measurement and the actual power performance of the wind turbine. Often there is a diurnal cycle of atmospheric stability, with stable atmosphere forming at night and neutral or unstable atmosphere during the day as the sun heats the ground, increasing turbulence and mixing in the boundary layer. Wind shear, wind veer, and turbulence are all a function of atmospheric stability and impact the relationship between the hub height wind speed to the rotor equivalent wind speed and unusual profiles may impact a wind turbine's energy conversion. In addition, flow distortion effects may cause the wind speed at the position of the wind speed measurement and wind turbine to be different, though correlated.

The test site shall be assessed for sources of wind flow distortion in order to:

a) choose the position of the wind measurement equipment;

b) define a suitable measurement sector;

c) determine if a site calibration is required then determine the appropriate flow corrections by measurement according to Annex C;

d) evaluate the uncertainty due to wind flow distortion.

The following factors shall be considered, in particular:

1) topographical variations and roughness;

2) other wind turbines;

3) obstacles (buildings, trees, etc.).

The test site shall be documented as detailed in Clause 10.

6.3.2 Location of the wind measurement equipment

Care shall be taken in locating the wind measurement equipment. The wind measurement equipment shall not be located too close to the wind turbine, since the wind speed will be influenced in front of the wind turbine. Also, it shall not be located too far from the wind turbine, since the correlation between wind speed and electric power output will be reduced. The wind speed measurement instrumentation shall be positioned at a distance from the wind turbine of between 2 and 4 times the rotor diameter D of the wind turbine. A distance of 2,5 times the rotor diameter D is recommended. In the case of a vertical axis wind turbine, refer to Clause H.4.

Prior to carrying out the power performance test and in helping to select the location for the wind measurement equipment, account should be taken of the need to exclude measurements

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from all sectors in which either the wind measurement equipment or the wind turbine will be subject to flow disturbance.

In most cases, the best location for the wind measurement equipment will be upwind of the wind turbine in the direction from which most valid wind is expected to come during the test. In other cases, however, it may be more appropriate to place the wind measurement equipment alongside the wind turbine as the wind conditions will be more similar, for example for a wind turbine sited on a ridge.

6.3.3 Measurement sector

The measurement sector(s) shall exclude directions having significant obstacles and other wind turbines, as seen from both the wind turbine under test and the wind measurement equipment.

For all neighbouring wind turbines and significant obstacles, the directions to be excluded due to wake effects shall be determined using the procedure in Annex A. The disturbed sectors to be excluded due to the wind measuring equipment being in the wake of the wind turbine under test are shown in Figure 1 for distances of $2D$, $2{,}5D$ and $4D$. Reasons to reduce the measurement sector(s) might be special topographic conditions or unexpected measurement data from directions with complicated structures. All reasons for reducing the measurement sector shall be clearly documented.

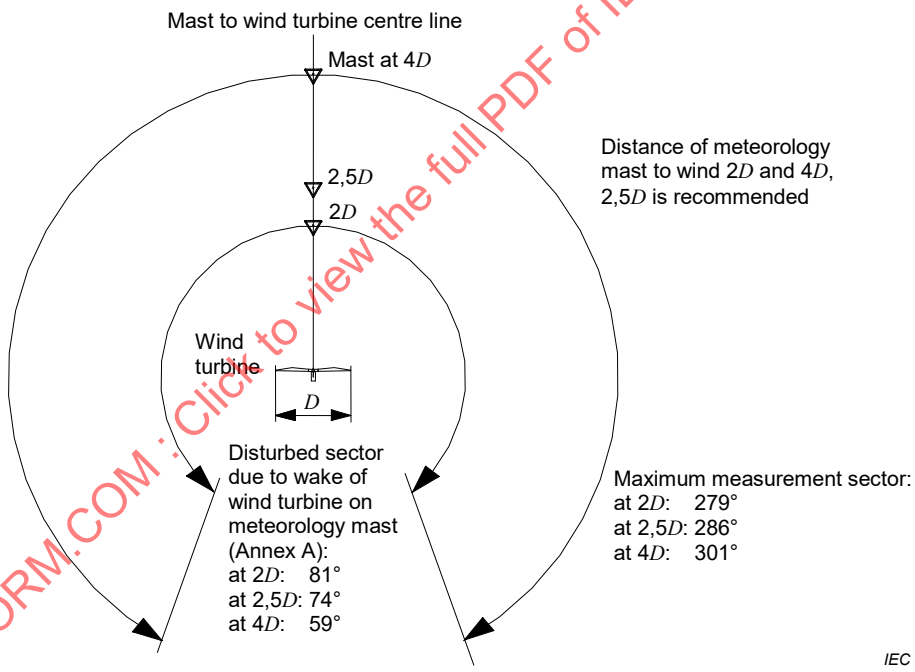

Figure 1 – Requirements as to distance of the wind measurement equipment and maximum allowed measurement sectors

6.3.4 Correction factors and uncertainty due to flow distortion originating from topography

The test site shall be assessed for sources of wind flow distortion due to topographical variations. The assessment in Annex B shall identify whether the power curve can be measured without a site calibration. If the criteria of Annex B are met, the wind flow regime of the site does not need a site calibration. However, in assuming that no flow correction is necessary, the applied uncertainty due to flow distortion of the test site shall be a minimum of 2 % of the measured wind speed if the wind measurement equipment is positioned at a distance between 2 and 3 times the rotor diameter of the wind turbine and 3 % or greater if

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the distance is between 3 and 4 times the rotor diameter[9], unless objective evidence can be provided quantifying a different uncertainty.

If the criteria of Annex B are not met, or a smaller uncertainty due to flow distortion of the test site is desired, then an experimental site calibration shall be undertaken in accordance with Annex C. The measured flow correction factors for each sector shall be used.

7 Test equipment

7.1 Electric power

The net electric power of the wind turbine shall be measured using a power measurement device (e.g. power transducer) and be based on measurements of current and voltage on each phase.

The class of the current transformers shall meet the requirements of IEC 61869-2 and the class of the voltage transformers, if used, shall meet the requirements of IEC 61869-3. They shall be of class 0,5 or better.

The accuracy of the power measurement device, if it is a power transducer, shall meet the requirements of IEC 60688 and shall be class 0,5 or better. If the power measurement device is not a power transducer then the accuracy should be equivalent to class 0,5 power transducers. The operating range of the power measurement device shall be set to measure all positive and negative instantaneous power peaks generated by the wind turbine. As a guide for MW-size active control regulated wind turbines, the full-scale range of the power measurement device should be set to –25 % to +125 % of the wind turbine rated power[10]. All data shall be periodically reviewed during the test to ensure that the range limits of the power measurement device have not been exceeded. The power transducer shall be calibrated to traceable standards. The power measurement device shall be mounted between the wind turbine and the electrical connection to ensure that only the net active electric power (i.e. reduced by self-consumption) is measured. It shall be stated whether the measurements are made on the wind turbine side or the network side of the transformer.

7.2 Wind speed

7.2.1 General

The wind speed measured at Hub Height only (HH) is the default wind speed definition and shall always be used. This may be considered the limiting case of the rotor equivalent wind speed where there is only one measurement height and additional uncertainty due to the lack of a wind shear or wind veer profile measurement (see E.11.2.2). It is recommended that the hub height wind speed measurement is supplemented with wind shear measurements in the lower half of the rotor to reduce the wind speed uncertainty. To further reduce the wind speed uncertainty, the Rotor Equivalent Wind Speed (REWS), see 9.1.3.2 and Annex Q, should be used as the wind speed input variable to the power curve.

The wind speed measurement configurations are summarized in Table 2 which takes account of the current limitations of each measurement technology with respect to the terrain complexity classification. Remote sensing devices that assume horizontal flow uniformity through the scanned volume limit the application of these technologies to non-complex terrain conditions for power performance testing. Thus only configurations based on Table 2 shall be applied.

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[9] These uncertainties were derived from a WAsP (Wind Atlas Analysis and Application Program, DTU Wind Energy) analysis of a Gaussian hill meeting the terrain requirements of Annex B.

[10] In other cases, a higher range may be necessary. This has to be checked individually.

Table 2 – Wind speed measurement configurations (X indicates allowable configuration)

Wind speed measurement	HH	HH	REWS	REWS
Terrain type	Non-complex	Complex	Non-complex	Complex
Hub height meteorological mast	X	X		
Hub height meteorological mast + RSD	X	X	X	
RSD + non-hub height meteorological mast	X		X	
Meteorological mast covering heights above HH + 2/3 R	X	X	X	X

The different possible sensor configurations comprise meteorological mast top-mounted anemometers, meteorological mast side-mounted anemometers and remote sensing devices and these provide measurements of hub height wind speed, rotor equivalent wind speed and wind shear profile. Subclauses 7.2.3 to 7.2.5 describe the general, common requirements of top-mounted, side-mounted and remote sensing sensor configurations whilst 7.2.6 to 7.2.8 describe the application specific details for the measurements using these sensor configurations.

7.2.2 General requirements for meteorological mast mounted anemometers

The following requirements apply to all cup and sonic anemometer applications described in Subclauses 7.2.3 to 7.2.8.

The sensor shall meet the requirements in Annex I for cup and sonic anemometers. For power performance measurements an anemometer with a class better than 1,7A or 1,7C shall be used. Additionally, in terrain that requires a site calibration, it is recommended that a class better than class 2,5B, 2,5D or 1,7S shall be used, see Annex I and Annex J.

The anemometer shall be calibrated before and, if required, calibrated again after the measurement campaign (post-calibration). It is mandatory to check and document that the anemometer maintains the validity of its calibration throughout the measurement period. This can be achieved by either comparing the initial calibration results with the outcome of the post-calibration or as an alternative, the in-situ anemometer comparison following Annex K is permissible.

Where a post-calibration is carried out, the difference between the regression lines of calibration and post-calibration shall be within ± 0,1 m/s in the range 4 m/s to 12 m/s. Only the calibration before the measurement campaign shall be used for the performance test. Calibration of the anemometer shall be made according to the procedure of Annex F. If the maximum difference between the regression lines of calibration and post-calibration is outside of ± 0,1 m/s in the range of 4 m/s to 12 m/s, then the standard uncertainty of the anemometer calibration $u_{VS,precal,i}$ shall be increased (at least to this max. difference, but not to more than ± 0,2 m/s). If the difference is above ± 0,2 m/s, then the in-situ anemometer comparison of Annex K is to be used to identify the point in time when the deviation in the data occurred and the subsequent faulty data shall be rejected. If the in-situ test cannot determine the point at which the deviation began then the post-calibration difference is added as an uncertainty.

As an alternative, the in-situ calibration procedure of Annex K shall be used to check the anemometer integrity throughout the measurement period. In this procedure a control anemometer is used to monitor the primary anemometer. Where a cup anemometer is used as the primary anemometer, then either a cup anemometer or a sonic anemometer may be used as the control anemometer. Where a sonic anemometer is used as the primary anemometer, then the control anemometer shall be a cup anemometer. In the case where a REWS derived power curve is obtained from taller than hub height meteorological mast measurements, there shall be a side mounted primary anemometer at hub height on the mast with an associated control anemometer satisfying the mounting requirements from Annex G.

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The uncertainty in wind speed measurement derives from several sources of uncertainty as specified in Table D.1 Uncertainty in calibration shall be derived from Annex F. Uncertainty due to operational characteristics shall be derived from Annex I on classification of anemometry. Uncertainty due to mounting effects shall be derived from Annex G.

7.2.3 Top-mounted anemometers

Where wind speed measurements are made with a top-mounted anemometer the requirements given in Annex G with respect to mounting shall be adhered to. The installed height of the sensor above ground level[11] shall be verified by measurement and the measurement method and its standard uncertainty documented[12]. The standard uncertainty of the measurement of the height of the wind speed sensor above the estimated ground level shall be less than or equal to 0,2 m. The control anemometer shall be mounted according to the requirements of Annex G.

7.2.4 Side-mounted anemometers

The mounting shall follow the requirement for side mounted anemometers according to Annex G. The installed height of the side-mounted anemometers above ground level (see footnote 11) shall be verified by measurement and the measurement method and its uncertainty documented. The height measurement standard uncertainty shall be less than or equal to 0,2 m.

Correction of side-mounted anemometers for meteorological mast flow distortion is permitted and further described in 9.1.2 and Annex S. The technical basis for the correction and the effect of the correction shall be documented. The booms shall have identical orientations to ensure similarity of flow distortion between different heights. The meteorological mast and boom design should have similar flow distortion effect at the sensor with a maximum allowed difference in wind speed distortion of 1 % between all different heights. The meteorological mast cross-sectional dimensions should be consistent at each elevation, thus in the case of free-standing meteorological masts where the meteorological mast cross-sectional area is larger at the lower elevations, special care should be taken following the recommendations in Annex G. An alternative option is to mount a second anemometer at each measurement height on a separate boom and to limit the measurement sector such that the wind speed measurements do not deviate by more than 1 %.

7.2.5 Remote sensing device (RSD)

Remote sensing devices that assume horizontal flow uniformity through the scanned volume limit the application of these technologies to non-complex terrain conditions for power performance testing as defined by Annex B. The remote sensing device shall be verified before the measurement campaign or in-situ according to Clause L.3. The remote sensing device can be used to measure hub height wind speed, wind shear profile, wind veer and/or the rotor equivalent wind speed based on measurements at more than one height (see 7.2.8). In any case, the remote sensing device shall be simultaneously compared with a top-mounted anemometer on a meteorological mast at a height not less than the minimum of the wind turbine rotor lower tip-height or 40 m as defined in Clause L.1. Requirements on the top-mounted anemometer are identical to those described in 7.2.3.

The uncertainty of the RSD wind speed measurements shall be derived according to Annex L.

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[11] For the purpose of defining ground level, an estimate of the mean elevation over a radius of 2 m around the mast base or 5 m radius around the turbine base can be made. The sensor height measurement uncertainty should exclude the uncertainty of the ground level estimate. For offshore conditions, ground level should be considered as mean sea level.

[12] The measurement can be performed by means of measurement device with a traceable calibration for example a theodolite able to derive heights from an angle measurement in the vertical plane.

7.2.6 Rotor equivalent wind speed measurement

If the wind speed is measured at three or more heights across the wind turbine rotor as defined in 7.2.8, then the rotor equivalent wind speed can be calculated according to 9.1.3. Note that more than three measurement heights are recommended. There are three options for measuring the rotor equivalent wind speed as described below.

a) Where a hub height top-mounted anemometer satisfying the requirements of 7.2.3 is used together with an RSD satisfying the requirements of 7.2.5 and the terrain meets the requirements of Annex B then the measurements from the hub height anemometer and RSD are combined to determine the rotor equivalent wind speed according to 9.1.3.

b) Where an anemometer not at hub height but otherwise satisfying the requirements for top-mounted anemometers of 7.2.3 is used with an RSD satisfying the requirements of 7.2.5 and the terrain meets the requirements of Annex B then the RSD measurements are used directly to determine the rotor equivalent wind speed according to 9.1.3.

c) Where a taller than hub height meteorological mast is used with side-mounted measurements distributed across the rotor height, including an anemometer at hub height, then the side-mounted anemometer wind speed measurements may be used directly to measure the rotor equivalent wind speed according to 9.1.3.

7.2.7 Hub height wind speed measurement

There are three options for measuring hub height wind speed as described below.

a) Where a hub height meteorological mast is used, the hub height wind speed measurements shall meet the requirements described in 7.2.3.

b) If the terrain meets the requirements of Annex B, then the hub height wind speed can be measured with an RSD meeting the requirements of 7.2.5 and noting specifically the requirement to compare the RSD against a simultaneous top-mounted anemometer.

c) A meteorological mast that is taller than the hub height may be used to better capture the wind speeds across the rotor area. In this case, the hub height wind speed shall be measured with a side-mounted sensor on a boom following the requirements described in 7.2.4.

For the hub height definition of wind speed, the lack of knowledge of the vertical wind shear or wind veer across the wind turbine rotor shall be accounted for by adding an uncertainty term according to Annex E based on the estimated or measured wind shear or wind veer. Where only a hub height wind speed measurement is available, an estimated wind shear or wind veer based on site characteristics (e.g. roughness) or prior measurement or modelling at the site (e.g. during a resource assessment campaign) shall be used as input to the uncertainty analysis. Where the hub height wind speed is determined using an RSD or taller than hub height meteorological mast with side-mounted wind speed measurements across the rotor or where below hub height side-mounted instruments are present and satisfying the minimum requirements described in 7.2.8, then wind shear or wind veer derived from the RSD or side-mounted instruments shall be used as input to the uncertainty assessment.

7.2.8 Wind shear measurements

Where wind speed measurements are available over a range of heights wind shear shall be measured and used for the rotor equivalent wind speed or for wind shear exponent determination.

Wind shear measurements shall either be performed using side-mounted anemometers as described in 7.2.4 or by a single remote sensing instrument as described in 7.2.5. Further specifications on wind shear measurement using remote sensing instruments or meteorological mast measurements are given in Annex L and Annex G respectively.

The rotor equivalent wind speed measurement shall include wind speed measurements above hub height. To apply a measurement-based wind shear correction, there shall be at least three wind speed measurements distributed over the rotor swept area. However, to minimise

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wind speed uncertainty, it is recommended to have as many measurement heights as possible. Measurement heights should be distributed symmetrically around hub height and evenly over the vertical range of the rotor swept area.

The measurement heights shall include the following heights as a minimum:

a) hub height ±1,0 %;

b) between $H - R$ and $H - 2/3R$;

c) between $H + 2/3R$ and $H + R$,

where H is the hub height of the wind turbine and R the radius of the rotor swept area, see Figure 2.

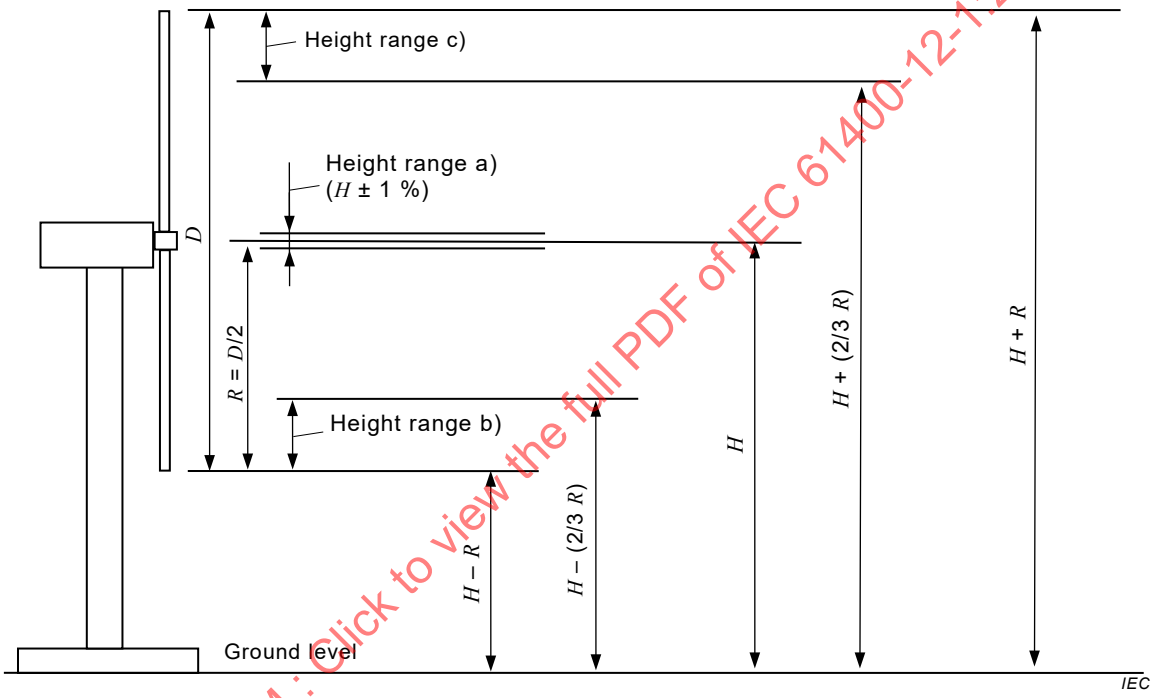

Figure 2 – Wind shear measurement heights appropriate to measurement of rotor equivalent wind speed

If the meteorological mast is hub height or a little above, then no wind speed measurements above hub height may be available for wind shear measurement. In that case, the measurements used to derive wind shear shall include at least the following heights:

a) a side-mounted anemometer as close to hub height satisfying the requirements of Annex G for separation from the top-mounted anemometer,

b) between $H - R$ and $H - 2/3R$ and satisfying the requirements of Annex G for side mounted anemometers.

where H is the hub height of the wind turbine and R the radius of the rotor swept area, see Figure 3.

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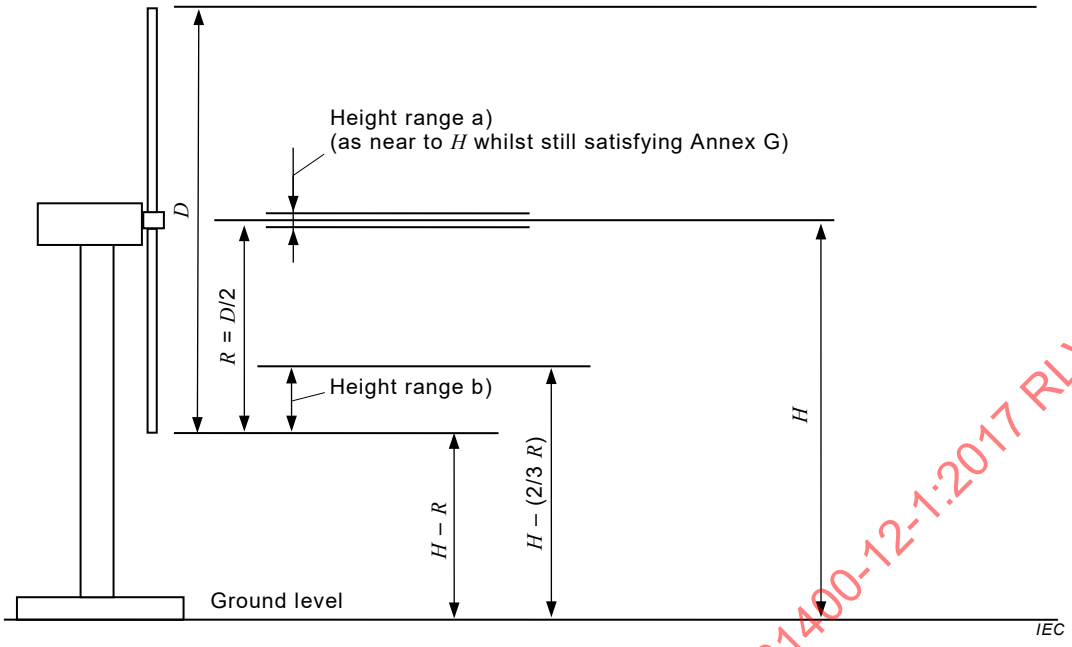

Figure 3 – Wind shear measurement heights when no wind speed measurements above hub height are available (for wind shear exponent determination only)

7.3 Wind direction

Wind direction measurements are used as an input to the site calibration, for filtering data to the valid direction sector and for determining wind veer. Wind direction shall be measured with a wind direction sensor. This may be a wind vane or a 2D or 3D sonic anemometer or an RSD. Where a sonic anemometer is used it shall be used in conjunction with a conventional wind vane as a control. If an RSD is used, it should be subjected to a verification test on the wind direction according to Annex L.

The instantaneous horizontal wind direction shall be determined and averaged over 10 min. Vector averaging (averaging of cosine and sine components of instantaneous wind direction values taking arc tan of the average values and adjusted to the 0° to 360° scale) is one method for deriving the average wind direction. Another method is to extend the wind direction scale for values above 360° and calculating the 10 min average, then adjusting the average value to the 0° to 360° range. Data measured within the dead band of a wind vane, usually at the north mark of the wind direction sensor body, are usually not defined (open circuit or short circuit) and shall be excluded. The combined calibration, operation, and orientation standard uncertainty of the wind direction measurement shall be less than 5°. The wind direction sensor shall be calibrated. Annex N provides guidance.

7.4 Air density

Air density shall be derived from measurement of air temperature, air pressure and relative humidity. As an alternative to the humidity measurement, an assumed value of 50 % relative humidity may be used if humidity is not measured. The air density shall be calculated using Equation (12) in 9.1.5.

The air temperature sensor shall be mounted within 10 m of hub height to represent the air temperature at the wind turbine rotor centreline. Refer to Annex G for temperature sensor mounting requirements where a meteorological mast shorter than hub height is used.

The air pressure sensor should be mounted within 10 m of hub height to represent the barometric pressure at the wind turbine rotor centreline. Air pressure measurements shall be always corrected to the appropriate hub height according to ISO 2533.

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The humidity sensor should be mounted within 10 m of hub height to represent the humidity at the wind turbine rotor centreline.

7.5 Rotational speed and pitch angle

Rotational speed and pitch angle should be measured throughout the test if there is a specific need for it. For example if there is a need to apply the measurements in connection with acoustic noise tests. If measured, the measurements shall be reported according to Clause 10.

7.6 Blade condition

The condition of the blades may influence the power curve particularly for stall regulated wind turbines. It may be useful in understanding the characteristics of the wind turbine to monitor the factors that affect blade condition including precipitation, icing and bug and dirt accretion.

7.7 Wind turbine control system

Sufficient status signals shall be identified, verified and monitored to allow the rejection criteria of 8.4 to be applied. Obtaining these parameters from the wind turbine controller's data system is adequate[13]. The definition of each status signal shall be reported.

7.8 Data acquisition system

A digital data acquisition system having a sampling rate per channel of at least 1 Hz shall be used to collect measurements and store either sampled data or statistics of the data sets as described in 8.3.

The calibration and accuracy of the data system chain (transmission, signal conditioning and data recording) shall be verified by injecting known signals from a traceable, calibrated source at the transducer ends and comparing these inputs against the recorded readings. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors.

8 Measurement procedure

8.1 General

The objective of the measurement procedure is to collect data that meet a set of clearly defined criteria to ensure that the data are of sufficient quantity and quality to determine the power performance characteristics of the wind turbine accurately. The measurement procedure shall be documented, as detailed in Clause 10, so that every procedural step and test condition can be reviewed and, if necessary, repeated.

Accuracy of the measurements shall be expressed in terms of standard uncertainty, as described in Annex D. During the measurement period, data should be periodically validated to ensure high quality. Test logs shall be maintained to document all important events during the power performance test.

8.2 Wind turbine operation

During the measurement period, the wind turbine shall be in normal operation, as prescribed in the wind turbine operations manual, and the machine configuration shall not be changed. The operational status of the wind turbine shall be reported as described in Clause 10. Normal maintenance of the wind turbine shall be carried out throughout the measurement

[13] A status signal on generator cut-in is adequate to verify cut-out hysteresis control algorithm.

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period, but such work shall be noted in the test log. Any special maintenance actions, such as frequent blade washing, which ensure good performance during the test shall in particular be noted. Such special maintenance actions should be avoided.

8.3 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or higher. Air temperature, air pressure and humidity and precipitation, if measured, may be sampled at a slower rate, but at least once per minute.

The data acquisition system shall store either sampled data or statistics of data sets as follows:

a) mean value;

b) standard deviation;

c) maximum value;

d) minimum value.

Selected data sets shall be based on 10-min periods derived from contiguous measured data. Data shall be collected until the requirements defined in 8.5 are satisfied.

8.4 Data rejection

To ensure only data obtained during normal operation of the wind turbine are used in the analysis, and to ensure data are not corrupted, data sets shall be excluded from the database under the following circumstances:

a) external conditions other than wind speed are out of the operating range of the wind turbine;

b) the wind turbine cannot operate because of a wind turbine fault condition;

c) the wind turbine is manually shut down or in a test or maintenance operating mode;

d) failure or degradation (e.g. due to icing) of measurement equipment;

e) wind direction outside the measurement sector(s) as defined in 6.3.3;

f) wind directions outside valid (complete) site calibration sectors;

g) any special atmospheric condition filtered during the site calibration shall also be filtered during the power curve test.

Any other rejection criteria shall be clearly reported.

The effect on the power curve of a large hysteresis loop in the cut-out control algorithm may be considerable. This effect shall not be included in the power curve, and all data sets where the wind turbine has stopped generating power due to cut-out at high wind speed shall be excluded. If cut-out behaviour has been reached during the measurement period, the measurements may be presented in a special database that includes all data points in the database. The power curve shall capture the effect of hysteresis at the cut-in control algorithm, as well as the effect of parasitic losses below cut-in. Cut-out hysteresis affects the higher wind speed bins and neglecting it may therefore lead to overestimation of energy production especially for scenarios with higher annual average wind speeds.

Subsets of the database collected under special operational conditions (e.g. high blade roughness due to dust, salt, insects and ice or if grid conditions vary significantly) or atmospheric conditions (e.g. precipitation, wind shear) that occur during the measurement period may be selected as special databases.

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8.5 Database

After data normalisation (see 9.1) the selected data sets shall be sorted using the “method of bins” procedure, see 9.2. The wind speed range shall be divided into 0,5 m/s contiguous bins centred on multiples of 0,5 m/s. The selected data sets shall at least cover a wind speed range extending from 1 m/s below cut-in to 1,5 times the wind speed at 85 % of the rated power of the wind turbine. Alternatively, the wind speed range shall extend from 1 m/s below cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated", see 9.3, where “AEP-measured” and “AEP-extrapolated” are defined using the appropriate, consistent definitions of wind speed (i.e. the hub height wind speed derived power curve and wind speed distribution and, in the case where REWS is derived, by the REWS derived power curve and wind speed distribution). For active pitch controlled wind turbines, the power curve may also be considered complete when the rated power has been reached and the average power does not change by more than the larger of 0,5 % of the power or 5 kW for three consecutive wind speed bins and there is not a trend of increasing power across these three bin-averages. The report shall state which of the three wind speed range criteria has been used.

The database shall be considered complete when it has met the following criteria:

a) each bin includes a minimum of 30 min of sampled data;

b) the database includes a minimum of 180 h of sampled data.

Should a single incomplete bin be preventing completion of the test, then that bin value can be estimated by linear interpolation from the two adjacent complete bins.

The database shall be presented in the test report as detailed in Clause 10.

9 Derived results

9.1 Data normalisation

9.1.1 General

In the following subclauses, three methods of normalisation are described for the main atmospheric drivers on the power curve results: air density, wind shear and turbulence intensity.

The purpose of these normalisations is to improve the accuracy of the results by means of concrete formulations for each variable. This will to some extent allow the comparison of results from different data sets bringing them to similar scale.

The various normalisations should be applied as indicated in the flow chart in Figure 4.

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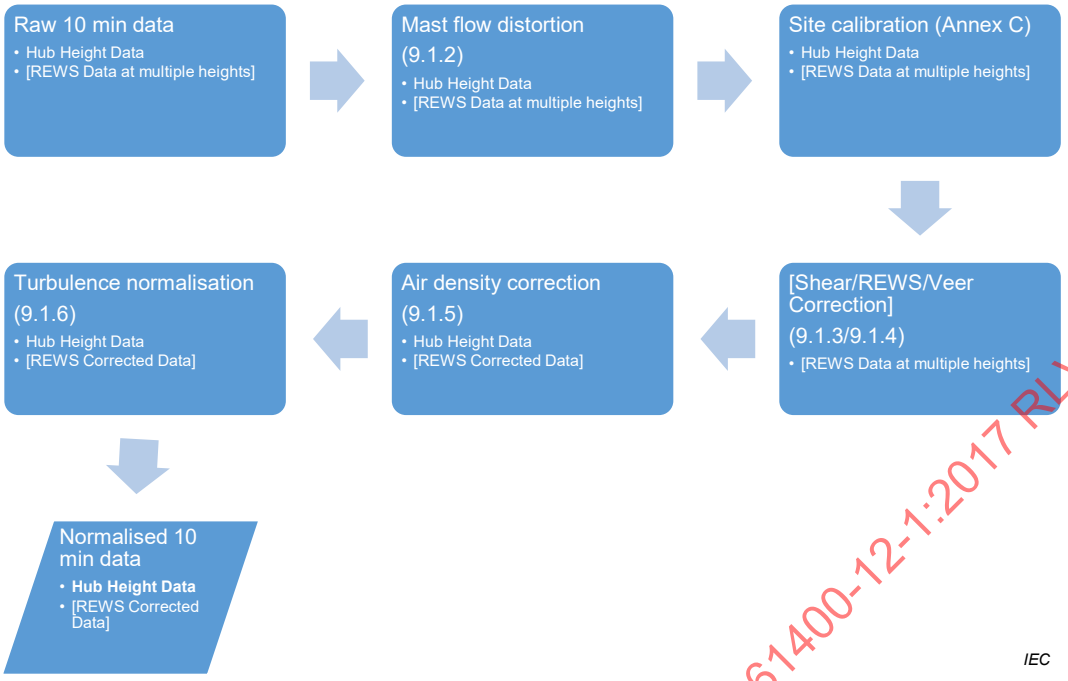

Figure 4 – Process of application of the various normalisations[14]

9.1.2 Correction for meteorological mast flow distortion of side-mounted anemometer

Correction of the wind speeds from side mounted anemometers for meteorological mast flow distortion is permitted (the requirement from Annex G for a maximum of 1 % meteorological mast flow distortion before application of the correction is still required). Any correction method shall be documented and reported following the requirements of 10.

The impact of the meteorological mast flow distortion on the wind shear measurement may be minimized by reducing the measurement sector where meteorological mast flow distortion is below a certain limit. The technical basis for any such reduction in sector width shall be documented. Annex S gives a possible method for determining the flow distortion correction for a lattice mast.

9.1.3 Wind shear correction (when REWS measurements available)

9.1.3.1 General

If the wind speed over the wind turbine rotor area is constant, the wind speed at hub height would be representative of the wind speed over the wind turbine rotor and the use of the hub height wind speed would be justified. However, the assumption of a point wind speed such as at hub height representing the wind speed over the wind turbine rotor area may not be representative for large wind turbines. It is therefore necessary to introduce corrections that account for the wind speed at hub height and the variations introduced by the wind shear over the wind turbine rotor. In the following, three quantities are defined:

a) the rotor equivalent wind speed;

b) the wind shear correction factor;

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14 Where the optional REWS measurements are available, the REWS data follow a normalisation path parallel to the default hub height data normalisations as indicated by the terms in square brackets. The normalisation of the REWS data is carried out separately at each measurement height for all normalisation steps up to the step where the results from each height are combined into the wind shear/REWS/veer correction. A single REWS corrected value is derived for each 10-minute data point at each subsequent step in parallel to the corrections applied to each hub height data point.

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c) the wind shear corrected wind speed.

The wind shear correction factor may be used to derive a climate specific power curve as explained in Annex P. However, this correction is based on the assumption that a wind turbine is able to convert all of the available kinetic energy.

9.1.3.2 Rotor equivalent wind speed

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. Where the wind speed for at least three measurement heights are available (see 7.2.6), the rotor equivalent wind speed is defined as:

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n_{\mathrm{h}}} v_i^3 \frac{A_i}{A} \right)^{1/3} \tag{5}$$

where

n_{h} is the number of available measurement heights ($n_{\mathrm{h}} \geq 3$);

v_i is the wind speed measured at height i;

A is the complete area swept by the rotor (i.e. πR^2 with radius R);

A_i is the area of the i^{th} segment, i.e. the segment the wind speed v_i is representative for, derived from Equation (6).

The segments (with areas A_i) shall be chosen in the way that the horizontal separation line between two segments lies in the middle of two measurement points. The segment areas are then derived according to Equation (6):

$$A_i = \int_{z_i}^{z_{i+1}} c(z)\,\mathrm{d}z = g(z_{i+1}) - g(z_i) \tag{6}$$

where

z_i is the height of the i^{th} segment separation line ($H-R<z_i<H+R$), numbered in the same order as v_i (either top down or bottom up).

The rotor width at height z is:

$$c(z) = 2\sqrt{R^2 - (z-H)^2} \tag{7}$$

where

R is the rotor radius;

H is the hub height.

The integrated function is:

$$g(z) = (z-H)\sqrt{R^2 - (z-H)^2} + R^2 \arctan\left(\frac{z-H}{\sqrt{R^2 - (z-H)^2}} \right) \tag{8}$$

Example of REWS calculation for one 10 minute wind speed profile

In this example, a wind turbine is assumed to have a hub height of 80 m and a rotor diameter of 100 m. The wind speed was measured at 5 heights with a meteorological mast. If the

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heights could have been chosen, ideally they would have been evenly distributed (40 m, 60 m, 80 m, 100 m and 120 m). This example shows a case where the heights were fixed independently from the REWS evaluation purpose. The segment limits were set in the middle of two consecutive measurements. The resulting REWS is equal to 9,38 m/s, see Table 3.

Table 3 – Example of REWS calculation

Measurement Heights [m]	Wind speed [m/s]	Segment weighting* [%]	Segment inferior limit height (z_i) [m]	Segment superior limit height (z_{i+1}) [m]	Segment height [m]
116	11,46	16,31	108	130	22
100	10,43	21,04	90	108	18
80	9,24	25,29	70	90	20
60	7,81	23,12	50	70	20
40	6,05	14,24	30	50	20
* Segment weighting is defined as the ratio between the segment area and the total swept rotor area.					

9.1.3.3 Wind shear correction factor

9.1.3.3.1 Case 1: Hub height meteorological mast with remote sensing device or remote sensing device with short (below hub height) meteorological mast

A wind shear correction factor measured using a remote sensing device is defined as the ratio of the rotor equivalent wind speed relative to the wind speed measured at hub height according to Equation (9):

$$f_{\mathrm{r,RSD}} = v_{\mathrm{eq,RSD}} / v_{\mathrm{h,RSD}} \tag{9}$$

where

$v_{\mathrm{eq,RSD}}$ is the rotor equivalent wind speed measured by the remote sensing device, as defined in Equation (5);

$v_{\mathrm{h,RSD}}$ is the wind speed measured at hub height by the remote sensing device.

9.1.3.3.2 Case 2: Meteorological mast above hub height

A wind shear correction factor measured using a meteorological mast is defined as the ratio of the rotor equivalent wind speed to the wind speed measured at hub height according to Equation (10)[15]:

$$f_{\mathrm{r,MM}} = v_{\mathrm{eq,MM}} / v_{\mathrm{h,MM}} \tag{10}$$

where

$v_{\mathrm{eq,MM}}$ is the rotor equivalent wind speed measured by the anemometers on the meteorological mast, as defined in Equation (5);

$v_{\mathrm{h,MM}}$ is the wind speed measured by the anemometer at hub height.

15 Note that $f_{\mathrm{r,MM}}$ is for reporting purposes only.

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9.1.3.4 Wind shear correction of wind speed

If the hub height wind speed and the wind shear are measured with the same type of WME, the rotor equivalent wind speed is calculated according to Equation (5).

If the hub height wind speed is measured using an anemometer mounted on a meteorological mast and the wind shear measurement with an RSD, the final rotor equivalent wind speed is calculated according to Equation (11):

$$v_{\text{eq,final}} = f_{\text{r,RSD}} v_{\text{h,MM}} \tag{11}$$

9.1.4 Wind veer correction

As explained in Annex Q, the change of wind direction over the rotor height range (wind veer) can have a significant impact on the wind turbine power output. In the case of large wind turbine rotors, it is recommended to apply the extended definition of equivalent wind speed including wind veer.

9.1.5 Air density normalisation

The air density shall be determined from measured air temperature, air pressure and relative humidity according to the Equation (12):

$$\rho_{10\text{min}} = \frac{1}{T_{10\text{min}}}\left(\frac{B_{10\text{min}}}{R_0} - \Phi P_{\text{w}}\left(\frac{1}{R_0} - \frac{1}{R_{\text{w}}}\right)\right) \tag{12}$$

where

$\rho_{10\text{min}}$ is the derived 10 min averaged air density;

$T_{10\text{min}}$ is the measured absolute air temperature averaged over 10 min [K];

$B_{10\text{min}}$ is the air pressure corrected to hub height averaged over 10 min [Pa];

R_0 is the gas constant of dry air 287,05 [J/kgK];

Φ is the relative humidity (range 0 % to 100 %);

R_{w} is the gas constant of water vapour 461,5 [J/kgK];

P_{w} is the vapour pressure equal to 0,000 020 5 exp(0,0631 846 $T_{10\text{min}}$) [Pa];

Vapour pressure P_{w} depends on mean air temperature over the 10 min.

The selected data sets shall be normalised to at least one reference air density. The reference air density shall be the average of the measured air density of the valid collected data at the site during the test period (see 8.4), or alternatively a pre-defined nominal air density for the site. The average measured air density shall be rounded to the nearest 0,01 kg/m^3 and reported in accordance with 10.

For a stall-regulated wind turbine with constant pitch and constant rotational speed, data normalisation shall be applied to the measured power output according to Equation (13):

$$P_{\text{n}} = P_{10\text{min}}\left(\frac{\rho_0}{\rho_{10\text{min}}}\right) \tag{13}$$

where

P_{n} is the normalised power output;

$P_{10\text{min}}$ is the measured power averaged over 10 min;

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ρ_0 is the reference air density;

$\rho_{10\text{min}}$ is the air density derived according to Equation (12) averaged over 10 min.

For a wind turbine with active power control, the normalisation shall be applied to the wind speed according to Equation (14):

$$V_{\text{n}} = V_{10\,\text{min}}\left(\frac{\rho_{10\,\text{min}}}{\rho_0}\right)^{1/3} \tag{14}$$

where

V_{n} is the normalised wind speed;

$V_{10\text{min}}$ is the measured wind speed averaged over 10 min.

9.1.6 Turbulence normalisation

Wind turbine power curve measurements are influenced by the turbulence intensity. A significant part of the turbulence intensity effect is caused by the averaging of the measured power output and the measured wind speed over 10-minute periods. It is recommended to remove this effect from the measurements by normalising the power curve data to a reference turbulence intensity according to Annex M. The reference turbulence intensity shall be defined prior to the power curve test. It may be defined as a function of the wind speed at hub height. If not defined otherwise, a reference turbulence intensity of 10 % shall be applied. The uncertainty of the turbulence normalisation shall be accounted for. If no turbulence normalisation of the power curve data is performed, the uncertainty of the power curve due to turbulence effects shall be estimated. As a recommendation use the uncertainty method described in Annex M[16].

9.2 Determination of the measured power curve

The power curve shall be determined based on the hub height wind speed and, if measured, the rotor equivalent wind speed. However, it should be remembered that the uncertainty in a power curve derived from hub height measurements only is subject to higher uncertainty due to the lack of knowledge of other influential wind condition parameters. Therefore to account for the vertical wind shear, wind veer and turbulence intensity and to reduce power curve measurement uncertainty, it is recommended to consider the rotor equivalent wind speed as the representative wind speed and the turbulence normalised power output according to Annex M as the relevant power output. The derivation of power curves based on wind speed normalised for a specific wind shear profile (see Annex P) and the turbulence normalised power output are options that are recommended if a comparison between different power curves is wanted or if the power curves are applied for wind resource assessment.

To indicate single 10-min averages, a further index j should be added to the respective wind speeds.

The measured power curve is determined by applying the "method of bins" for the normalized data sets, using 0,5 m/s wind speed bins and by calculation of the mean values of the normalized wind speed and normalized power output for each wind speed bin according to Equations (15) and (16):

$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{\text{n},i,j} \tag{15}$$

16 It should be noted that turbulence intensity measured by cup anemometers, remote sensing devices and ultra sonic anemometers are measured differently. This should be considered when interpreting the results.

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$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{\mathrm{n},i,j} \tag{16}$$

where

V_i is the normalized and averaged wind speed in bin i;

$V_{\mathrm{n},i,j}$ is the normalized wind speed of data set j in bin i;

P_i is the normalized and averaged power output in bin i;

$P_{\mathrm{n},i,j}$ is the normalized power output of data set j in bin i;

N_i is the number of 10 min data sets in bin i.

The measured power curve shall be presented as detailed in Clause 10 and where REWS power curves are measured, the hub height wind speed power curve shall also be presented.

9.3 Annual energy production (*AEP*)

The *AEP* shall be calculated in two ways, one designated "*AEP*-measured", the other "*AEP*-extrapolated". If the measured power curve does not include data up to cut-out wind speed, the power curve shall be extrapolated from the maximum complete measured wind speed up to cut-out wind speed.

Furthermore, *AEP* may be defined as generic *AEP* or site specific *AEP*. Generic *AEP* is estimated by applying the measured power curve to different reference wind speed frequency distributions. For a specific development, nominal site conditions specifying the wind climate of the site may be known. If so, a site specific *AEP* may, additionally, be reported and computed based on this site specific information.

It is emphasised that a power curve derived from hub height wind speed measurements shall only be combined with a wind speed frequency distribution based on the hub height wind speed definition to derive *AEP* whereas a power curve derived from REWS measurements shall only be combined with a REWS frequency distribution to derive *AEP*. The *AEP* derived from combining a REWS power curve with a hub height wind speed frequency distribution (and vice versa) is not a valid calculation. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. *AEP* estimations shall be made for hub height annual average wind speeds of 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, 10 m/s and 11 m/s according to Equation (17):

$$AEP = N_{\mathrm{h}} \sum_{i=1}^{N} \left[F(V_i) - F(V_{i-1}) \right] \left(\frac{P_{i-1} + P_i}{2} \right) \tag{17}$$

where

AEP is the annual energy production;

N_{h} is the number of hours in one year ≈ 8 760;

N is the number of bins;

V_i is the normalized and averaged wind speed in bin i;

P_i is the normalized and averaged power output in bin i.

$$F(V) = 1 - \exp\left(-\frac{\pi}{4} \left(\frac{V}{V_{\mathrm{ave}}} \right)^2 \right) \tag{18}$$

where

$F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;

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V_{ave} is the annual average wind speed;

V is the wind speed.

The summation is initiated by setting V_{i-1} equal to V_i – 0,5 m/s and P_{i-1} equal to 0,0 kW.

For a specific site, nominal site conditions specifying the wind climate of the site may be known. If so, a site specific AEP may, additionally, be reported and computed based on this site specific information. If the site specific wind distribution is known and is present in tabular form, the site-specific AEP may be calculated by first transforming the wind distribution to the corresponding cumulative distribution. The amount of hours up to each measured wind speed of the measured power curve will be derived by linear interpolation between two adjacent values of the cumulative distribution. The hours will be divided by the sum of hours in the table, which is typically the nominal number of hours within a calendar year. Finally the AEP will be calculated by using Equation (17). The tabular wind speed distribution shall use the same definition of wind speed (hub height or REWS) as the measured power curve otherwise a valid AEP cannot be derived.

If the site specific wind distribution is presented as a Weibull distribution with known shape and scale factors, then the AEP may be calculated with Equation (17) and substituting the cumulative Rayleigh distribution Equation (18) with the Weibull distribution Equation (19):

$$F(V) = 1 - e^{-\left(\frac{V}{A_W}\right)^k} \tag{19}$$

where

$F(V)$ is now the Weibull cumulative probability distribution function for wind speed;

V is the wind speed;

A_W is the Weibull scale factor;

k is the Weibull shape factor;

AEP-measured shall be obtained from the measured power curve by assuming zero power for all wind speeds above and below the range of the measured power curve and carrying out the summation according to Equation (17).

AEP -extrapolated shall be obtained from the measured power curve by assuming zero power for all wind speeds below the lowest wind speed in the measured power curve and constant power for wind between the highest wind speed in the measured power curve and the cut-out wind speed. 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.

AEP -measured and AEP -extrapolated shall be presented in the test report, as detailed in Clause 10. For all AEP calculations, the availability of the wind turbine shall be set to 100 %. For given annual average wind speeds, estimations of AEP -measured shall be labelled as "incomplete" when calculations show that the AEP -measured is less than 95 % of the AEP -extrapolated.

Estimations of measurement uncertainty in terms of standard uncertainty of the AEP according to Annex D, shall be reported for the AEP -measured for all the used wind speed distributions.

The uncertainties in AEP, described above, only deal with uncertainties originating from the power performance test and do not take into account uncertainties due to other important factors relating to actual energy production for a given installation.

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9.4 Power coefficient

The power coefficient, C_P, of the wind turbine shall be added to the test results and presented as detailed in Clause 10. C_P shall be determined from the measured power curve according to Equation (20):

$$C_{P,i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \tag{20}$$

where

$C_{P,i}$ is the power coefficient in bin i;

V_i is the normalized and averaged wind speed in bin i (matching the defined wind speed as either rotor equivalent wind speed or hub height wind speed);

P_i is the normalized and averaged power output in bin i;

A is the swept area of the wind turbine rotor;

ρ_0 is the reference air density.

10 Reporting format

The test report shall contain the following information:

a) Identification and description of the specific wind turbine configuration under test (see 6.2), including:
   1) wind turbine make, type, serial number, production year;
   2) rotor diameter and a description of the verification method used or reference to rotor diameter documentation;
   3) rotor speed or rotor speed range;
   4) rated power and rated wind speed;
   5) blade data: make, type, serial numbers, number of blades, fixed or variable pitch, and pitch angle(s);
   6) hub height and tower type;
   7) description of the control system (device and software version) and documentation of status signals being used for data reduction;
   8) description of grid conditions at the wind turbine, i.e. voltage, frequency and their tolerances, and a drawing indicating where the power transducer is connected, specifically in relation to an internal or external transformer and self-consumption of power;

b) A description of the test site (see 6.3), including:
   1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;
   2) a test site map showing the surrounding area covering a radial distance of at least 20 times the wind turbine rotor diameter and indicating the topography, location of the wind turbine, wind measurement equipment, significant obstacles, other wind turbines, and measurement sector;
   3) results of site assessment, i.e. the limits of the valid measurement sector(s);
   4) if site calibration is undertaken, the limits of the final measurement sector(s) shall also be reported, including the rationale for any changes from the results of the site assessment;
   5) a table of the coordinates and elevation of the test wind turbine, wind measurement equipment and any significant obstacles considered in the assessment of obstacles;

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c) A description of the test equipment (see Clause 7):

1) identification of all sensors, wind measurement equipment and data acquisition system, including documentation of calibrations of sensors, wind measurement equipment, transmission lines, and data acquisition system;

2) sketch of the arrangement of the meteorological mast showing dimensions of the mast and instrument mounting, to document compliance with Annex G;

3) description of method to ensure the calibration of the wind measurement equipment was maintained over the duration of the measurement period and documentation of results that show that the calibration is maintained;

d) A description of the measurement procedure (see Clause 8):

1) documentation of the procedural steps, test conditions, sampling rate, averaging time, and measurement period including;

– documentation of the calibrations, corrections or transfer functions applied by the data logger and/or by post-processing;

2) a test log book that records all important events during the power performance test, including:

– a listing of all maintenance activities that occurred during the test;

– a listing of any special actions (such as blade washing) that were completed to ensure good performance;

3) a complete list of all filter criteria used to produce the reported result, including:

– the parameter, measurement or time period or combination of parameters being filtered on;

– the range or logical criteria for the filter;

– the justification for the filter;

– the order that the filters were applied shall be reported with the number of points removed each iteration. Alternatively, the number of data points the filter would remove from the database by itself;

– the starting number of datasets in the database and the final number of datasets after all filters have been applied;

e) Presentation of measured data (see 8.3 to 8.5). Data from each selected data set shall be presented in both tabular and graphical formats, providing statistics of measured power output as a function of wind speed and of important meteorological parameters including (where REWS measurements are available, the measured data shall be presented separately for both the hub height data and the REWS data):

1) scatter plots of mean, standard deviation, maximum, and minimum power output as a function of wind speed (plots shall include information on sample frequency). An example is shown in Figure 5;

2) scatter plots of mean wind speed and turbulence intensity as a function of wind direction;

3) scatter plots of the turbulence intensity as a function of wind speed, and the average turbulence intensity in each wind speed bin shall be presented;

4) special databases consisting of data collected under special operational or atmospheric conditions should also be presented as described above;

5) if measured, rotational speed and pitch angle shall be presented with a scatter plot including binned values versus wind speed and a table with the binned values;

6) definition of status signals and plots of status signals during the measurement period;

7) scatter plots of air density as a function of wind direction and wind speed including average per bin;

8) scatter plot of the wind shear exponent vs. time of day and as function of wind speed. The wind shear exponent in the lower rotor half and in the upper rotor half shall be

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presented separately. In addition, the average values of both wind shear exponents per wind speed bin shall be represented;

9) the average wind shear exponent or equivalent representation of the site wind shear conditions during the test;

10) wind shear correction factor according to 9.1.3.3, if applicable based on measurement set up (use Equation (9) or Equation (10) depending on measurement configuration);

11) the average air density measured during the test;

f) Presentation of measured power curve for the reference air density (see 9.1 and 9.2) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:

1) the power curve shall be presented in a table similar to Table 4[17]. For each wind speed bin, the table shall list:

– normalized and averaged wind speed;

– normalized and averaged power output;

– number of data sets;

– calculated C_P value;

– standard uncertainties of category A (see Annex D and Annex E);

– standard uncertainties of category B (see Annex D and Annex E);

– combined standard uncertainty (see Annex D and Annex E);

2) the power curve shall be presented in a graph similar to Figure 6. The graph shall show the following as a function of normalized and averaged wind speed:

– normalized and averaged power output;

– combined standard uncertainty;

3) the C_P curve shall be presented in a graph similar to Figure 7;

4) both the graph and the table shall state the reference air density used for the normalisation;

5) if cut-out wind speed has been reached during the measurement period, the power curve and C_P curve, or the parts of the curves influenced by the cut-out hysteresis, can be presented in a similar way to items 1), 2), 3) and 4).

g) Presentation of measured power curves collected under special operational and atmospheric conditions:

1) power curves derived from subsets of the database for special operational or atmospheric conditions may also be reported. If this is the case, a power curve should be reported in the same way as for the reference air density but with the density derived from the average of the measured air density of the subsets of the database or alternatively using a pre-defined nominal air density for the site.

h) Presentation of estimated annual energy production for the reference air density (see 9.3) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:

1) a table similar to Table 5 for each annual average hub height wind speed shall include:

– AEP-measured;

– standard uncertainty of AEP-measured (see Annex D and Annex E);

– AEP-extrapolated;

2) the table shall also state:

[17] In addition to presenting the measured power curve in a table according to f) 1), the measured power curve can be presented as bin-centre values. The recommended method is to use a cubic spline for interpolation between the bin-values in the table to represent the measured wind speed, power and power coefficient values at the bin centre.

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- reference air density;
- cut-out wind speed;

3) if at any annual average wind speed AEP-measured is less than 95 % of AEP-extrapolated, the table shall also include the label “incomplete” in the column of values of AEP-measured;

i) Presentation of measured power coefficient (see 9.4):

1) measured power coefficient should be presented as a function of wind speed in a table and a graph in which the swept area of the rotor shall be indicated;

j) Presentation of results of site calibration (see Annex C for reporting requirements):

1) if a site calibration is undertaken, it shall be presented in the report as a table;
2) the table shall for each wind direction bin present:
   - minimum and maximum wind direction limits;
   - the bin-averaged wind direction;
   - the characteristics of the wind speed correction;
   - number of hours of data;
   - combined standard uncertainty of the wind speed ratio for 6 m/s, 10 m/s and 14 m/s;
3) the report shall furthermore include graphs and tables as required in Annex C;

k) Uncertainty of measurement (see Annex D):

1) uncertainty assumptions on all uncertainty components shall be provided;

l) Deviations from the procedure:

1) any deviations from the requirements of this standard shall be clearly documented in a separate clause. Each deviation shall be supported with the technical rationale and an estimate of its effect on test results.

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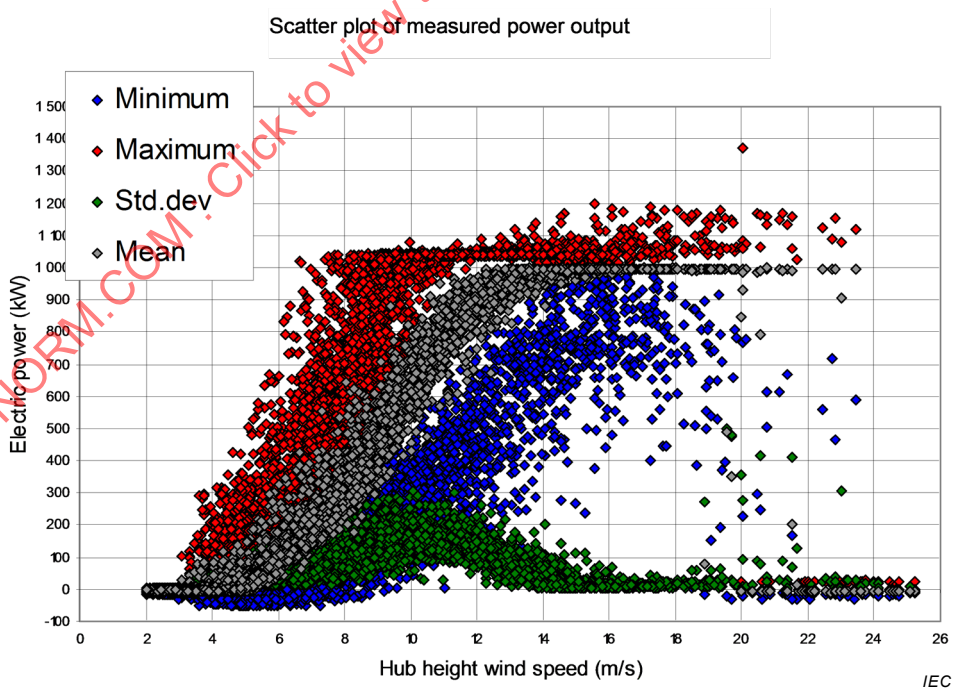

Figure 5 – Presentation of example database: power performance test scatter plot sampled at 1 Hz (mean values averaged over 10 min)

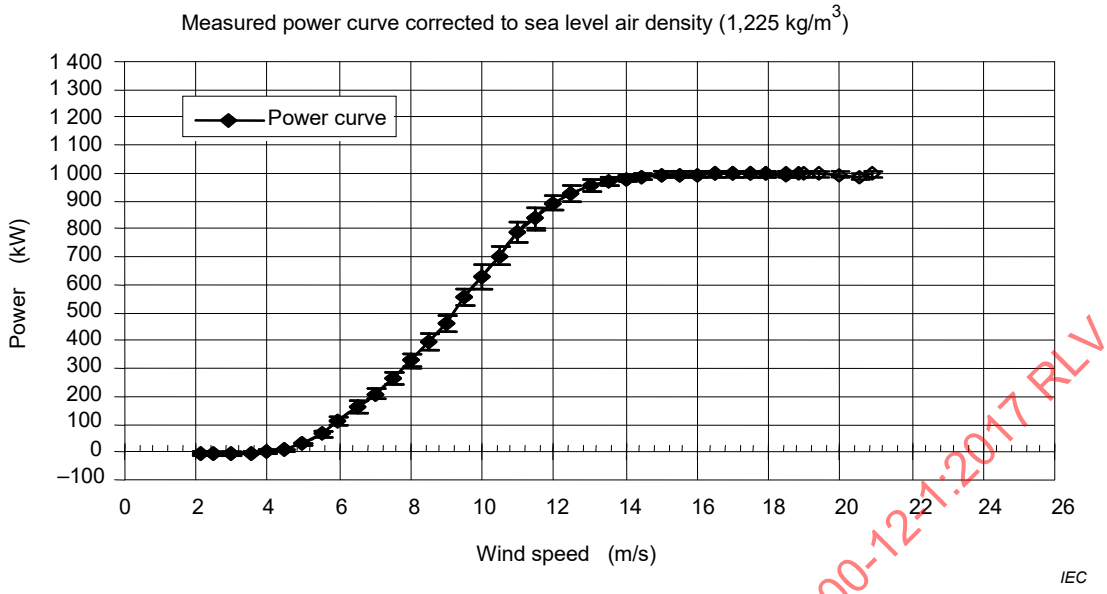

Figure 6 – Presentation of example measured power curve

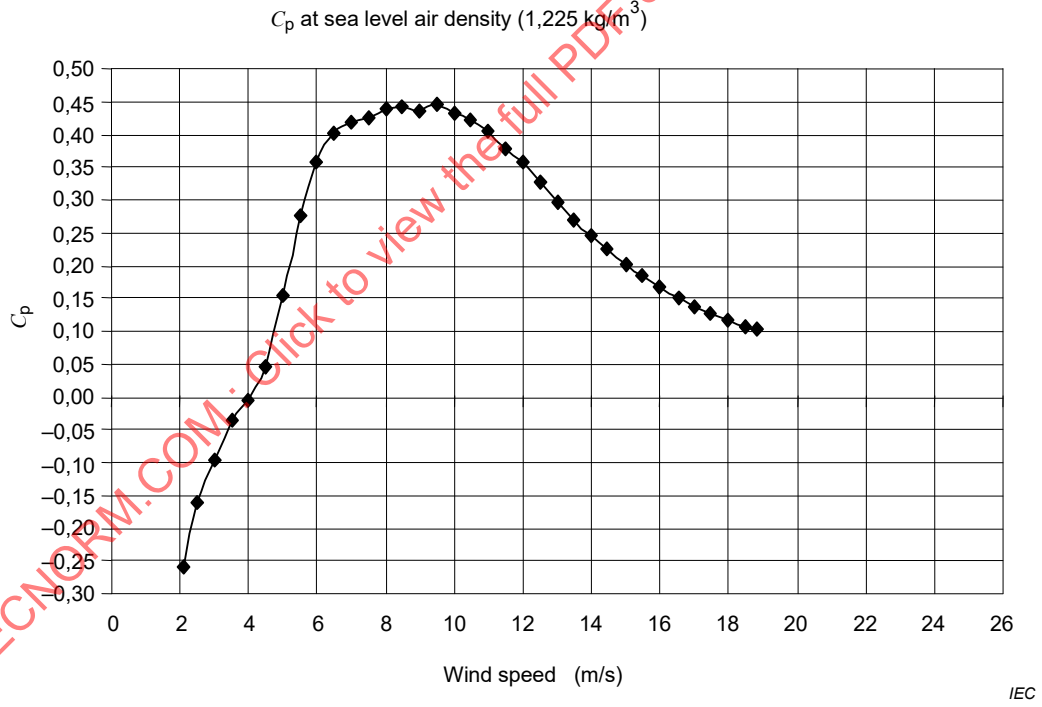

Figure 7 – Presentation of example C_P curve

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Table 4 – Example of presentation of a measured power curve

Measured power curve							
Reference air density: 1,225 kg/m^3					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed [m/s]	Power output [kW]	C_P	No. of data sets (10 min. avg.)	Standard uncertainty s_i [kW]	Standard uncertainty u_i [kW]	Standard uncertainty u_{ci} [kW]
4	2,1	–3,6	–0,26	138	0,05	6,3	6,3
5	2,5	–3,6	–0,16	275	0,04	6,3	6,3
6	3,0	–3,8	–0,10	270	0,13	6,3	6,3
7	3,5	–2,2	–0,03	320	0,56	6,3	6,3
8	4,0	–0,4	0,00	347	0,56	6,3	6,3
9	4,5	6,0	0,05	362	0,67	6,3	6,4
10	5,0	27,7	0,15	333	1,09	6,8	6,9
11	5,5	67,4	0,28	285	1,65	10,9	11,0
12	6,0	111,3	0,36	262	2,26	16,1	16,3
13	6,5	160,9	0,40	265	3,08	20,1	20,3
14	7,0	209,4	0,42	286	3,22	20,4	20,7
15	7,5	262,0	0,43	287	3,23	20,7	20,9
16	8,0	327,6	0,44	248	3,28	23,3	23,5
17	8,5	395,2	0,44	215	4,38	28,6	28,9
18	9,0	462,0	0,44	179	4,94	29,8	30,2
19	9,5	556,1	0,45	183	5,02	29,9	30,3
20	10,0	629,8	0,43	133	5,83	41,5	41,9
21	10,5	703,1	0,42	127	6,82	32,8	33,5
22	11,0	786,5	0,41	119	6,75	36,1	36,7
23	11,5	836,5	0,38	101	6,65	36,5	37,1
24	12,0	893,5	0,36	94	7,27	25,2	26,2
25	12,5	928,6	0,33	74	5,59	28,8	29,3
26	13,0	956,4	0,30	70	6,38	19,5	20,5
27	13,5	971,3	0,27	63	4,66	16,5	17,1
28	14,0	980,9	0,25	71	3,19	13,5	13,8
29	14,5	988,2	0,22	77	2,53	12,2	12,4
30	15,0	993,5	0,20	64	1,37	11,9	11,9
31	15,5	993,7	0,18	47	0,84	11,6	11,6
32	16,0	995,7	0,17	54	0,83	11,3	11,3
33	16,5	996,2	0,15	33	0,42	11,4	11,4
34	17,0	996,4	0,14	23	0,23	11,3	11,3
35	17,5	996,5	0,13	30	0,24	11,3	11,3
36	18,0	996,5	0,12	13	0,18	11,3	11,3
37	18,5	995,7	0,11	11	0,21	11,3	11,3
38	19,0	996,6	0,10	14	0,59	11,3	11,3
39	19,4	996,1	0,09	10	0,21	11,3	11,3

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Measured power curve							
Reference air density: 1,225 kg/m^3					Category A	Category B	Combined uncertainty
Bin no.	Hub height wind speed [m/s]	Power output [kW]	C_P	No. of data sets (10 min. avg.)	Standard uncertainty s_i [kW]	Standard uncertainty u_i [kW]	Standard uncertainty u_{ci} [kW]
40	20,0	994,1	0,09	5	0,41	11,3	11,3
41	20,5	987,4[18]	0,08	2	2,67	11,4	11,7
42	20,9	996,9	0,08	3	3,38	11,8	12,3

Table 5 – Example of presentation of estimated annual energy production

Estimated annual energy production Reference air density: 1,225 kg/m^3 Cut-out wind speed: 25 m/s (extrapolation by constant power from last bin)					
Hub height annual average wind speed (Rayleigh) m/s	*AEP*-measured (measured power curve) MWh	Standard uncertainty in *AEP* MWh	Standard uncertainty in *AEP* %	*AEP*-extrapolated (extrapolated power curve) MWh	
4	480	82	17	480	
5	1081	113	10	1 081	
6	1 824	138	8	1 824	
7	2 595	155	6	2 603	
8	3 305	163	5	3 342	
9	3 889	165	4	3 995	
10	4 318	162	4	4 536	
11	4 592	157	3	4 954	Incomplete

NOTE The standard uncertainty figures in the above tables are based on a coverage factor of 1. This implies that the level of confidence (percentage of times in repeated power curve measurements the intervals will contain the "true" *AEP* value) is in the order of 58 % to 68 %. The level of confidence is only an estimate since detailed knowledge of the probability distribution of the measurand is normally not known. The upper value (68 %) applies to normal distributions and the lower value (58 %) applies to rectangular distributions.

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[18] The dataset in bin 41 is incomplete (less than three data sets), therefore, the power value in bin 41 for *AEP* calculation is interpolated as 995,7.

Annex A
(normative)

Assessment of influences caused by wind turbines and obstacles at the test site

A.1 General

Annex A describes a procedure to determine one or more sectors which are not usable for the test because the flow at the wind turbine under test and/or the flow at the position of the wind measurement equipment (WME: a meteorological mast or a remote sensing device) might be affected by an operating wind turbine and/or by an obstacle.

The procedure consists of two steps, to be applied in the following order[19]:

a) evaluation of influences caused by operating wind turbines (wind turbine under test, as well as neighbouring and operating wind turbines), as described in Clause A.2;

b) evaluation of influences caused by obstacles, as described in Clause A.3 (under consideration of the special requirements for extended obstacles, as described in Clause A.5).

The valid sector which remains after this procedure shall be used for the terrain assessment according to Annex B.

The purpose of site calibration is generally to measure the change in the boundary layer as it follows the orography, which is generally attached flow, whereas obstacles often generate more turbulent wakes associated with them, which are affected by sharp edges and vertical surfaces that may trigger flow separation. A site calibration does not typically work well for correcting the effects of flow separation. This should be considered when deciding whether to treat an object as an obstacle or as terrain as flow separation and highly turbulent wakes are to be avoided. With this in mind, it is recommended that an object (including orographic elements which satisfy the dimensional criteria) whose height is more than half of its width be treated as an obstacle.

A.2 Requirements regarding neighbouring and operating wind turbines

The WME shall not be influenced by the wind turbine under test.

The wind turbine under test and the WME shall not be influenced by neighbouring operating wind turbines. If a neighbouring wind turbine is operated at any time during the power performance test, its wake shall be determined and accounted for as described in this annex (using the calculation given in Clause A.4). Small wind turbines of total height less than (2/3)(H – D/2) shall be treated as obstacles, and accounted for as described in Clause A.3.

If a wind turbine is stopped at all times during the power performance test, it shall be considered as an obstacle and accounted for as described in Clause A.3.

The minimum distance from the wind turbine under test and the neighbouring and operating wind turbines shall be two rotor diameters D_n of the neighbouring wind turbine. The minimum distance from the WME to any neighbouring and operating wind turbine shall be two rotor diameters of the respective wind turbine. The sectors to exclude due to wakes from neighbouring and operating wind turbines shall be taken from Figure A.1. The dimensions to be taken into account are the actual distance L_n and the rotor diameter D_n of the neighbouring

[19] Note that step b) requires the preliminary measurement sector, which is the result of step a).

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and operating wind turbine. The sectors to be excluded shall be derived for both the wind turbine under test and the WME, and they shall be centred on the direction from the neighbouring and operating wind turbine to the wind measurement equipment or the wind turbine. An example is shown in Figure A.2.

A.3 Requirements regarding obstacles

Obstacles near the wind turbine under test or near the WME shall be evaluated. Each obstacle shall be evaluated either as part of the orography (as described in Annex B[20]), or – alternatively – according to the procedure which is described here as follows.

No significant obstacles (e.g. buildings, trees, parked wind turbines) shall exist in the measurement sector within a reasonable distance from the wind turbine or from the WME. Only small buildings, connected to the wind turbine operation or the wind measurement equipment, are acceptable. Where significant obstacles are present then the measurement sector shall be reduced as described in Clause A.4 and A.5.

The criterion for the significance of an obstacle (with respect to the wind turbine under test and/or with respect to the WME) is to exceed one or more of the limits given in Table A.1, where Table A.1 shall be applied for all locations:

a) for the evaluation of the surroundings of the wind turbine under test (i.e. using the centre of the wind turbine under test as centre of the $2L$, $4L$, $8L$, and $16L$ circles);

b) for the evaluation of the surroundings of the WME (i.e. using the position(s) of the equipment as centre of the $2L$, $4L$, $8L$, and $16L$ circles)

Table A.1 – Obstacle requirements: relevance of obstacles

Distance[a]	Sector[b]	Maximum obstacle height from terrain surface[c]
$<2L$	360°	$<1/3\ (H - 0{,}5\ D)$
$\geq 2L$ and $< 4L$	Preliminary measurement sector	$<2/3\ (H - 0{,}5\ D)$
$\geq 4L$ and $<8L$	Preliminary measurement sector	$<(H - 0{,}5\ D)$
$\geq 8L$ and $<16L$	Preliminary measurement sector	$<4/3\ (H - 0{,}5\ D)$
$\geq 2L$ and $<16L$	Clearly outside preliminary measurement sector by 40° or more	No limit to height

a from obstacle to wind turbine under test, respectively from obstacle to WME – whereas L is the horizontal distance between wind turbine under test and wind measurement equipment.

b *Preliminary measurement sector* shall be understood here as the valid sector which remains after evaluation of neighbouring operating wind turbines (as described in Clause A.2, using the calculation described in Clause A.4), whereas all directions which are less than 40° outside shall also be considered.

c H is the hub height and D is the rotor diameter of the wind turbine under test.

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A.4 Method for calculation of sectors to exclude

The wind turbine under test shall always be evaluated according to Figure A.1 with respect to its wake influence on the WME.

20 The consideration of an obstacle in this way will typically increase mainly the terrain variation, whereas the effect on the slope might be very small (except for extended obstacles, e.g. forests).

A neighbouring and operating wind turbine shall always be evaluated according to Figure A.1 with respect to its wake influence on the wind turbine under test and also with respect to its wake influence on the WME.

With respect to operating wind turbines, the dimensions to be taken into account are the actual distance L_n (from centre of wind turbine under test to the position of the WME) and the rotor diameter D_n of the wind turbine that causes the wake[21].

An obstacle shall be evaluated according to Figure A.1 with respect to its wake influence on the wind turbine under test if the obstacle is significant with respect to the wind turbine under test according to Table A.1.

An obstacle shall be evaluated according to Figure A.1 with respect to its wake influence on the WME if the obstacle is significant with respect to the WME according to Table A.1.

With respect to obstacles, the dimensions to be taken into account are the actual horizontal distance L_e (from the centre of wind turbine under test or from the position of the WME as appropriate) and an equivalent rotor diameter D_e of the obstacle. A stopped neighbouring wind turbine may be treated as a cylinder with a diameter equal to the tower base diameter and a height equal to the upper tip height. The equivalent rotor diameter of the obstacle shall be defined as:

$$D_e = \frac{2 l_h l_w}{l_h + l_w} \tag{A.1}$$

where

D_e is the equivalent rotor diameter;

l_h is the height of obstacle;

l_w is the width of obstacle as seen from the wind turbine under test or from the WME.

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21 The influence of the turbine under test on the WME is evaluated by means of L (distance between turbine under test and wind measurement equipment) and D (rotor diameter of turbine under test).

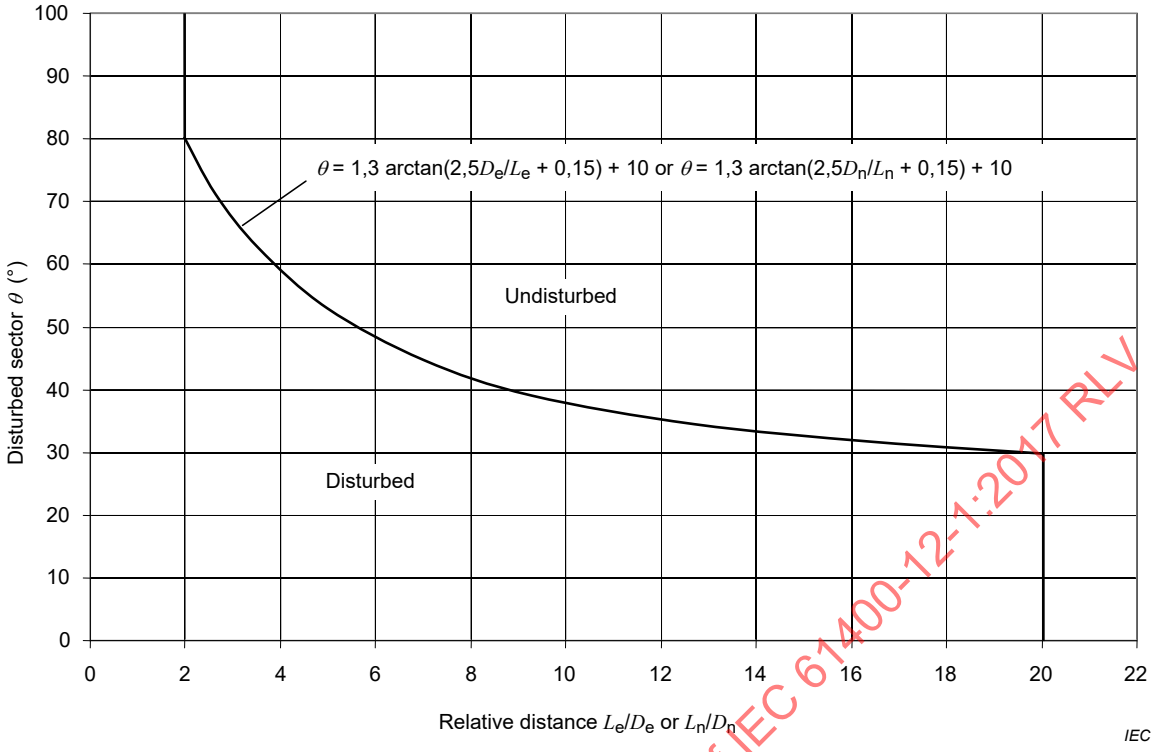

Figure A.1 – Sectors to exclude due to wakes of neighbouring and operating wind turbines and significant obstacles

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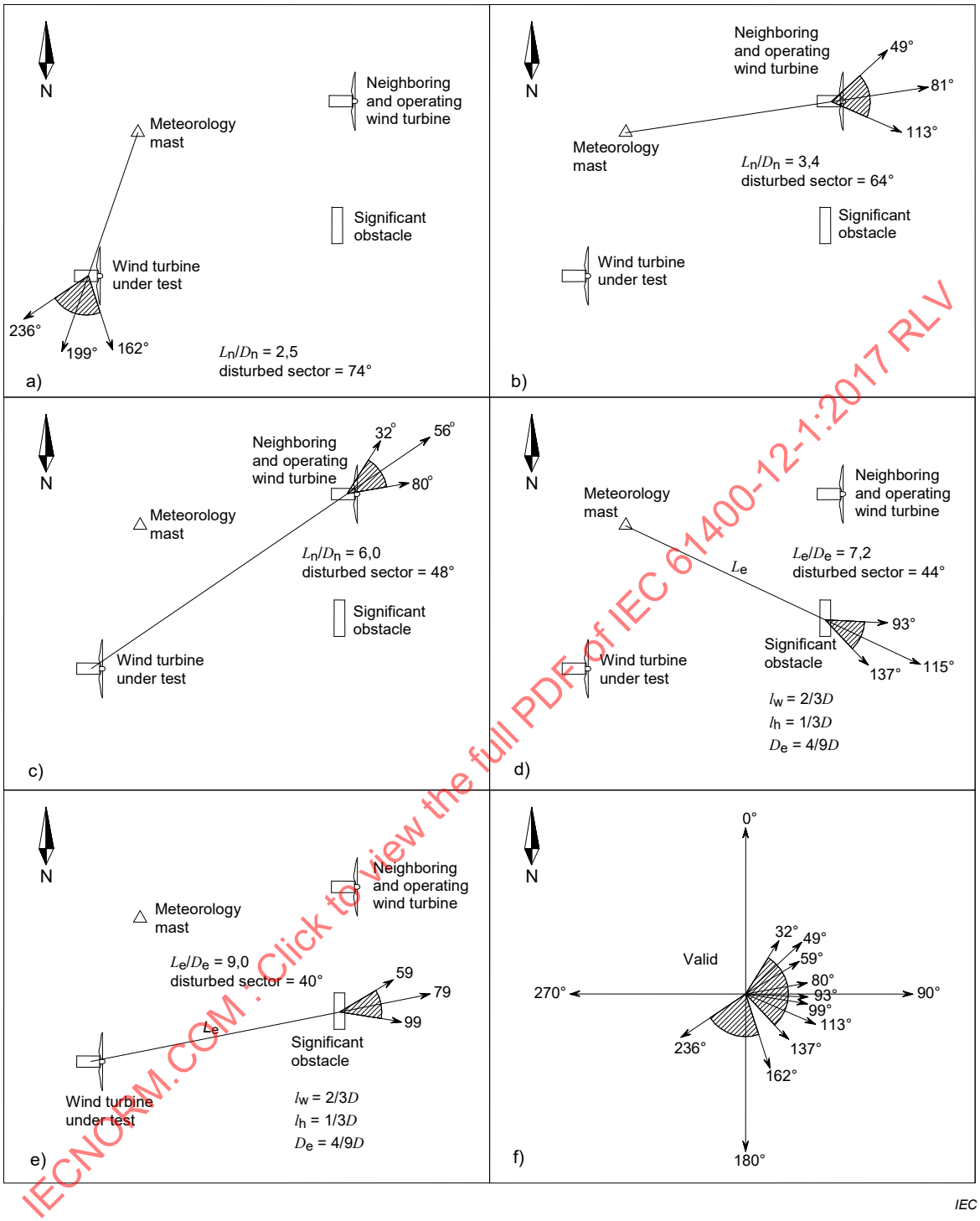

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Figure A.2 – An example of sectors to exclude due to wakes of the wind turbine under test, a neighbouring and operating wind turbine and a significant obstacle

The figures show the sectors to exclude if:

a) the WME (meteorological mast or remote sensing device) is in the wake of the wind turbine under test;

b) the WME is in the wake of the neighbouring and operating wind turbine;

c) the wind turbine under test is in the wake of the neighbouring and operating wind turbine;

d) the WME is in the wake of the significant obstacle;

e) the wind turbine under test is in the wake of the significant obstacle;

f) all of the above effects a) to e) are combined.

NOTE The example shown in Figure A.2 is based on the assumption that the obstacle is significant (according to Table A.1) with respect to the wind turbine under test and also significant with respect to the wind measurement equipment.

A.5 Special requirements for extended obstacles

Obstacles within a distance of less than $4L$ (from centre of the wind turbine under test or from the wind measurement equipment) which extend more than 50 m in any horizontal direction shall be divided into partial obstacles that do not extend more than 50 m in any horizontal direction and exactly 50 m in any dimension that is more than 50 m. These partial obstacles may overlap each other. The combination of these partial obstacles shall at least[22] cover the original obstacle completely. Each partial obstacle shall be evaluated separately. The significance of each partial obstacle shall be assessed, and if it is found to be significant, the sector to be excluded shall be determined. For example:

a) An obstacle 90 m by 90 m is divided into 4 partial obstacles 50 m by 50 m each. These partial obstacles are chosen such that they overlap each other by 10 m so that the set union of the 4 partial obstacles is identical to the original obstacle.

b) An obstacle 70 m by 10 m is divided into 2 partial obstacles 50 m by 10 m each. These partial obstacles are chosen such that they overlap each other by 30 m so that the set union of the 2 partial obstacles is identical to the original obstacle.

A grouping of trees or forest shall be treated in this way.

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22 For practical purposes, it makes sense to create partial obstacles which all have the same shape (e.g. squares of 50 m x 50 m). This is a conservative approach and therefore permitted. (In this case, the set union of all partial obstacles covers a larger area than the original obstacle.)

Annex B
(normative)

Assessment of terrain at the test site

For testing without a site calibration (in terrain which is defined as “flat terrain”), the following criteria shall be kept (see Figure B.1 and Table B.1 for details):

– orography at the test site may only show minor variations from a plane, which passes both through the base of the tower of the wind turbine, and the terrain within the respective sector;

– each of these planes shall not exceed a certain limit for the slope.

The assessment of the terrain shall be made using a digital model of the terrain with a grid resolution of 30 m or finer.

Table B.1 shall be applied for the locations below for the measurement sector:

a) for the evaluation of the surrounding of the wind turbine under test (i.e. using the centre of the wind turbine under test as centre of the $2L$, $4L$, $8L$, and $16L$ circles);

b) for the evaluation of the surrounding of the WME (i.e. using the position of the equipment as centre of the $2L$, $4L$, $8L$, and $16L$ circles).

If the terrain complies with all of the requirements of Table B.1 in both cases, then no site calibration is required[23] due to orography. Otherwise the terrain is defined as “complex terrain” and a site calibration measurement is required.

In Table B.1, L is the distance between the wind turbine and the WME, H is the hub height and D is the rotor diameter (of the wind turbine under test).

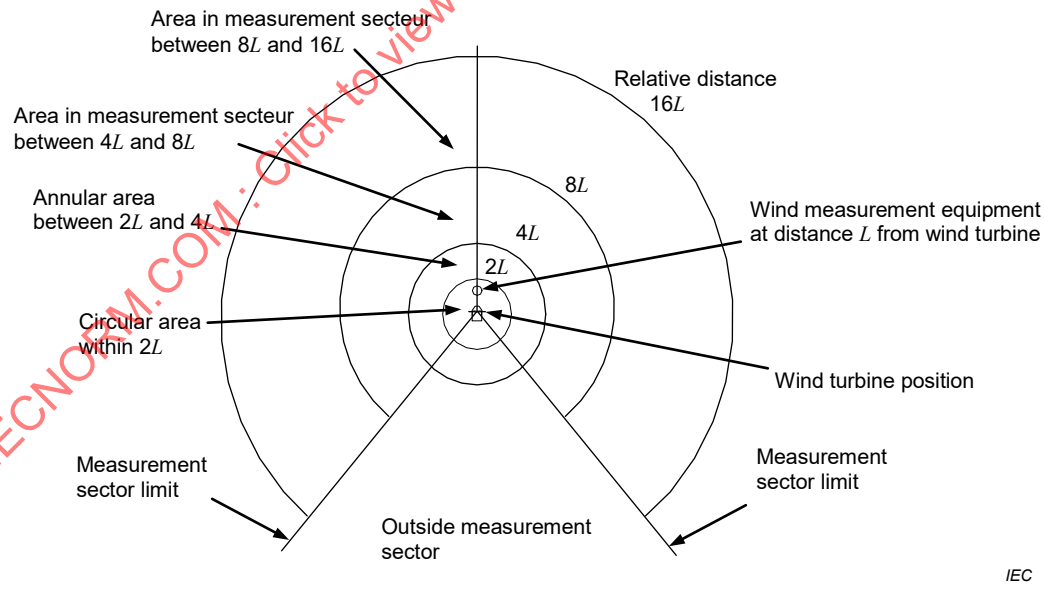

Figure B.1 – Illustration of area to be assessed, top view

23 Nevertheless, other aspects of the terrain such as roughness, distance to the sea coast, or other considerations, may lead to the conclusion that a site calibration is recommended.

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Table B.1 – Test site requirements: topographical variations

Distance	Sector[a]	Maximum slope %	Maximum terrain variation from plane
<2L	360°	<3[b]	<1/3 (H – 0,5 D)
≥2L and < 4L	Measurement sector	<5[b]	<2/3 (H – 0,5 D)
≥2L and <4L	Outside measurement sector	<10[c]	Not applicable
≥4L and <8L	Measurement sector	<10[b]	< (H – 0,5 D)
≥8L and <16L	Measurement sector	<10[c]	Not applicable

a Measurement sector is understood here by default as the remaining valid sector after execution of the procedure defined in Annex A, whereas it is also allowed to use a smaller measurement sector[24].

b The maximum slope of the plane, which provides the best fit to the terrain in the sector being considered and passes through the tower base. See Figure B.2 for an example.

c The line of steepest slope that connects the tower base to individual terrain points on the surface of the terrain within the sector. See Figure B.3 for an example.

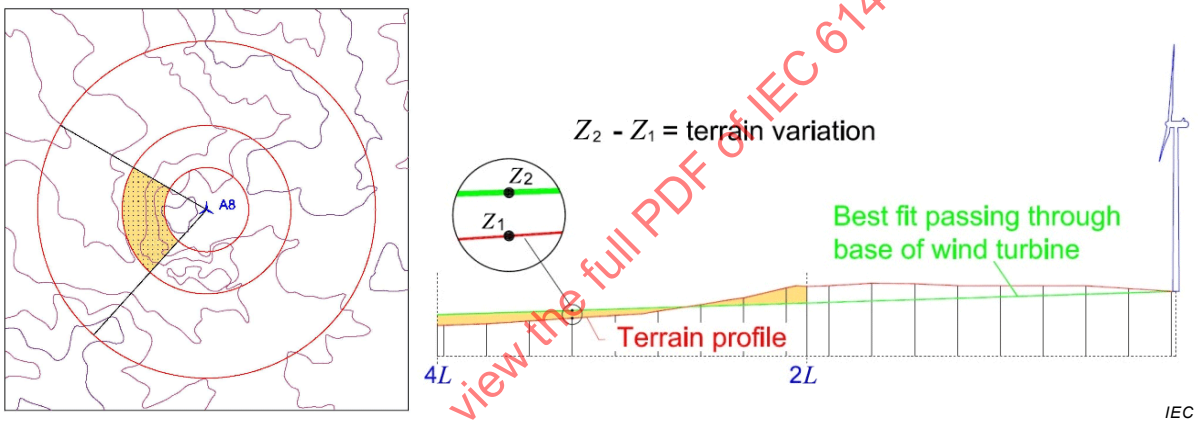

Figure B.2 – Example of determination of slope and terrain variation from the best-fit plane: "2L to 4L" and the case "measurement sector" (Table B.1, line 2)

NOTE 1 This figure shows just one direction. All directions within the measurement sector are considered for the calculation of the plane which provides the best fit, and then the maximum terrain variation against this plane is determined by analysing all directions as shown above.

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24 It is additionally recommended to check if significant terrain variation exists slightly outside the borders of this sector. If this is the case, the final sector which is considered for the power performance test should keep a clear directional distance to these critical directions.

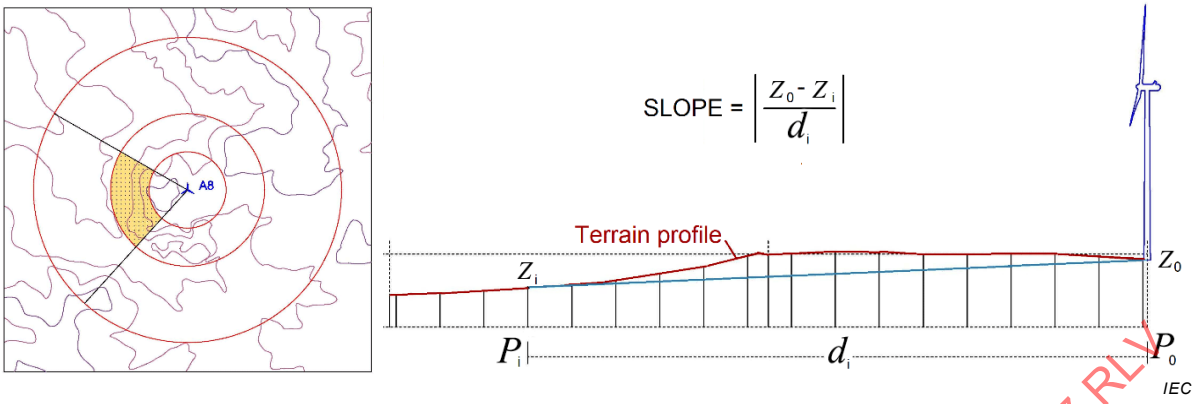

Figure B.3 – Determination of slope for the distance "2L to 4L" and "8L to 16L" and the case "outside measurement sector" (Table B.1, line 3 and line 5)

NOTE 2 This figure shows just one direction. All directions outside the measurement sector are analysed in the same way, and the worst-case result (i.e. highest slope) is considered.

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Annex C
(normative)

Site calibration procedure

C.1 General

A site calibration quantifies and potentially reduces the effects of terrain on the power performance measurement. Terrain may cause a systematic difference in wind speed between the position on the meteorological mast where the power performance anemometer is mounted and the equivalent height above ground at the centre of the turbine rotor at the turbine position. In addition, the relationship between the reference meteorological mast wind speed and the wind speed at the turbine position may also be affected by changes in atmospheric stability and/or the shear profile. Wind shear, which is the change in wind speed with height above the ground, may be also an influential parameter on this relationship as different shear profiles may cause a different relationship between the measurement points, especially if the turbine and met mast are at different elevations.

Seasonal considerations: atmospheric stability, turbulence and wind shear can be related to different seasonal conditions. There are also concerns of the effects of changes in roughness due to changes in the vegetation in the testing area or other roughness changes directly caused by different seasonal surface characteristics (water/land vs. ice/land, snow, crops, etc.…). In light of these considerations, the site calibration and power curve measurement should be conducted during the same season or seasons. If the measurements are conducted in different seasons, additional uncertainty shall be applied as discussed in Clause C.7.

The outputs of the site calibration are:

a) a table of flow corrections for all wind directions within the measurement sector(s) and

b) an estimate of the standard uncertainty of these flow corrections.

There are two distinct methods in which the site calibration may be evaluated. Only one method is required, where the method is chosen by evaluating the data to assess shear as discussed in C.5.1. The output for each method is:

1) Subclause C.5.2 Site calibration with shear: the flow corrections consist of a matrix of wind direction bins and wind shear bins where a single wind speed ratio correction factor is calculated for each point in the matrix.

2) Subclause C.5.3 Site calibration where shear is not a significant influence: the flow corrections consist of a slope and an intercept value for each wind direction bin. The coefficient of determination, r^2, value for the regression shall also be reported.

This procedure is given for the wind speed defined as the hub height wind speed. This is so that the procedure does not mandate upper tip height meteorological masts, which are expensive and may be impractical, as remote sensing devices may not be suitable for measurements in complex terrain. However, where a power curve is to be derived for the REWS definition of wind speed, then the procedure is repeated for each pair of measurement heights rather than just for the hub height on each meteorological mast.

C.2 Overview of the procedure

Prior to the installation of the wind turbine (or after the removal of it if already existing) two meteorological masts shall be erected. One meteorological mast is the reference position meteorological mast, which will also be used for the power performance test. The second meteorological mast is a wind turbine meteorological mast at the wind turbine position.

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This procedure intends to characterize the correlation of the wind speeds between the two positions. Further recommendations for the selection of these positions are provided in C.3.1.

The flowchart in Figure C.1 provides a general overview of the preparation and analysis process.

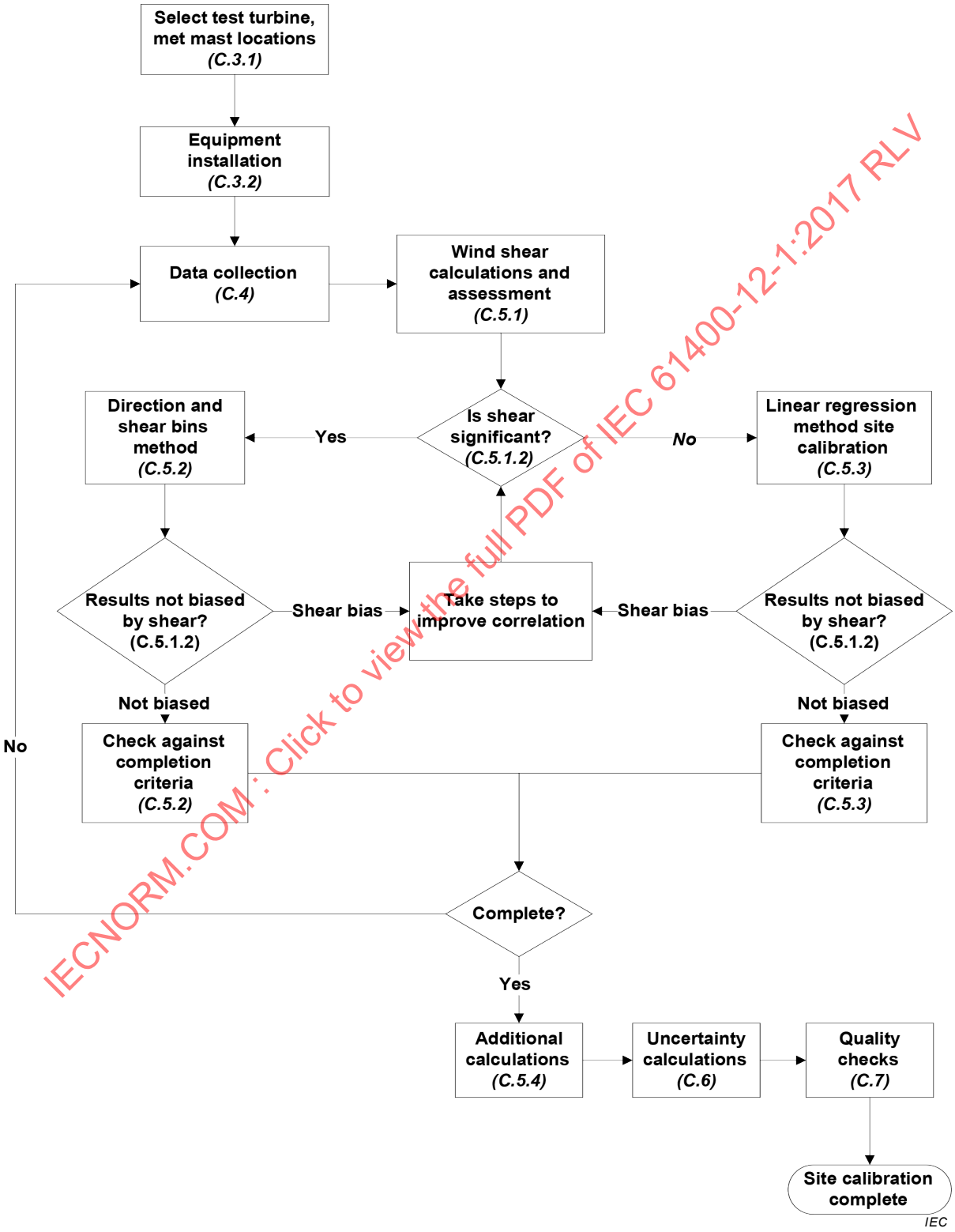

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Figure C.1 – Site calibration flow chart

C.3 Test set-up

C.3.1 Considerations for selection of the test wind turbine and location of the meteorological mast

The reference meteorological mast shall be the same meteorological mast that is used for power curve measurement. The wind turbine meteorological mast shall be located as close as possible to the position where the test wind turbine will be or was located and shall be no more than 0,2 H from the centreline of the wind turbine where H is the wind turbine hub height. It is recommended that the wind turbine and reference meteorological masts be of the same type and have the same boom geometry so as to have similar mounting effects on the WME.

There are a number of factors that can affect site calibration. The most notable of these are terrain, meteorological mast location, and atmospheric conditions including wind shear, turbulence and stability. These factors can vary significantly from one location to another but are often correlated with each other.

The test wind turbine location should be selected to optimise valid data collection and provide a good correlation between the reference and wind turbine meteorological masts. The purpose of site calibration is to measure the change in the boundary layer as the wind follows the orography of the terrain, which is generally attached flow, whereas obstacles have more turbulent wakes associated with them, which are affected by sharp edges and vertical surfaces that may trigger flow separation. Additionally, certain terrain features such as cliffs or steep hills may also cause the flow to separate, resulting in a poor correlation. As a guide, the terrain type should be taken into consideration when selecting the test wind turbine and the reference meteorological mast location. The terrain types discussed here are informative, qualitative descriptions to aid selection of the test wind turbine and reference meteorological mast locations and to provide insight on what to expect when conducting measurements in these terrain types. Examples of these terrain types are illustrated in Figure C.2.

Type A:

Type A terrain is the least complex terrain type. A Type A site typically does not have significant changes in elevation relative to the hub height of the wind turbine or particularly steep slopes over long distances. Examples of Type A terrain include terrain that meets the requirements of Annex B, gentle rolling hills, and possibly wind turbines located on a ridge facing a plain.

When conducting site calibrations at Type A sites, the wind shear conditions at the reference meteorological mast may be different from the wind shear conditions at the wind turbine location. If this is the case, then the site calibration results will likely be dependent on wind shear and wind direction.

Type B:

Type B terrain is moderate to complex terrain. Type B terrain includes mountains, ridgelines, large hills, and hilly sites with moderate to steeply sloping terrain and significant changes in elevation relative to the hub height of the wind turbine. Typically the wind shear at Type B sites is low and relatively consistent, though at times negative wind shear may occur. Thus wind shear is not expected to be as significant a factor as for Type A sites. However, at Type B sites the site calibration results often depend on both wind speed and wind direction, especially if the difference in elevation between the reference meteorological mast and the test wind turbine is more than 10 m. Thus a linear regression correction is often appropriate for a Type B site.

The upflow/vertical wind speed component induced by the terrain at Type B sites can have a significant impact on the uncertainty, depending on the response of the anemometers to upflow. A vertical wind speed measurement may be used to assess the upflow angle, which

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can then be used in conjunction with the anemometer classification report to calculate an S-type anemometer operational characteristic with user-defined influence parameter ranges as defined in Clause I.3.

Type C:

Type C terrain includes the most extreme terrain from a measurement perspective. Type C sites typically have a steep terrain feature such as a mountain or canyon that may cause flow separation directly upwind of the test wind turbine and create a recirculation zone at the test wind turbine location. The scale of the flow separation is defined by the terrain feature and may disrupt the wind speed correlation between the test wind turbine and reference meteorological mast even if the terrain feature is located farther than $16L$ away from the test wind turbine. Type C terrain is typically so complex that the correlation between the winds at the reference meteorological mast and the test wind turbine may be poor. The flow corrections may differ significantly between adjacent wind direction bins. Caution shall be taken when selecting test wind turbines at Type C terrain locations because the data will typically have very high scatter and high uncertainty in the result.

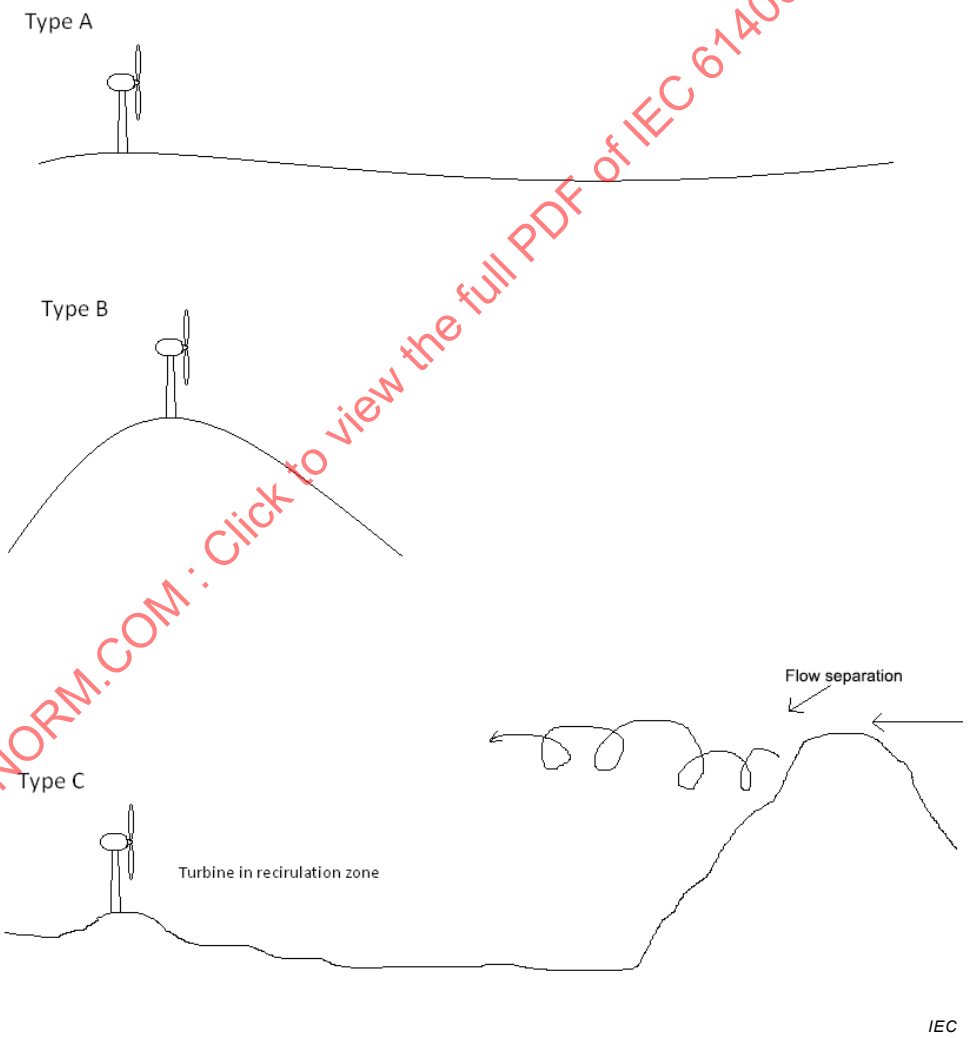

Figure C.2 – Terrain types

In order to improve the correlation, the reference meteorological mast should be located such that it has a similar elevation and wind conditions as those of the test wind turbine. For example, if the test wind turbine is located on a ridge, then the reference meteorological mast

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is recommended to be located on the ridge next to the wind turbine instead of at a lower elevation in front of the wind turbine.

C.3.2 Instrumentation

The test set-up requires as a minimum measurements of hub height wind speed, wind direction near hub height, and wind shear at both meteorological masts according to 7.2.8.

WME used in the site calibration shall meet the requirements of 7.2 and follow the guidelines for mounting of Annex G. The anemometers shall be of the same type with the same operating characteristics and shall be calibrated in the same wind tunnel. The anemometers shall be of the same type with the same operating characteristics for the power curve measurement as for site calibration.

Depending on the site characteristics, additional measurements are recommended so as to provide more information about the site conditions and thus are not normative. These measurements may also be used to improve the overall quality of the site calibration and power curve measurement by identifying unusual atmospheric conditions that correlate with outliers or may be used to determine the right instrument classification and in conjunction with the relevant classification report quantify the site-specific anemometer operational characteristic standard uncertainty:

a) A vertical wind speed measurement (e.g. using a 3D ultrasonic anemometer) is recommended within 10 % of hub height or within 5 m of hub height for smaller wind turbines so as not to violate the mounting requirements of Annex G for top mounted sensors. This measurement may be used to determine the correct class for the instrument classification and in conjunction with the instrument classification report to quantify the uncertainty due to operational characteristics in accordance with Annex I.

b) A wind veer measurement is recommended with the lower wind direction measured within 10 m of the lower tip height wind speed measurement;

c) If icing conditions are expected during the site calibration campaign, a temperature sensor or other means for icing detection is recommended near hub height.

Furthermore, to avoid the introduction of bias in the wind direction measurement due to uncertainty of the wind direction sensor installation, the reference meteorological mast and its wind direction sensor(s) should not be removed between the site calibration and the power curve measurement. If the primary wind direction sensor is removed or replaced, an additional uncertainty component shall be included (see C.7.4). If the reference meteorological mast is removed and re-installed between the site calibration and the power curve measurement, the instruments shall be mounted in the same configuration and with the same boom angles during both periods so as to have similar mounting effects.

C.4 Data acquisition and rejection criteria

Data shall be collected continuously at the same sampling rate as for the power performance test. Data sets shall be based on 10 min periods derived from contiguous measured data. The mean, standard deviation, minimum and maximum values for each 10 min period shall be derived and stored.

The wind direction bin size shall be 10°.

Data sets shall be rejected from the database under the following circumstances:

a) failure or degradation (e.g. due to icing) of test equipment;

b) wind direction outside the measurement sector(s) as defined in 6.3.3;

c) mean wind speed at wind turbine meteorological mast less than 4 m/s or greater than 16 m/s;

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d) any other special atmospheric conditions that are found to influence the site calibration result and chosen to be rejection criteria;

e) special atmospheric conditions to be used as rejection criteria during the power performance test that are found to influence the site calibration.

Any special atmospheric condition filtered during the site calibration shall also be filtered during the power curve test.

C.5 Analysis

The site calibration measures the relationship of wind speeds at two specific points in space. Orography represents a static influence on this relationship (the terrain is not moving over time) however wind shear adds a dynamic element to this relationship, as the wind speed gradient with height may vary significantly, or it may not if the site only sees a fairly steady shear over a limited range.

The first step in the site calibration process is therefore to assess the shear conditions at the site. The calculations and plots in C.5.1 are performed first to make this assessment, then based on the outcome either C.5.2 or C.5.3 is followed to complete the calculation of the flow corrections. Once the flow corrections have been calculated according to either C.5.2 or C.5.3, the procedure then continues with the additional calculations in C.5.4 which are inputs to the uncertainty calculations in Clause C.6 and the quality checks in Clause C.7.

C.5.1 Assessment of site shear conditions

C.5.1.1 Shear calculations and characterisation plots

For each 10 min data point, the following calculations shall be made:

a) the wind speed ratio, which is the hub height wind speed at the turbine location divided by the hub height wind speed at the reference meteorological mast;

b) the shear exponent at both met masts shall be calculated using the power law (see 3.31);

c) the time of day using a 24 hour clock shall be determined from the timestamp and any offset to the site local time. Any adjustment to the local clocks for more daylight hours in summer vs. winter (i.e. Daylight Savings Time, summer time) shall be noted if it is applied to the data logger timestamps.

The analysis method shall depend on whether or not wind shear is determined to be a significant factor at the site. High shear, or more specifically a wide range of shear values, is typically due to a diurnal cycle of stable atmosphere at night and unstable atmosphere during the day. To illustrate the shear conditions at the site and to assist with the shear evaluation, the following scatter plots shall be generated for both the turbine location and reference met mast data from the filtered database:

1) scatter plot of wind shear exponent vs. time of day;

2) scatter plot of wind shear exponent vs. wind direction;

3) scatter plot of wind shear exponent vs. wind speed;

4) scatter plot of wind speed vs. time of day.

Please note that time of day should be used with care. What really lies behind this are the correlation to local sun-rise and sun-set times as these often strongly influence atmospheric stability. Especially for longer data sets and higher latitudes, the correlation between sun-rise, sun-set and time of day becomes quite poor.

For a site where these effects occur, typically the shear exponents observed during the day time will be low as the sun heats the ground causing turbulence and mixing of the layers and at night the shear will be high. Thus there may be a wide range of shear exponents and a noticeable change in the shear exponents from day time to night time for these sites.

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C.5.1.2 Assess significance of shear

Regardless of atmospheric stability, shear shall be considered to be a significant factor if more than 25 % of the data points have a shear exponent greater than 0,25.

Shear shall be confirmed to be a significant parameter if the wind speed correlation improves following binning by direction and shear according to Method 1 in C.5.2; otherwise the site calibration may be evaluated following Method 2 – linear regression method described in C.5.3.

Dividing the measurement sector to allow for different methodologies for different sectors is permitted. This may be useful if, for example, the terrain from part of the measurement sector is Type A and from another direction it is Type B.

The goal is to ensure that the site calibration is not biased by unusual shear conditions; either the site calibration method accounts for the impact of shear or unusual conditions are filtered out. The site calibration results using either method C.5.2 or C.5.3 may be assessed using the method in C.5.4, where the site calibration corrections are applied to the permanent mast wind speed and this is then compared to the turbine location wind speed. Comparing the site calibration residuals against wind shear or other atmospheric stability metrics will show if the selected method accurately corrects the permanent location wind speed for all conditions or if additional steps are necessary to improve quality and reduce uncertainty. Specifically:

a) the self-consistency parameter (Equation (C.3) in C.5.4) bin-averaged against wind speed should be between 0,98 and 1,02 in the range of 4 m/s to 16 m/s within each sector;

b) a linear regression of $V_{\text{Turb_predicted}}$ (Equation (C.1)) vs. $V_{\text{Turb_measured}}$ should have an R^2 value > 0,95 within each sector.

C.5.1.3 Establish correlation of shear between locations

If shear is determined to be significant at the site and where there is a requirement to filter on shear at the turbine location, then it shall be established that the shear at the turbine location can be predicted from the shear measured at the reference met mast. The simplest method to achieve this is to plot the shear at the turbine location vs. the shear at the reference mast and calculate an Ordinary Least Squares linear regression. This shall be done using the filtered database. Note that this regression may be used during the power curve measurement to predict shear at the turbine location.

If the shear at the turbine location and the shear at the reference mast are not correlated for all cases, then steps shall be taken so that the data is correlated for all cases. For example, non-correlation may occur where there is a significant difference in elevation between the reference mast and test turbine location in conjunction with high shear, which is often correlated with time of day. In these cases, the suggested method to achieve correlated results is to filter the data based on time of day to remove the high shear night time data, although other methods to remove non-correlating data are permitted. The time of day filter may be established using the shear exponent vs. time of day plots. Reducing the measurement sector such that only directions with similar flow conditions are considered, filtering or breaking the site calibration up by seasons, or other methods to achieve a fully correlated data set may be used. The plots of wind shear exponent vs. wind direction may be useful in determining which sectors to use.

Any additional filter applied to the site calibration results shall also be applied to the power curve measurement. If a time of day filter is used, the filter may be adjusted seasonally to reflect longer days during the summer and shorter days during the winter. Only data from the reference mast should be used for any additional filters because it will not be possible to filter on the turbine location data during the power curve measurement.

Shear, turbulence, and wind speed are often correlated. The plots of wind shear exponent vs. wind direction, wind shear exponent vs. wind speed, and wind speed vs. time of day may be used to assess the potential impact of these filters on the power curve data in terms of

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reduced data at certain wind speeds. For example, if applying a time of day filter will result in the loss of most of the data at high wind speeds, then this filter may not be practical. In the extreme case a solution could be to have multiple site calibrations, each valid for a specific range of atmospheric conditions.

C.5.2 Method 1: Bins of wind direction and wind shear

To determine if the site calibration correction factors are influenced by the shear on the site, the data shall be sorted into bins of wind direction and shear. The size of the wind direction bins shall be 10° and shall not be less than the uncertainty of the wind direction sensor. At the edges of the measurement sector, the data shall be filtered to the extents of the measurement sector. For example, where the measurement sector ends at 43°, the site calibration at the edge of the sector will be evaluated from 35° to 43° only. It is required that the choice of direction bin centre definition (e.g. either bins centred on integer multiples of 10° or bins beginning on integer multiples of 10°) shall be carried through consistently from the site calibration to the power curve test. The wind shear bins shall be in increments of 0,05 shear exponent centred on integer multiples of 0,05.

The wind speed ratios within each wind direction and wind shear bin shall be averaged.

The completion criteria for the wind direction and wind shear bins is as follows:

a) For each wind direction bin, the number of data points across all wind shear bins within that wind direction bin shall total at least 144 (24 hours of data). Incomplete wind shear bins may be included in this total. Furthermore, each wind direction bin shall contain at least 6 hours above and 6 hours below 8 m/s.

b) Each wind shear bin within a complete wind direction bin shall contain at least 3 data points.

c) Wind shear bins in incomplete wind direction sectors that contain at least 6 hours of data may also be considered complete.

If after the matrix has been completed it is found that the site calibration corrections do not change with increasing wind shear, then the wind shear bins may be eliminated and the data evaluated only on a wind direction bin basis according to C.5.3. The level of change shall be evaluated against the statistical uncertainty of the site calibration.

If the variation between wind shear bins causes a higher variability in site calibration factors than twice the statistical uncertainty of the site calibration in one or more wind direction bins, the wind shear bins shall be included in the analysis alongside the wind direction bins.

If the variation between wind shear bins causes a lower variability in site calibration factors than twice the statistical uncertainty of the site calibration in one or more wind direction bins, the wind shear bins may be eliminated and the data evaluated only on a wind direction basis per C.5.3.

During the power curve measurement, the data shall be sorted into wind direction bins. For each 10 min data point, the wind shear exponent at the reference mast shall be calculated. The correction applied to the hub height wind speed shall be the wind speed ratio interpolated to the measured wind shear value from the wind shear bin average values and the measured wind shear exponent for that wind direction bin. Extrapolation is permitted for wind shear exponents falling within the last complete wind shear bins; for example if the last complete site calibration wind shear bin is the 0,6 wind shear bin, extrapolation is permitted for measured wind shear exponent values between 0,600 and 0,625 (where 0,625 is the upper edge of the 0,6 wind shear bin with a bin width of 0,05 and a range of 0,575 to 0,625). Interpolation between two complete wind shear bins across an incomplete wind shear bin is permitted. Interpolation between wind direction bins is not permitted.

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C.5.3 Method 2: Linear regression method where shear is not a significant influence

The data sets shall be sorted into wind direction bins. The size of the wind direction bins shall be 10°. It is required that the choice of direction bin centre definition (e.g. either bins centred on integer multiples of 10° or bins beginning on integer multiples of 10°) shall be carried through consistently from the site calibration to the power curve test. At the edges of the measurement sector, the data shall be filtered to the extents of the measurement sector. For example, where the measurement sector ends at 43°, the site calibration at the edge of the sector will be evaluated from 35° to 43° only.

For each wind direction bin, an ordinary least squares linear regression shall be made with the turbine location wind speed as the dependent variable and the reference wind speed as the independent variable. Therefore, there will be one slope and one intercept for each wind direction bin.

Each wind direction bin shall have at least 24 h of data in total and shall have at least 6 h of data where winds are above 8 m/s and at least 6 h of data where winds are below 8 m/s. There should be a wide distribution of wind speeds within the bin to get a good correlation (see C.7.2), and it is therefore recommended that data with wind speeds at least up to 11 m/s be present. Note that outliers are highly weighted by the ordinary least squares regression method. Any outliers that appear to have a significant impact on the regression should be investigated and documented.

To illustrate the correlation between the reference and turbine location wind speed, the following plots shall be generated for each complete wind direction bin within the measurement sector:

> Turbine mast wind speed vs. reference mast wind speed, including an indication of the linear regression and correlation coefficients (commonly known as the R^2 value);

On a single axis, plot the following. See Figure C.11 in Clause C.9 for an example:

a) wind speed ratio vs. reference wind speed;

b) bin averages of the wind speed ratios in 0,5 m/s wind speed bins;

c) a curve $y = m+b/x$ where m is the slope of the linear regression, b is the intercept and x is the reference wind speed, and y is the predicted turbine location wind speed normalized to the reference mast wind speed, i.e. y = the wind speed ratio;

d) a horizontal line indicating the average of all wind speed ratios within the wind direction bin.

C.5.4 Additional calculations

The site calibration flow corrections shall be applied to the reference meteorological mast data to calculate the predicted wind turbine location wind speed for each data point. This shall be done using the filtered database.

$$V_{\text{Turb_predicted}} = F(WD, \alpha) \times V_{\text{PM}} \quad \text{(C.1)}$$

where

$V_{\text{Turb_predicted}}$	is the predicted wind turbine location wind speed;
$F(WD,\alpha)$	is the site calibration flow correction determined in C.5.2;
V_{PM}	is the reference meteorological mast wind speed;
WD	is the wind direction bin;
α	is the wind shear exponent, if applicable.

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A site calibration residual shall be calculated as follows for each 10 min data point as the difference between the predicted wind turbine location wind speed and the measured wind turbine meteorological mast wind speed.

$$residual = V_{\text{Turb_predicted}} - V_{\text{Turb_measured}} \tag{C.2}$$

A self-consistency parameter shall be calculated as follows for each 10 min data point: divide the predicted wind turbine location wind speed by the actual wind turbine meteorological mast wind speed.

$$self_consistency_paramenter = \frac{V_{\text{Turb_predicted}}}{V_{\text{Turb_measured}}} \tag{C.3}$$

The residuals and the self-consistency parameter are used to assess the variation and any biases in the results. The mean of the residuals and self-consistency parameter reflect the mean bias, where mean values of 0 and 1,0 translate to zero bias, respectively. The standard deviation of these parameters is indicative of the variation around the mean bias, and is used for the calculation of the statistical uncertainty of the site calibration.

In addition to the statistical uncertainty calculations, which are based on the variation about an assumed mean bias of zero, these parameters are used for calculation of additional uncertainty to be added in certain scenarios listed in Clause C.7, which are based on assessments of the estimated mean bias introduced by the scenario which are reflected in shifts in the mean of these parameters away from 0 and 1,0, respectively.

C.6 Site calibration uncertainty

C.6.1 Site calibration category A uncertainty

C.6.1.1 Site calibration k-fold analysis

The site calibration trains a model to predict the wind speed at the turbine location based on the wind speed at the met mast location. To avoid the risk of under-estimating the category A uncertainty due to over-fitting the model to the data, the category A uncertainty shall be calculated using k-fold cross validation with k = 10. Note that in the wind industry, k has different meanings, however the use of the term 'k' here is consistent with its use in statistical learning, as the method applied is known as *k-fold cross validation*.

The final filtered data set shall be divided into k equally sized folds (partitions) based on timestamp.

For each fold (k = 1 through 10):

a) the site calibration corrections shall be calculated according to Clause C.5 using only data from the other 9 folds;

b) the site calibration corrections shall be used to calculate the predicted wind speed at the turbine location using the reference mast wind speeds measured during fold k;

c) the predicted turbine wind speeds in fold k shall be compared to the actual measured turbine wind speeds in fold k according to both the residual and self-consistency parameters defined in C.5.4;

d) the statistical uncertainty for fold k shall be determined per C.6.1.2.

The total category A uncertainty is the square root of the sum of the squares of the uncertainty calculated for each fold divided by the square root of k.

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$$s_{sc} = \sqrt{\frac{\sum_{i=1}^{k} s_{sc,i}^2}{k}} \tag{C.4}$$

A value of k=10 is chosen so that there is a higher probability that there will be sufficient information in the remaining sets to cover the range of wind speeds present in the data set being evaluated, however other values of k are allowed so long as $k \geq 2$.

The folds are divided by timestamp rather than randomly chosen since it is expected that the variations in relationship in wind speeds between the two locations may be correlated with meteorological events which are correlated with time, and so folds that are time based are more likely to better capture variation between the conditions during the site calibration and the power curve measurement time periods.

C.6.1.2 Site calibration statistical uncertainty for each fold

For each fold in the k-fold cross validation, the deviation between the site calibration corrected wind speed at the wind turbine location and the wind speed measured at the wind turbine meteorological mast is calculated for each 10 min period, and the standard deviation of the wind speed deviation over all 10 min periods is calculated as follows:

$$d_{std,k} = \sqrt{\frac{\sum_{j=1}^{N} \left(d_{j,k} - \bar{d}_k\right)^2}{N_k - 1}} \tag{C.5}$$

where

$d_{j,k}$ is the residual in the j-th 10 min period of fold k, see Equation (C.2);

$\bar{d}_k$ is the mean value of the residuals in fold k;

N_k is the number of data sets in fold k;

$d_{std,k}$ is the standard deviation of site calibration residuals in fold k.

Only data that has been included in the assessment of the site calibration shall be included in the calculation of the standard deviation.

The statistical, category A, standard uncertainty of fold k is:

$$s_{sc,k} = d_{std,k} \cdot \frac{\sqrt{N_k - 1}}{\sqrt{f \cdot N_k}} \tag{C.6}$$

where

f is number of degrees of freedom of the site calibration.

The number f is the number of 10 min periods included in the site calibration minus the total number of parameters of the site calibration algorithm. In the case where the site calibration flow corrections are in the form of bin-averaged wind speed ratios, the number of parameters of the site calibration algorithm per wind direction sub-sector equals the number of wind shear bins. f is then N_k minus the number of wind direction sub sectors (normally number of 10° wide sectors). In the case where the site calibration flow corrections are in the form of linear regressions (slopes and offsets), the number of parameters of the site calibration algorithm is 2 per wind direction sub sector. f is then N_k minus twice the number of wind direction bins. In

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the case where the site calibration flow corrections are in the form of bin-averaged wind speed ratios per wind direction and wind shear bin, f is N_k minus the sum of the number of all wind shear bins in all wind direction sub-sectors.

C.6.2 Site calibration category B uncertainty

The following components of uncertainty should be considered to be independent of each other in evaluating the combined category B standard uncertainty.

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

$u_{\mathrm{VT,class},i}$: Anemometer operational characteristics – the wind turbine meteorological mast anemometer operational standard uncertainty shall be taken into account in the site calibration uncertainty calculation. The correlation of the operational characteristics during the site calibration shall be studied to determine to what extent the turbine and reference anemometer operational characteristic uncertainties are to be taken into account. Depending on the differences in the environmental conditions during the power curve measurement compared to during the site calibration, an increase in operational characteristics uncertainty may be required. During the site calibration the turbine anemometer operational uncertainty should be fully accounted for.

$u_{\mathrm{VT,mnt},i}$: Mounting effects – the wind turbine meteorological mast anemometer as well as the reference meteorological mast anemometer mounting standard uncertainty shall be taken into account in the site calibration uncertainty evaluation.

$u_{\mathrm{dVT},i}$: Standard uncertainty in wind speed due to the data acquisition system shall be estimated per Annex D and E.

C.6.3 Combined uncertainty

The Category A and B components of uncertainty should be considered as independent of each other for the purpose of evaluating the combined uncertainty of the site calibration.

Narrowing the measurement sector with the goal of reducing uncertainty by eliminating higher uncertainty wind direction bins is permitted.

C.7 Quality checks and additional uncertainties

C.7.1 Convergence check

A convergence check shall be carried out using the self-consistency parameter from Equation (C.3) for each wind direction bin. The most illustrative graph for this purpose plots cumulative average of the self-consistency parameter against the number of hours per wind direction bin. The cumulative averages should be seen to converge to within 0,5 % of the final average within the larger of 16 h of data or 25 % of the total number of data points in that bin. If this criteria is not met, steps such as additional filtering may be applied to try to explain and correct the non-convergence. If these steps do not result in convergence, the self-consistency check according to Clause C.8 may be performed during the power curve measurement to assess if the non-convergence is an issue. If criteria for the self-consistency check during the power curve test is not met, then the bin shall be excluded from the measurement sector.

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The k-fold cross validation method used to calculate the statistical uncertainty for the site calibration should reflect a higher test uncertainty for any non-convergence, so no uncertainty penalty is applied for this check.

C.7.2 Correlation check for linear regression (see C.5.3)

For each wind direction bin, the level of correlation shall be assessed based on the correlation coefficient of the regression, commonly known as the r value. This assessment shall be included in the report.

C.7.3 Change in correction between adjacent wind direction bins

It is recommended that wind direction bins from the measurement sectors be eliminated when flow corrections change by more than 2 % between neighbouring bins. This shall be evaluated by applying the self-consistency parameter method from C.5.4 as follows:

a) evaluate the data and calculate the site calibration flow corrections;

b) shift the site calibration flow corrections by one direction sector so that the flow corrections or regressions are applied to the adjacent wind direction bin. For example, if the flow correction applied to the 290° bin is 1,024x + 0,1, then apply this correction instead to the 280° bin;

c) using the adjusted site calibration flow corrections from the previous step and the site calibration data, calculate the predicted wind turbine location wind speed for each 10 min period and then calculate the self-consistency parameter with Equation (C.3);

d) average the self-consistency parameters for each wind direction bin. If the average is less than 0,98 or greater than 1,02, then those wind direction bins should be eliminated. If those wind direction bins are not eliminated, then the uncertainty in those bins shall be increased by the value of 1 minus the average self-consistency parameter multiplied by 100 % and divided by 2 and the square root of 3. If a sector has this applied from both adjacent sectors, then the increase in uncertainty is the average of the two.

This method shall be applied by both adding and subtracting to the wind direction bin, for example applying the 290° bin results to both the 280° and 300° bins. The uncertainty adjustment for bins not on the edge shall be the average impact of moving one adjacent bin in each direction.

$$u_{VT,\mathrm{coc},i,j} = \frac{1}{2} \cdot \left(\frac{\left|1 - \mathrm{sccp}_{j,j-1}\right|}{2\sqrt{3}} + \frac{\left|1 - \mathrm{sccp}_{j,j+1}\right|}{2\sqrt{3}} \right) \tag{C.7}$$

where

$u_{VT,\mathrm{coc},i,j}$ is the standard uncertainty due to change in correction in wind direction bin j;

$\mathrm{sccp}_{j,j-1}$ is the site calibration consistency parameter for wind direction bin j using the site calibration corrections in bin j–1;

$\mathrm{sccp}_{j,j+1}$ is the site calibration consistency parameter for wind direction bin j using the site calibration corrections in bin j+1.

For sub sectors at the edges of the measurement sector, the uncertainty shall be assessed only by applying the correction from the respective neighbouring sub sector.

C.7.4 Removal of the wind direction sensor between site calibration and power performance test

If the wind direction sensor is removed between site calibration and the power performance test, error may be introduced due to the uncertainty of the wind direction sensor alignment

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between the two installations. An additional uncertainty component for each wind direction bin shall be applied. This uncertainty component shall be calculated for each wind direction bin as follows:

a) For each wind direction bin, apply the method in C.7.3 except that the uncertainty will also be applied where the average of the self-consistency parameters is between 0,98 and 1,02.

b) Determine the relative uncertainty in the wind direction measurements.

c) Multiply the result of bullet a) by the ratio of the relative uncertainty in the wind vane measurements to the total wind direction bin size.

For example, the wind vane fails and is replaced by a similar model between site calibration and power curve measurement. The uncertainty in the wind vane alignments is determined to be 3° and the bin size is 10°. Multiply the change in correction between adjacent bins from C.7.3 by $\frac{3}{10}$. This uncertainty is applied in addition to any uncertainty applied due to C.7.3.

$$u_{VT,\mathrm{rmv},i,j} = u_{VT,\mathrm{coc},i,j} \cdot \left(\frac{u_{w,i}}{\mathrm{BinSize}_j} \right) \tag{C.8}$$

where

$u_{w,i}$ is the wind direction uncertainty calculated according to Clause E.12;

BinSize is the bin size of wind direction bin j, e.g. 10°.

Please note that $u_{w,i}$ may be evaluated on a relative basis, i.e. uncertainty components that are fully correlated between the site calibration and power curve measurement may be neglected. For example, if the met mast remains in place and only the sensor is replaced on the same boom and mount with an identical make and model, $u_{WVbo,i}$ *and* $u_{WVoe,i}$ may be neglected.

C.7.5 Site calibration and power performance measurements in different seasons

Seasonal changes in wind conditions and changes in surface roughness due to vegetation, precipitation (snow and ice) and freezing of bodies of water may cause a seasonal dependency in the site calibration flow corrections. It is therefore recommended that the site calibration and power performance measurements be conducted in the same part of the year, for example both occurring in summer. To assess the possible impact of this the following steps shall be taken:

The average wind conditions at the reference meteorological mast during the site calibration (wind shear, turbulence, upflow) shall be compared to the average wind conditions at the same meteorological mast during the power performance measurement for the wind directions within the measurement sector. An additional uncertainty shall be calculated for seasonal effects if any of these conditions for a wind direction bin differs by more than the following amounts:

a) 0,05 for wind shear exponent;

b) 3 % for turbulence intensity;

c) if upflow is measured, a limit of ± 2° change in vertical upflow is recommended.

The additional uncertainty for seasonal effects shall be calculated as one third of the magnitude of the site calibration flow correction.

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C.8 Verification of results

An example of a method to verify the results from a power performance measurement with or without site calibration is to use the measured electrical power data to derive a wind speed representative for the wind turbine for each 10 min period included in the power curve measurement. This wind speed is compared to the wind speed measured by the anemometer or RSD. Ideally this ratio should not vary as a function of the wind direction. Wind direction bins where the ratio varies strongly should be investigated and possibly excluded. If the power curve is a function of the rotor equivalent wind speed, the rotor equivalent wind speed should be applied for the self-consistency check.

a) The reverse power curve is defined as the wind speed bin-averaged as a function of the power output for the data sets that have been used for the power curve evaluation. For actively controlled wind turbines, the air density normalised wind speed is used for the evaluation of the reverse power curve. For non-actively controlled wind turbines, the air density normalised power output is applied for the evaluation of the reverse power curve. If a site calibration has been performed, the site calibrated and, if applicable, air density normalised wind speed should be used for the bin analysis. The results used should include power data where the maximum power does not reach the measured nominal rated power and for which the normalized wind speed is above 4 m/s.

b) The reverse power curve (RPC) is applied in order to evaluate the wind speed representative of the wind turbine rotor from the measurement of the active power for each 10 min interval in which the test wind turbine is operational. For this, the wind speed is interpolated linearly between the bins of the RPC according to the measured active power. The result is the wind speed representative of the wind turbine rotor. For actively controlled wind turbines, the result is the air density normalised ambient wind speed representative of the wind turbine rotor. For non-actively controlled wind turbines, the air density normalised power output should be used for the evaluation of the ambient wind speed.

c) The ratio of the two wind speeds (derived/measured) should be bin-averaged as function of the wind direction in 5° sectors.

d) The derived and measured wind speeds are expected to be in good agreement for the measurement sector and hence the ratio should be near unity. Deviations from unity may occur due to site effects, imperfections of the site calibration procedure, or influences of environmental variables on the power curve. Sectors where the wind speed determined via the meteorological mast is not representative for the test wind turbine can clearly be identified as variations of the bin-averaged ratio. Larger deviations should be analysed further. These sectors should be excluded from the final power curve test if site effects are identified as the reason.

e) The power curve should be re-evaluated for the remaining sector. The self-consistency check may be repeated with the re-calculated RPC. If necessary, the measurement sector should be adjusted in accordance with the results of the repeated test.

An example of a result of a verification test is shown in Figure C.3.

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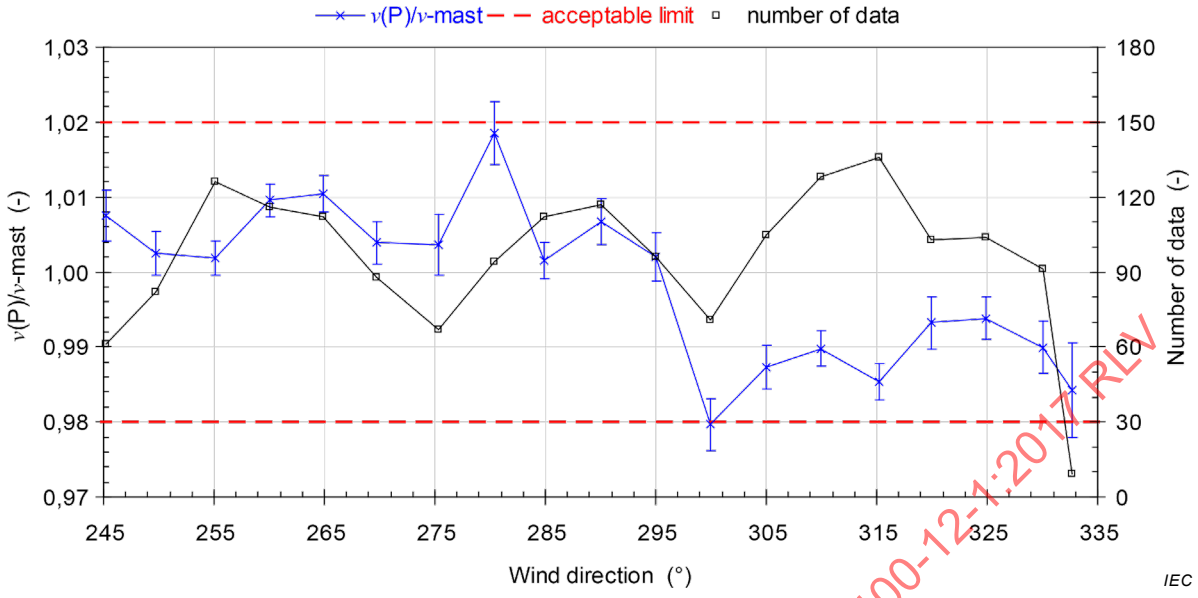

The error bars indicate the category A standard uncertainty of the bin averaged ratios of v_P and v_{mast}. The acceptable range is for ratios of 0,98 to 1,02 for L < 3 rotor diameters and 0,97 to 1,03 for L between 3 and 4 rotor diameters.

Figure C.3 – Example of the results of a verification test

C.9 Site calibration examples

C.9.1 Example A

Site description:

A power curve measurement is to be undertaken on a ridgeline site (Type B Terrain). The ridgeline is perpendicular to the principle wind direction, facing a plain and the ridge is approximately 40 m to 60 m higher than the plane. The wind turbines have a hub height of 80 m and are located in a single row along the top of the ridge.

The terrain type is between a type A and type B terrain. The relatively flat terrain up-wind of the ridge means that high wind shear may be a concern due to atmospheric stability; however the terrain local to the wind turbines is closer to a type B site where high upflow angles may also be a concern. The test wind turbine and meteorological mast location are therefore chosen to best minimize the possible upflow angle (lower local terrain slope) and to minimize the difference in elevation between the two locations (which will maximise correlation of wind speed flow corrections with different wind shear profiles) as much as possible given the wind turbine layout and terrain constraints.

Site calibration setup:

The reference meteorological mast is located on the ridge, next to the test wind turbine but at a slightly lower elevation that is about 10 m lower than the wind turbine elevation.

In addition to top mounted hub height cup anemometers in a side-by-side configuration, wind shear measurements are included in the form of anemometers located at 43 m elevation on both meteorological masts. A 3D ultrasonic anemometer is mounted on each meteorological mast to assess the operational characteristics of the hub height anemometers to quantify the uncertainty at the given terrain complexity.

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Site calibration evaluation:

Data are collected for several months. The collected data are filtered based on the measurement sector, the wind speeds from 4 m/s to 16 m/s as recorded at the reference meteorological mast, sensor malfunction, and anemometer icing.

For each 10 min period, the following calculations are made according to C.5.1:

a) the ratio of the hub height wind speed at the wind turbine location to the hub height wind speed at the reference meteorological mast;

b) the wind shear exponents at each meteorological mast are calculated from the power law using the wind speed measurements at 80 m and 43 m;

c) a tag representing the time of day on a 24 h clock is calculated from the timestamp;

d) upflow angle is calculated from the vertical and horizontal wind speeds from the ultrasonic anemometers at each meteorological mast.

Step 1: Check the significance of wind shear at the site according to C.5.1.2:

For the filtered data, the wind shear exponent at each meteorological mast is plotted against time of day.

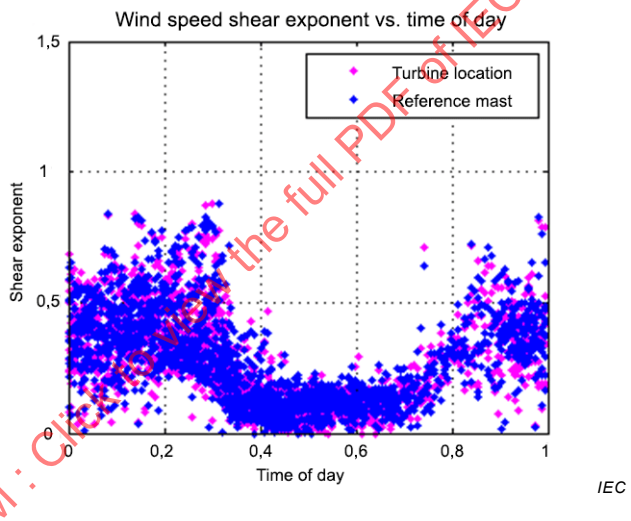

Figure C.4 – Wind shear exponent vs. time of day, example A

From Figure C.4 it is observed that wind shear is high at night and low during the day. This is typical of a site experiencing a diurnal cycle of atmospheric stability. At night, the atmosphere forms thermal layers (stable atmosphere). These layers suppress turbulence and result in variably high wind shear. During the day, the sun heats up the ground, introducing turbulent mixing which results in a more uniform wind speed profile (low wind shear) and higher turbulence.

It also appears that similar values of wind shear are occurring at both the wind turbine and reference meteorological mast locations.

Step 2: Verify correlation of wind shear at wind turbine and reference meteorological mast locations – Example A

To verify that the wind shear exponent values are correlated between the wind turbine and reference meteorological mast locations, a plot of the wind shear exponents at the wind turbine location vs. the wind shear exponents at the reference meteorological mast is made (see Figure C.5):

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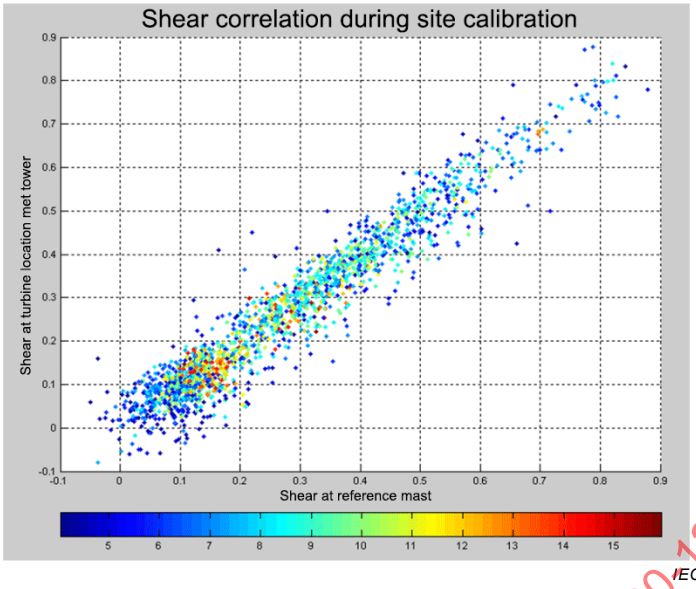

Figure C.5 – Wind shear exponents at wind turbine location vs. reference meteorological mast, example A where the colour axis = wind speed (m/s)

The wind shear exponents at the reference meteorological mast are a reasonably good indicator of the wind shear exponents at the wind turbine location.

Step 3: Calculate results according to C.5.1.3

The following calculations are made for each 10-minute data set based on measurements at the reference mast:

- wind shear bins centred on integer multiples of 0,05 values of wind shear exponent (–0,025 to 0,025, 0,025 to 0,075, 0,075 to 0,125, etc.).

It is now possible to make a matrix of wind shear exponent and wind direction. For each point in this matrix, the following calculations are made:

- the correction for each point in the matrix is calculated as the average of the wind speed ratios in that matrix bin;
- a count of all valid data points within that matrix bin.

Table C.1 and Table C.2 show the site calibration flow corrections and bin count, respectively. Figure C.6 is a graphical illustration of these results.

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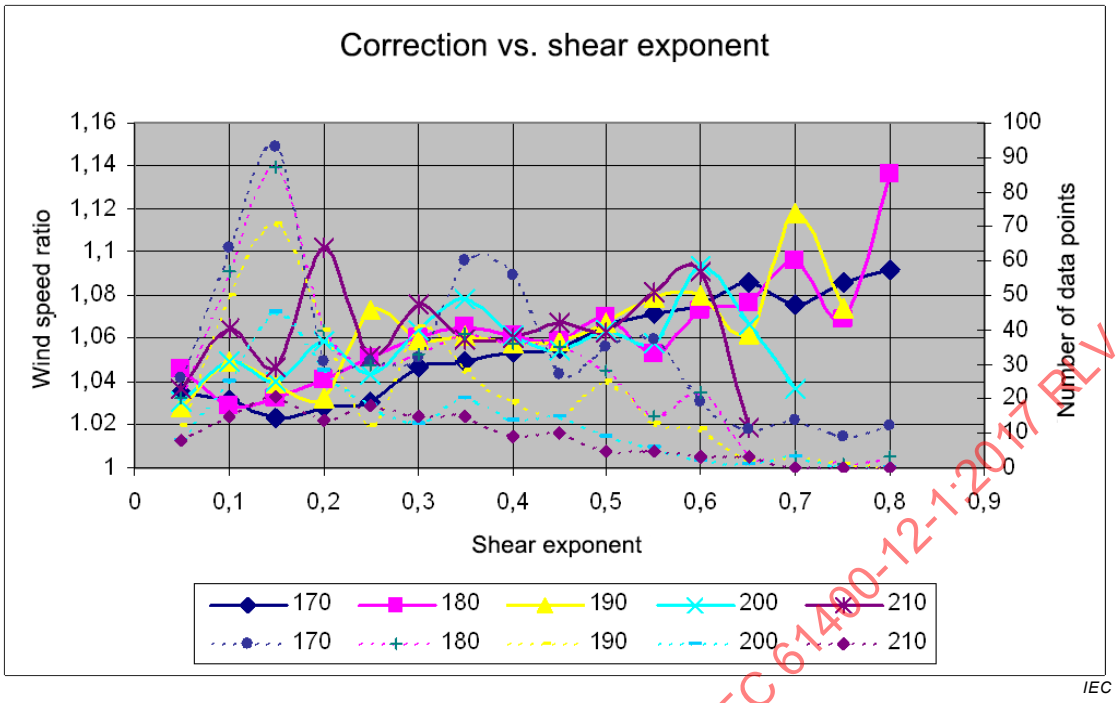

Figure C.6 – Wind speed ratios and number of data points vs. wind shear exponent and wind direction bin – wind speed ratios (full lines), number of data points (dotted lines)

Step 4: Quality checks and additional uncertainties

Anemometer operational characteristic uncertainty:

The upflow angle was recorded, which allows for the estimation of anemometer operational characteristic uncertainty at the site conditions according to C.3.2. The maximum upflow angle for all data points in all wind direction bins was 3° at the reference meteorological mast and 1° at the wind turbine location mast. All other parameters fell within the range of the Class A anemometer operational characteristics. Therefore, the Class A anemometer operational characteristic uncertainty may be used for both locations. The class is 1,4A.

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Table C.1 – Site calibration flow corrections (wind speed ratio)

	Wind direction bin				
Wind shear bin	**170**	**180**	**190**	**200**	**210**
0,05	1,035	1,046	1,028	1,031	1,037
0,10	1,031	1,029	1,05	1,05	1,064
0,15	1,023	1,033	1,039	1,04	1,047
0,20	1,028	1,041	1,032	1,059	1,102
0,25	1,031	1,051	1,073	1,044	1,052
0,30	1,047	1,06	1,06	1,064	1,076
0,35	1,049	1,066	1,062	1,078	1,06
0,40	1,054	1,061	1,058	1,061	1,06
0,45	1,055	1,058	1,059	1,055	1,067
0,50	1,066	1,07	1,067	1,064	1,063
0,55	1,072	1,053	1,079	1,058	1,081
0,60	1,076	1,074	1,08	INC	1,091
0,65	1,086	1,076	INC	INC	1,019
0,70	1,076	1,096	1,118	INC	INC
0,75	1,086	INC	INC	INC	INC
0,80	1,092	1,136	INC	INC	INC

Table C.2 – Site calibration data count

	Wind direction bin				
Wind shear bin	**170**	**180**	**190**	**200**	**210**
0,05	26	20	12	8	8
0,10	64	57	50	25	15
0,15	93	87	71	45	21
0,20	31	40	40	28	14
0,25	31	30	12	18	18
0,30	32	33	41	13	15
0,35	60	39	28	20	15
0,40	56	36	19	14	9
0,45	27	35	15	15	10
0,50	35	28	25	9	5
0,55	37	15	13	6	5
0,60	19	22	11	2	3
0,65	11	3	2	1	3
0,70	14	3	3	3	0
0,75	9	1	1	0	0
0,80	12	3	0	0	0

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Convergence check:

The convergence check found that the data converged to within 0,5 % of the final value (or within 0,995 and 1,005 in Figure C.7 for the 190° bin using over 50 h of data in the bin meeting the requirement, the larger of 16 h or 25 % of the total number of data points for all bins.

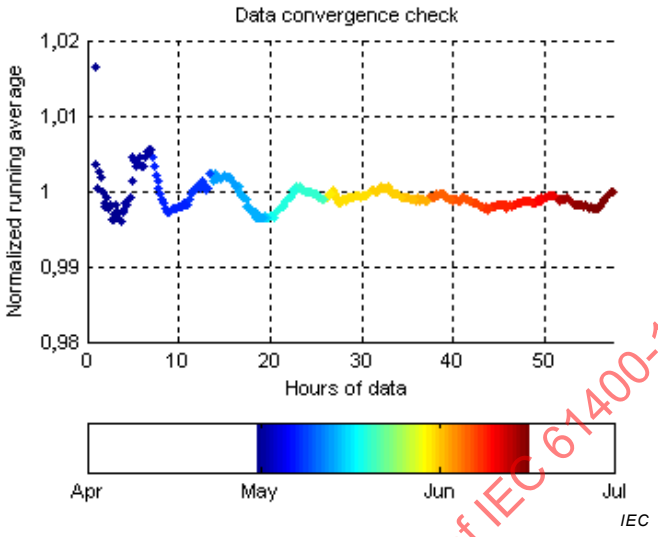

Figure C.7 – Data convergence check for 190° bin

Change in correction between bins:

The magnitude of the change in flow corrections was within 0,02 between all adjacent bins.

Wind vane adjustment:

No wind vane adjustment was made between measurements, so no additional uncertainty is required.

Seasonal uncertainty:

The power curve measurement fell during the same seasonal period and a comparison found that none of the changes in conditions exceeded the limits of C.7.5 so no additional uncertainty is needed to account for seasonal effects.

C.9.2 Example B

Site description:

The site is identical to the site in example A (Type B terrain) except that the local terrain to the wind turbine is slightly steeper.

Site calibration setup:

Unlike example A, it was not possible to locate the reference meteorological mast on the ridge. The reference meteorological mast is located at the base of the ridge (on the plain) 3 rotor diameters upwind of the test wind turbine that is on the top of the ridge. The difference in elevation between the test wind turbine and the reference meteorological mast is 45 m.

Step 1: Check the significance of wind shear at the site

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For the filtered data, the wind shear exponent at each meteorological mast is plotted against time of day (see Figure C.8).

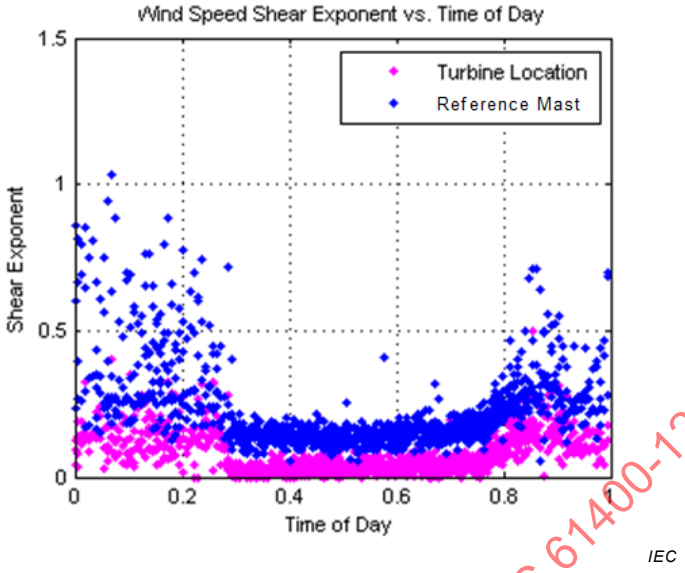

Figure C.8 – Wind shear exponent vs. time of day, example B

Similar to example A, the wind shear at night is higher than during the day, indicating a diurnal cycle of atmospheric stability. However, the wind shear at the wind turbine location appears to be significantly different than the wind shear at the reference meteorological mast. This will be problematic due to the change in elevation between the two locations, it is reasonable to assume that the relationship between the hub height wind speeds will be influenced by changes in the wind shear profile.

Step 2: Verify correlation of wind shear at wind turbine and reference meteorological mast locations – Example B

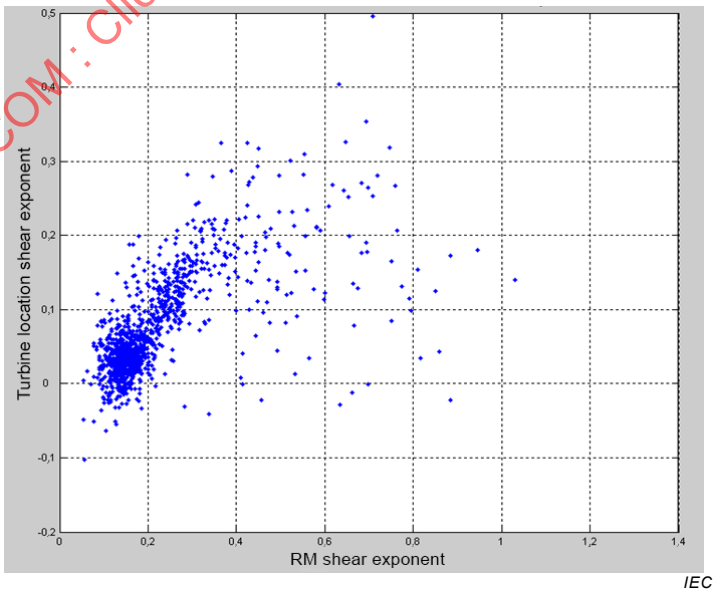

Figure C.9 – Wind shear exponents at wind turbine location vs. reference meteorological mast, example B

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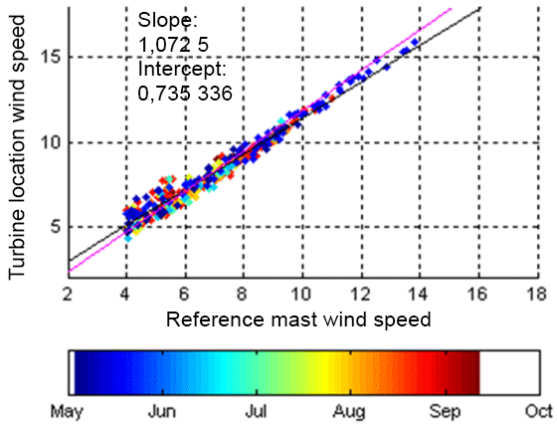
There is no correlation for wind shear values greater than 0,25. This suggests that the correlation of site calibration flow corrections will be inconsistent during stable atmospheric conditions. To illustrate/verify that this is the case, the plots specified in C.5.3 may be used (see Figure C.10):



The red line is the linear regression forced through origin (zero intercept), the black line is the two parameter linear regression (non-zero intercept).

Figure C.10 – Linear regression of wind turbine location vs. reference meteorological mast hub height wind speeds for 330° bin

The linear regression shows that there is a significant intercept in the linear regression. There is also high scatter at the lower wind speeds.

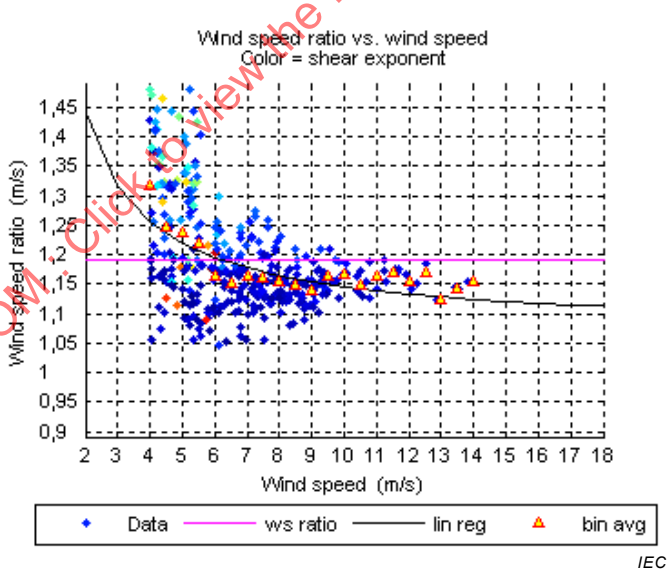


Figure C.11 – Wind speed ratios vs. wind speed for the 330° bin

The plot of wind speed ratio vs. wind speed (see Figure C.11) shows the high dependency of the flow correction on wind speed due to the high intercept. Also note that the overall magnitude of the flow correction is quite high, 19 % on average.

For illustrative purposes, a plot of the wind speed ratios vs. wind shear for the different wind bins is shown in Figure C.12.

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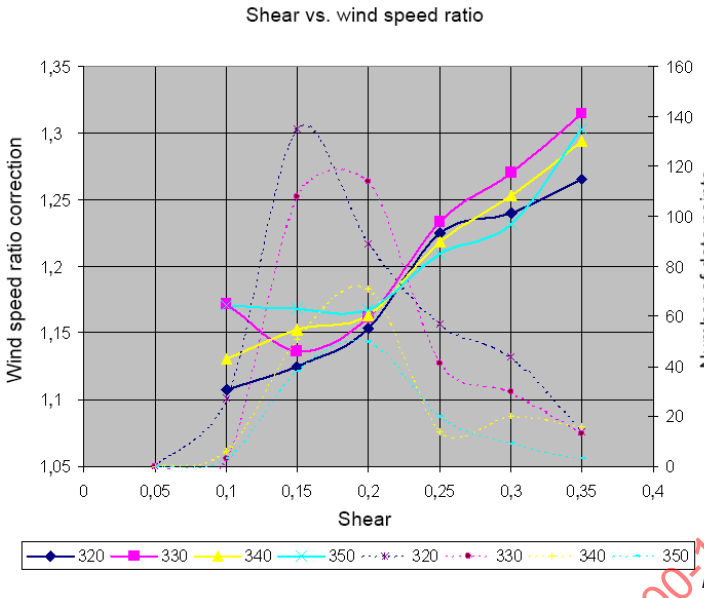

Figure C.12 – Wind speed ratios vs. wind shear for the 330° bin

These plots are useful illustrations of the impact to the site calibration due to the conditions at this site and the test setup. Figure C.12 shows that the correction changes by more than 5 % between 0,20 and 0,25, and Figure C.9 shows that the wind shear at the reference meteorological mast is not a good predictor of the wind shear at the wind turbine location for values greater than 0,25. Corrections using the wind direction-wind shear matrix method may not be reliable. Wind shear has been shown to have a significant influence and wind shear at the two locations is not well correlated so therefore additional filtering is necessary to try to improve the correlation.

Step 2B: Attempt to remove non-correlating wind shear data

Low wind shear values appear to be correlated between the two locations. Low wind shear values occur during the day time (periods of atmospheric instability), therefore from the plots, a time-of-day filter is applied to select all daytime data between 07:00 and 19:00.

Plots according to C.5.2 are shown for the newly filtered data set (see Figure C.13, Figure C.14 and Figure C.15).

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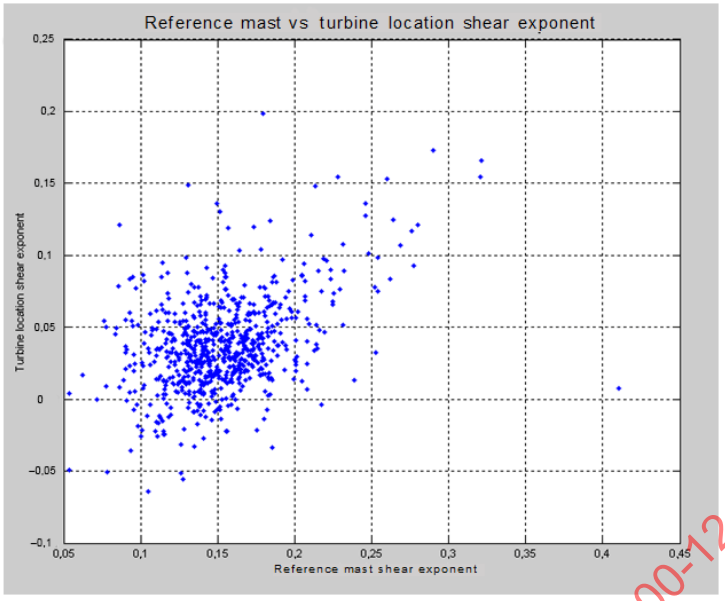

Figure C.13 – Wind shear exponents at wind turbine location vs. reference meteorological mast post-filtering

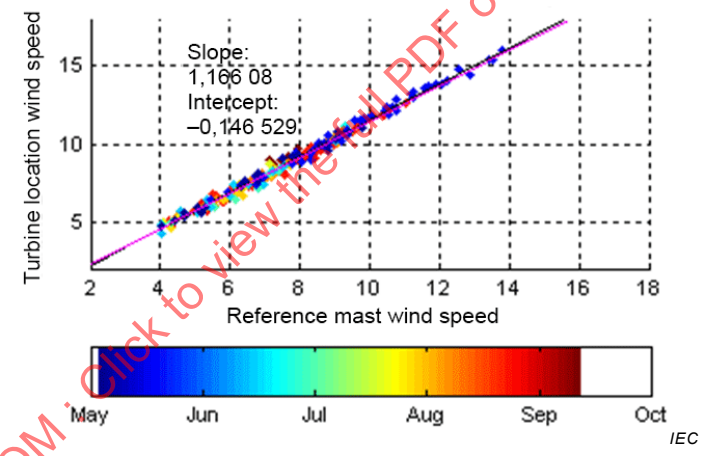

Figure C.14 – Linear regression of wind turbine location vs. reference meteorological mast hub height wind speeds for 330° bin, post-filtering

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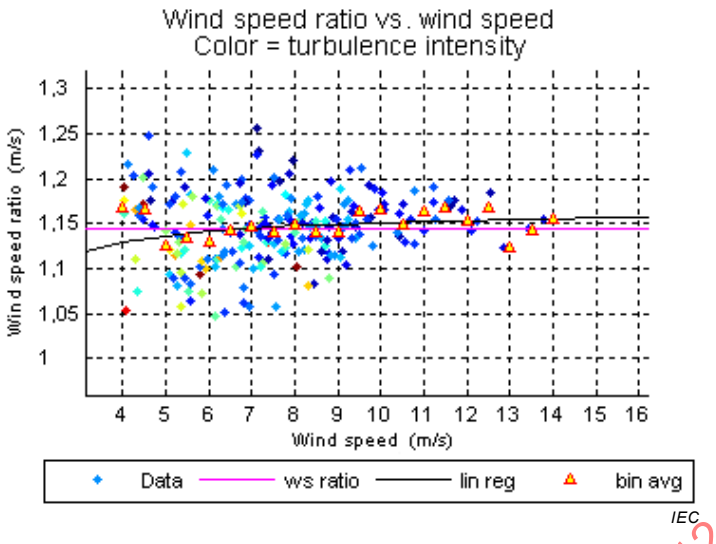

Figure C.15 – Wind speed ratios vs. wind speed for the 330° bin, post-filtering

Step 3: Calculate results

The previous step removed all of the data with high atmospheric stability leaving only day-time data with atmospheric instability. The wind shear values include a small range of wind shear exponents (0,10 to 0,20). This removes the dependence of the site calibration flow corrections on wind shear and so the linear regression method may be used instead of the wind direction – wind shear bin matrix.

For each wind direction bin, a linear regression of the wind speed at the wind turbine location vs. the wind speed at the reference meteorological mast is calculated along with the r^2 value of the regression. The count of total valid data points in each wind direction bin is also recorded.

Step 4: Additional uncertainties

Anemometer operational uncertainty:

No vertical wind speed measurement was included so the Class B operational characteristic uncertainty shall be used. The anemometer operational characteristic classification is 5,4B.

Convergence check (see Figure C.16**):**

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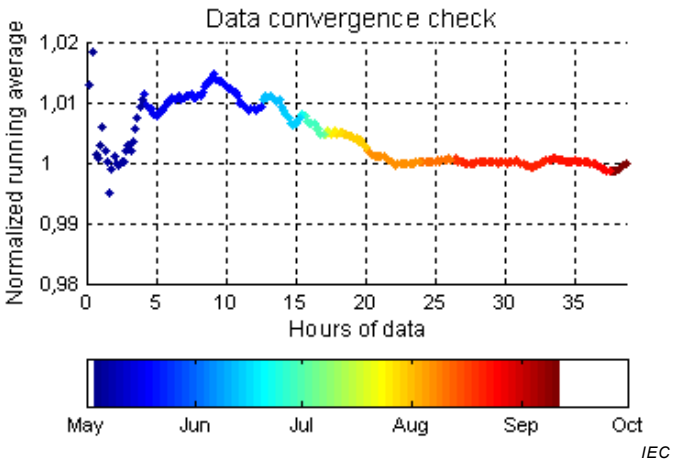

Figure C.16 – Data convergence check for 330° bin

Correlation check for linear regression:

As per C.7.2 (see Table C.3).

Table C.3 – r^2 values for each wind direction bin

Bin centre	r^2 value	Absolute value of residual mean (m/s)	Residual standard deviation (m/s)
320	0,978	0,00	0,33
330	0,988	0,00	0,26
340	0,979	0,00	0,26
350	0,981	0,00	0,23

Change in correction between bins:

As per C.7.3 (see Table C.4).

Table C.4 – Additional uncertainty due to change in bins

Bin centre	Magnitude of change between bins (left)	Magnitude of change between bins (right)	Additional standard uncertainty (%)
320	1,019	-	0 % (within limit)
330	1,009	0,981	0 % (within limit)
340	1,013	0,988	0 % (within limit)
350	-	0,992	0 % (within limit)

Wind vane adjustment:

The wind vane was left in place so no additional uncertainty is required per C.7.4.

Seasonal uncertainty:

The site calibration was conducted in the winter while the power curve measurement was conducted spanning multiple seasons, including the summer. Note that the time of day filter needed to be adjusted due to the change in sunrise and sunset. A comparison of the wind

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shear exponent values (see Figure C.17) found a change greater than 0,05 (0,15 vs. 0,22), which is greater than the limits of C.7.5 so additional uncertainty due to the measurements being in different seasons is required per C.7.5.

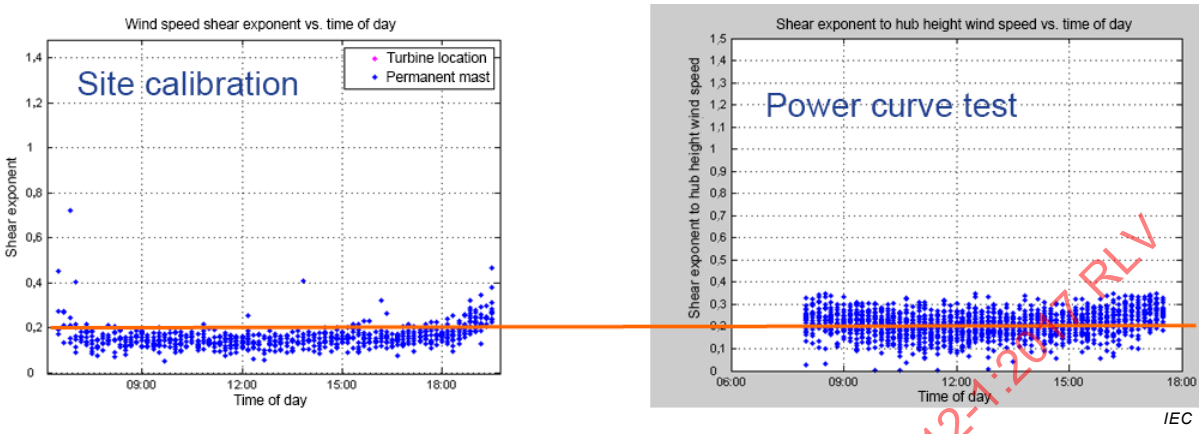

Figure C.17 – Site calibration wind shear vs. power curve test wind shear

The seasonal correction component is one-third of the magnitude of the total correction. This may be calculated for each data point as:

$$U = 1/3 \times \text{abs}(V_{\text{Turb_predicted}} - V_{\text{RM_measured}}) \quad \text{(C.9)}$$

where

U is the standard uncertainty in one data point;

$V_{\text{Turb_predicted-}i}$ is the wind turbine predicted wind speed applying site calibration flow correction;

$V_{\text{RM_measured-}i}$ is the measured wind speed from the reference meteorological mast used to predict the wind at the wind turbine.

The uncertainties during the power performance test may then be bin averaged against reference meteorological mast wind speed and direction to calculate the total uncertainty.

C.9.3 Example C

Site description:

The site is in very complex terrain. The site is a mountain top site within a mountain range. The site is a ridgeline site perpendicular to the principle wind direction, with terrain dropping off steeply in front of and behind the ridge. The wind is very mono-directional with nearly all winds coming from a 30° sector. There is another ridge line 3 km directly up-wind a few hundred meters taller than the ridgeline on which the site is located. The site is therefore considered to be type C terrain as it may be located in a recirculation zone from the upwind ridge.

Site calibration setup:

The meteorological mast is located 2,5 rotor diameters from the test wind turbine on the same ridge and at a very similar elevation (within 5 m). Wind shear was measured using anemometers mounted lower on the meteorological masts. A vertical wind speed measurement was not included.

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Step 1: Check the significance of wind shear at the site

Wind shear exponent values are low and sometimes negative. All wind shear values are between –0,05 and 0,20 and with no obvious correlation to time of day or other measured conditions. Turbulence is high. This indicates neutral to unstable atmosphere and wind shear is not therefore considered to be a significant factor for the site calibration, so the linear regression method may be used.

Step 2:

Skipped as wind shear has already been determined to be low. There is no stable atmosphere at this site.

Step 3: Calculate results

For each wind direction bin a linear regression of the wind speed at the wind turbine location vs. the wind speed at the reference meteorological mast is calculated along with the r^2 value of the regression. The count of total valid data points in each wind direction bin is also recorded. The data scatter is very high and the magnitude of the change in flow correction between bins was also very high.

Step 4: Quality checks and uncertainty

The data confirms that the site is in a recirculation zone of the up-wind ridge. The data scatter is very high and the results do not converge, indicating that despite the reference meteorological mast and test wind turbine being located side by side on the ridge at similar elevation with similar local terrain, the correlation in wind speed between the two locations is very poor. This will have negative consequences on the accuracy and uncertainty of a power curve measured at this location.

Anemometer operational uncertainty:

No vertical wind speed measurement was included so the Class B operational characteristic uncertainty shall be used. The anemometer operational characteristic classification is 5,4B.

Convergence check:

The data fails the convergence check for all wind direction bins. The data does not converge to within 0,5 % of the final value until 75 % of the data collected has been included. A sample check for one of the wind direction bins is shown in Figure C.18 below.

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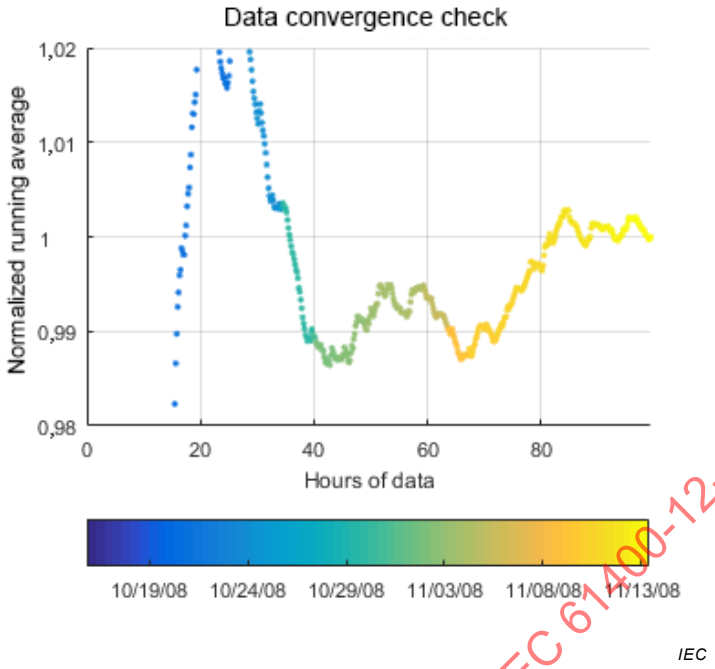

Figure C.18 – Convergence check for 270° bin

Change in magnitude of correction between bins:

All adjacent bins had changes in magnitude on the order of 10 %. The additional uncertainty is calculated as follows.

Table C.5 – Additional uncertainty due to change in bins

Bin centre	Magnitude of change between bins (left)	Magnitude of change between bins (right)	Additional standard uncertainty (%)
260	1,137	1,176	4,52 %
270	1,093	0,912	2,61 %
280	1,023	0,946	1,11 %

Wind vane adjustment:

No wind vane adjustment was made, so no additional uncertainty is required.

Seasonal uncertainty adjustment:

The site calibration and power performance test were conducted in different seasons (fall and summer), however the wind shear and turbulence values did not change by more than the allowable limits between seasons. A vertical wind speed was not recorded to assess the upflow angle, however given that the site is in a recirculation zone, a wide range of upflow angles are expected and there is no reason to expect seasonal dependence. The site was located in a hot climate with minimal vegetation, so no appreciable change in the surface roughness is expected.

No additional uncertainty for seasonal changes is necessary.

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Annex D
(normative)

Evaluation of uncertainty in measurement

Annex D addresses the requirements for the determination of uncertainty in measurement. The theoretical basis for determining the uncertainty using the method of bins, with a worked example of estimating uncertainties, can be found in Annex E.

The measured power curve shall be supplemented with an estimate of the uncertainty of the measurement. The estimate shall be based on the ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM:1995).

Following the ISO/IEC Guide 98-3, there are two categories of uncertainties: category A, the magnitude of which can be deduced from measurements, and category B, which are estimated by other means. In both categories, uncertainties are expressed as standard deviations and are denoted standard uncertainties.

a) The measurands

The measurands are the power curve, determined by the measured and normalized bin values of electric power and wind speed (see 9.1 and 9.2), and the estimated annual energy production (see 9.3). Uncertainties in the measurements are converted to uncertainty in the measurand by means of sensitivity factors.

b) Uncertainty components

Table D.1 provides a minimum list of uncertainty parameters that shall be included in the uncertainty analysis.

Table D.1 – List of uncertainty components

Measured parameter	Uncertainty component	Uncertainty category
Electric power	Current transformers	B
	Voltage transformers	B
	Power transducer or power measurement device	B
	Data acquisition system (see below)	B
	Variability of electric power	A
Wind speed (cup and sonic anemometer)	Anemometer calibration	B
	Classification	B
	Mast flow distortion	B
	Boom flow distortion	B
	Lightning finial	B
	Data acquisition system (see below)	B
	Post calibration / in-situ test	B
Wind speed (remote sensing device)	Verification test for RSD	B
	In-situ test	B
	RSD classification	B
	Mounting effects	B
	Flow variation across probe volume at same height	B
	Monitoring test	B
Rotor equivalent wind speed	Wind shear measurement	B

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Measured parameter	Uncertainty component	Uncertainty category
	Wind veer measurement	B
Wind direction (vane or sonic)	Calibration	B
	North mark	B
	Boom orientation	B
	Operation (influence of mast)	B
	Magnetic declination angle	B
	Data acquisition system (see below)	B
Wind direction (remote sensing device)	Verification test	B
	Classification	B
	Monitoring test	B
	Flow variation across probe volume at same height	B
	Alignment	B
	Magnetic declination angle	B
	Data acquisition system (see below)	B
Air temperature	Temperature sensor	B
	Radiation shielding	B
	Mounting effects	B
	Data acquisition system (see below)	B
Air pressure	Pressure sensor	B
	Mounting effects	B
	Data acquisition system (see below)	B
Relative humidity	Humidity sensor	B
	Mounting effects	B
	Data acquisition system (see below)	B
Data acquisition system	Signal transmission	B
	System accuracy	B
	Signal conditioning	B
Terrain (no site calibration)	Flow distortion due to terrain	B
Terrain (with site calibration)	Anemometer calibration before test	B
	Post calibration/In-situ calibration	B
	Anemometer classification	B
	Mounting effects	B
	Standard mounting	B
	Alternative mounting	B
	Side mounted	B
	Lightning finial	B
	Data acquisition system (see below)	B
	Change of correction (adjacent wind direction bins)	B
		B
	Removal of wind direction sensor between site calibration and power curve measurement	B
	Seasonal variation	A
	Statistical variability in site calibration	
Method	Air density correction	B
	Wind conditions – missing shear information	B

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Measured parameter	Uncertainty component	Uncertainty category
	Wind conditions – missing veer information	B
	Wind conditions – missing upflow information	B
	Wind conditions – missing turbulence information	B
	Seasonal effects	B
	Turbulence normalisation (or lack of turbulence normalisation)	B
	Cold climate measurements	B

It should be noted that the implicit assumption of the hub height wind speed power curve method of this standard is that the 10 min mean power yield from a wind turbine is fully explained by the simultaneous 10 min mean wind speed measured at hub height and the air density.

This is not the case. Other flow variables affect power yield and thus identical wind turbines will yield different power at different sites even if the hub height wind speed and air density are the same. These other variables include turbulence fluctuations of wind speed (in three directions), the inclination of the flow vector relative to horizontal, scale of turbulence and wind shear of mean wind speed over the rotor. Presently, analytical tools offer little help in identification of the impact of some of these variables and experimental methods encounter equally serious difficulties.

The result is that the power curve will vary from one site to the next which will appear as uncertainty.

This uncertainty stems from differences in observed power yield under different topographical and climatic conditions, i.e. when comparing an AEP measured in homogeneous terrain with an AEP measured at a non-homogeneous wind farm site.

Quantification of this apparent uncertainty is difficult. Depending on site conditions and climate, the uncertainty may amount to several percent. In general terms, the uncertainty may be expected to increase with increasing complexity of topography and with increasing frequency of non-neutral atmospheric conditions.

However, this issue of the standard presents methods to account for at least some of these influential variables (for example wind shear and turbulence). The uncertainty in these correction methods shall also be assessed. It is therefore implicit that where these variables are considered significant and a correction is not made then the uncertainty should be increased to account for the lack of a correction.

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Annex E
(informative)

Theoretical basis for determining the uncertainty of measurement using the method of bins

E.1 General

In Annex E, all the uncertainty statements made throughout the standard have been combined and added to in order to make a consistent uncertainty evaluation of a power curve measurement, covering both the power curve and the calculated AEP.

In order to achieve a clear structure to introduce this rather complex topic, this annex has been structured as shown below. The main structure is based on a separate section for each category of uncertainty components; as wind speed has many uncertainty components these have been given their own clauses, as seen below:

Clause E.2 A general mathematical outline and a table with an overview of all uncertainty components and their default magnitudes.

Clause E.3 Category A uncertainties

Clause E.4 Category B uncertainties – Introduction and data acquisition

Clause E.5 Category B – Power output

Clause E.6 Category B – Wind speed – Introduction and sensors

Clause E.7 Category B – Wind speed – RSD

Clause E.8 Category B – Wind speed – REWS

Clause E.9 Category B – Wind speed – Terrain

Clause E.10 Category B – Air density

Clause E.11 Category B – Method

Clause E.12 Category B – Wind direction

Clause E.13 Combining uncertainties.

In this annex, a calculation method is given for aggregating uncertainties, as well as relevant tables for correlation factors and a (non-exhaustive) numerical example.

For all the category B uncertainties, a description is given as to what that uncertainty component covers, the symbol used for each component, references to other annexes where the component is discussed and a discussion of the default magnitude.

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E.2 Combining uncertainties

E.2.1 General

In its most general form, the combined standard uncertainty of the power in bin i, $u_{c,i}$ can be expressed by:

$$u_{c,i}^2 = \sum_{k=1}^{M} \sum_{l=1}^{M} c_{k,i} u_{k,i} c_{l,i} u_{l,i} \rho_{k,l,i,i} \quad \text{(E.1)}$$

where

$c_{k,i}$ is sensitivity factor of component k in bin i;

$u_{k,i}$ is the standard uncertainty of component k in bin i;

M is the number of uncertainty components in each bin;

$\rho_{k,l,i,j}$ is the correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j (in the expression the components k and l are both in bin i).

The uncertainty component is the individual input quantity to the uncertainty of each measured parameter. The combined standard uncertainty in the estimated annual energy production, u_{AEP}, can in its most general form be expressed by

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{M} \sum_{l=1}^{M} f_i \, c_{k,i} \, u_{k,i} \, f_j \, c_{l,j} \, u_{l,j} \, \rho_{k,l,i,j} \quad \text{(E.2)}$$

where

f_i is the relative occurrence of wind speed within bin i;

N is the number of bins;

N_h is the number of hours in one year ≈ 8 760.

It is seldom possible to deduce explicitly all the values of the correlation coefficients $\rho_{k,l,i,j}$ and normally significant simplifications are necessary. To allow the above expressions of combined uncertainties to be simplified to a practical level, the following assumptions may be made:

a) uncertainty components are either fully correlated ($\rho_{k,l,i,j}$ = 1, implying linear summation to obtain the combined standard uncertainty) or independent ($\rho_{k,l,i,j}$ = 0, implying quadratic summation, i.e. the combined standard uncertainty is the square root of summed squares of the uncertainty components);

b) category A uncertainties are uncorrelated across wind speed bins, while category B uncertainties are fully correlated across wind speed bins;

c) only relevant for site calibration uncertainties: category A uncertainties are uncorrelated across wind direction bins, while category B uncertainties are fully correlated across wind direction bins.

The correlation of the same type of uncertainty across different wind measurement heights when calculating the uncertainty of the rotor equivalent wind speed or a wind shear/veer normalised wind speed shall be assessed individually for each component and each case. Each uncertainty may first be accumulated across the measurement heights for a certain bin of the rotor equivalent or wind shear/veer normalised wind speed. Afterwards the uncertainty components of the rotor equivalent wind speed or the wind shear/veer normalised wind speed can be treated as described in bullet points a) and b).

Using these assumptions, the combined uncertainty of the power within a bin, $u_{c,i}$ can be expressed by:

$$u_{c,i}^2 = \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + \sum_{k=1}^{M_B} c_{k,i}^2 \, u_{k,i}^2 = s_i^2 + u_i^2 \quad \text{(E.3)}$$

where

M_A is the number of category A uncertainty components;

M_B is the number of category B uncertainty components;

$s_{k,i}$ is the category A standard uncertainty of component k in bin i;

s_i is the combined category A uncertainties in bin i;

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u_i is the combined category B uncertainties in bin i.

It should be noted that $u_{c,i}^2$ is not independent of bin size due to the dependency of $s_{P,i}$ on the number of data sets in the bin (see Equation (E.10)).

The assumptions imply that the combined standard uncertainty in energy production, u_{AEP}, is:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} \left(\sum_{i=1}^{N} f_i \, c_{k,i} \, u_{k,i}\right)^2 \quad \text{(E.4)}$$

The significance of the second term in this equation is that each individual category B uncertainty component progresses through to the corresponding AEP uncertainty, applying the assumption of full correlation across bins for the individual components. Finally, the cross-bin combined uncertainty components are added quadratically into a resulting AEP uncertainty.

Furthermore, certain components of category A uncertainty cannot necessarily be conveniently derived or estimated on a bin-wise basis. For example the site calibration method category A components which may have been derived by a sensitivity analysis on the AEP calculation. In that case, these components should be added quadratically into the resulting AEP uncertainty. Refer to Equation (E.8) for an example of this.

In practice, it may not be convenient to sum category B uncertainty components across the bins before they are individually combined. An approximation, allowing the category B uncertainty components to be combined within bins before they are combined across bins (i.e. s_i and u_i can be used), leads to the more convenient expression:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \left(\sum_{i=1}^{N} f_i \sqrt{\sum_{k=1}^{M_B} c_{k,i}^2 \, u_{k,i}^2}\right)^2 = N_h^2 \sum_{i=1}^{N} f_i^2 s_i^2 + N_h^2 \left(\sum_{i=1}^{N} f_i u_i\right)^2 \quad \text{(E.5)}$$

The u_{AEP}, obtained by this expression is always equal to or larger than that obtained using Equation (E.4).

E.2.2 Expanded uncertainty

The combined standard uncertainties of the power curve and the AEP may additionally be expressed by expanded uncertainties. Referring to the ISO/IEC Guide 98-3 and assuming normal distributions, intervals having levels of confidence shown in Table E.1 can be found by multiplying these combined standard uncertainties by a coverage factor also shown in the table.

Table E.1 – Expanded uncertainties

Level of confidence %	Coverage factor
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

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E.2.3 Basis for the uncertainty assessment

The calculation methodology goes through an estimate of the category A and B uncertainties for each bin of a measured power curve. The uncertainty of the power curve is derived, and finally the uncertainty of the annual energy production (AEP) is estimated. Please note that a fully worked out example has not been included, due to the differences in calculations for the various measurement approaches. Where possible a worked-out example for part of the calculation has been included to show how the equations and estimates of default values for uncertainty components have been applied.

The calculation methodology follows the ISO guide and the assumptions made above. Using the combination of the category B uncertainty components according to Equation (E.5), all uncertainty components within each bin can be combined first to express the combined category B uncertainty of each measured parameter, as for example for the wind speed:

$$u_{V,i}^2 = u_{V1,i}^2 + u_{V2,i}^2 + \ldots \tag{E.6}$$

where uncertainty components refer to the uncertainty components in Table E.2, using symbols and indices as in the table.

Secondly, the standard uncertainties of the measurands can be expressed by the uncertainties of the measurement parameters in bin i:

$$u_{c,i}^2 = s_{P,i}^2 + c_{V,i}^2 s_{SC,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2 + c_{V,i}^2 u_{M,i}^2 \tag{E.7}$$

where

$s_{P,i}$ is the category A standard uncertainty of power in bin i;

$s_{SC,i}$ is the category A standard uncertainty of site calibration in bin i;

$u_{P,i}$ is the category B standard uncertainty of power in bin i;

$u_{V,i}$ is the category B standard uncertainty of wind speed in bin i;

$u_{T,i}$ is the category B standard uncertainty of temperature in bin i;

$u_{B,i}$ is the category B standard uncertainty of pressure in bin i;

$u_{RH,i}$ is the category B standard uncertainty of relative humidity in bin i;

$u_{M,i}$ is the category B standard uncertainty of the method in bin i;

$c_{V,i}$ is the sensitivity factor for wind speed in bin i;

$c_{T,i}$ is the sensitivity factor for temperature in bin i;

$c_{B,i}$ is the sensitivity factor for pressure in bin i;

$c_{RH,i}$ is the sensitivity factor for relative humidity in bin i.

This also gives

$$u_{AEP}^2 = N_h^2 \left(\sum_{i=1}^{N} f_i^2 (s_{P,i}^2 + c_{V,i}^2 s_{SC,i}^2) + \left(\sum_{i=1}^{N} f_i \sqrt{u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2 + c_{V,i}^2 u_{M,i}^2} \right)^2 \right) \tag{E.8}$$

In the above equation, the uncertainties due to the data acquisition system are part of the uncertainty of each measurement parameter.

The measured power curve, shown in Figure 6 and Table 4, is used in the uncertainty calculation in this annex. The results of the uncertainty analysis in the example are also shown in Figure 6, Table 4 and Table 5. All sensitivity factors are listed in Table E.10, and category B uncertainties are listed in Table E.11.

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Table E.2 – List of category A and B uncertainties

Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude
Power output		$u_{P,i}$	$c_{P,i}$ = 1	
Current transformers	a	$u_{P,CT,i}$		0,75 %
Voltage transformers	a	$u_{P,VT,i}$		0,5 %
Power transducer or power measurement device	a	$u_{P,PT,i}$		0,5 %
DAQ (see E.4.2)	d	$u_{dP,i}$		0,1 % to 0,2 %
Wind speed		$u_{V,i}$		
Wind speed measurement		$u_{VHW,i}$		
Wind speed (cup or sonic)		$u_{VS,i}$		
Calibration	b	$u_{VS,precal,i}$	For the AEP uncertainty (and for the last bin of the power curve uncertainty) use: $c_{V,i} \approx \frac{P_i - P_{i-1}}{V_i - V_{i-1}}$	From calibration
Post calibration / In-situ	b	$u_{VS,postcal,i}$		0,2 m/s
Classification	c	$u_{VS,class,i}$		1,0 %
Mounting effects				
Single top-mounted	d	$u_{VS,mnt,i}$	For the power curve uncertainty, use: $c_{V,i} \approx \frac{1}{2} \cdot \left(\frac{(P_{i+1} - P_i)}{(V_{i+1} - V_i)} + \frac{(P_i - P_{i-1})}{(V_i - V_{i-1})} \right)$	0,5 %
Side-by-side mounted	d	(same)		1,0 %
Side-mounted	d	(same)		1,5 %
Lightning finial	d	$u_{VS,lgt,i}$		0,1 % to 0,2 %
DAQ (see E.4.2)	d	$u_{dVS,i}$		0,1 % to 0,2 %
Wind speed (RSD)		$u_{VR,i}$	$c_{V,i}$ (see above)	
Calibration	bc	$u_{VR,ver,i}$		2 % to 3 %
In-situ check	c	$u_{VR,isc,i}$		See E.7.3
Classification	c	$u_{VR,class,i}$		1,0 % to 1,5 %
Mounting	c	$u_{VR,mnt,i}$		0,1 %
Flow variation in different probe volumes at same height	d	$u_{VR,flow,i}$		2 % to 3 % see E.7.6
Monitoring test	c	$u_{VR,mon,i}$		0,5 %
Rotor equivalent wind speed		$u_{REWS,\ i}$	$c_{V,i}$ (see above)	
Wind shear	c	$u_{REWS,shear,\ i}$		See E.8.2
Wind veer	c	$u_{REWS,veer,\ i}$		See E.8.3
Wind speed – Terrain effects		$u_{VT,i}$	$c_{V,i}$ (see above)	
Without site calibration				
Flow distortion due to terrain	d	$u_{VT,i}$	$c_{V,i}$ (see above)	2 % or 3 % (offshore 1 % or 2 %)
With site calibration				
Anemometer calibration	b	$u_{VT,precal,i}$		From calibration
Post calibration / In-situ	b	$u_{VT,postcal,i}$		0,2 m/s
Anemometer classification	c	$u_{VT,class}$		1,0 %
Mounting effects				
Single top-mounted	d	$u_{VT,mnt,i}$		0,5 %
Side-by-side mounted	d	(same)		1,0 %
Side-mounted	d	(same)		1,5 %
Lightning finial	d	$u_{VT,lgt,i}$		0,1 % to 0,2 %

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Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude
DAQ (see E.4.2)	d	$u_{dVT,i}$		0,1 % to 0,2 %
Change of correction (adjacent wind **direction** bins)	c	$u_{VT,coc,i}$		See E.9.8
Removal of wind direction sensor between site calibration and power curve measurement	c	$u_{VT,rmv,i}$		See E.9.9
Seasonal variation	c	$u_{VT,sv,i}$		See E.9.10
Air density		$u_{AD,i}$		
Temperature		$u_{T,i}$	$c_{T,i}$ (see E.10.2)	
Temperature sensor	ab	$u_{T,cal,i}$		0,4 K to 0,6 K
Radiation shielding	cd	$u_{T,shield,i}$		1,5 K to 2,5 K
Mounting effects	cd	$u_{T,mnt,i}$		0,25 K to 0,4 K
DAQ (see E.4.2)	c	$u_{dT,i}$		0,1 % to 0,2 %
Air pressure		$u_{B,i}$	$c_{B,i}$ (see E.10.7)	
Pressure sensor	ab	$u_{B,cal,i}$		2 hPa to 4 hPa
Mounting effects	a	$u_{B,mnt,i}$		10 % of correction
DAQ (see E.4.2)	c	$u_{dB,i}$		0,1 % to 0,2 %
Relative Humidity		$u_{RH,i}$	$c_{RH,i}$ (see E.10.11)	
Humidity sensor	ab	$u_{RH,cal,i}$		1 % to 2 % (RH)
Mounting effects	cd	$u_{RH,mnt,i}$		0,1 % to 0,2 %
DAQ (see E.4.2)	c	$u_{dRH,i}$		0,1 % to 0,2 %
Method	cd	$u_{AD,method,i}$	$c_{AD,method,I} = c_{V.,i}$ (for actively regulated turbines)	0,2 % to 0,3 % on wind speed
Air density normalisation			$c_{AD,method,I} = c_{V.,i} = I$ (for stall regulated turbines)	
Method		$u_{M,\ i}$	$c_{V,i}$ (see above)	
Wind conditions	d	$u_{M,wc,\ i}$		See E.11.2.1 bullet a) or b).
Wind conditions – wind shear	d	$u_{M,shear,\ i}$		See E.11.2.2
Wind conditions – wind veer	d	$u_{M,veer,\ i}$		See E.11.2.3
Wind conditions – upflow	d	$u_{M,upflow,\ i}$		See E.11.2.4
Wind conditions – turbulence	d	$u_{M,ti,\ i}$		0,3 % to 0,5 % (only for RSD with lower met mast) See E.11.2.5
Seasonal effects	d	$u_{M,sfx,\ i}$		0,7 % See E.11.3
Turbulence normalisation	d	$u_{M,tinorm,\ i}$		See E.11.4
Cold climate	d	$u_{M,cc,\ i}$		0,5 % to 1 %
Wind direction				
Wind direction vane / sonic		$u_{WV,\ i}$	None (see E.12.2.1)	
Calibration	b	$u_{WV,cal,\ i}$		See E.12.2.1
North mark	c	$u_{WV,nm,\ i}$		See E.12.2.2
Boom orientation	d	$u_{WV,bo,\ i}$		See E.12.2.3
Operation (influence of mast)	c	$u_{WV,oe,\ i}$		See E.12.2.4

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Category B: Instruments	Note	Uncertainty	Sensitivity	Magnitude
Magnetic declination angle	c	$u_{WV,mda,\,i}$		See E.12.2.5
DAQ (see E.4.2)	c	$u_{dWV,\,i}$		See E.12.2.6
Wind direction (RSD)		$u_{WR,\,i}$	None (see E.12.3)	
Verification	ab	$u_{WR,ver,\,i}$		See E.12.3.1
Classification	c	$u_{WR,class,\,i}$		See L.4.4
Monitoring test	c	$u_{WR,mon,\,i}$		See E.12.3.2
Flow variation in different probe volumes at same height	c	$u_{WR,fv,\,i}$		See E.12.3.3
Alignment	d	$u_{WR,align,\,i}$		See E.12.3.4
Magnetic declination angle	c	$u_{WR,mda,\,i}$		See E.12.3.5
DAQ (see E.4.2)	c	$u_{dWR,\,i}$		See E.12.3.6
Category A: Statistical				
Electric power	e	$s_{P,I}$	$c_{P,i}$ = 1	
Site calibration	e	s_{sc}	$c_{V,i}$ (see above)	

NOTE Identification of uncertainties:
a = reference to standard;
b = calibration;
c = other "objective" method";
d = "guesstimate";
e = statistics.				

The ranges for the uncertainty components given in Table E.2 should be considered. Where available, actual values from specific measurements should be used. It should be noted that uncertainty components should not be estimated with a value of zero, as per guidance in the GUM, unless the specific uncertainty components are not relevant for the specific test methodology applied (see Clause E.14).

Also, it is important to note that the wind direction uncertainty does not influence directly the uncertainty of the power curve or the AEP (unless a wind veer normalisation is applied). However, the wind direction uncertainty is included here as it is important to understand how accurate the measurement sector filtering is being implemented as well as how accurate the site calibration factors are applied to data from the right sectors. As the wind direction uncertainty shall be reported, this table gives the minimum uncertainty components that shall be considered for the wind direction uncertainty. An estimate of the magnitude of these components is not given, but these should be included in a reported power curve.

Note that some calibration reports report an uncertainty for a coverage factor of two instead of one. In order to combine uncertainties correctly, the uncertainties should be converted to a coverage factor consistent with all uncertainty inputs (by default, use a coverage factor of 1).

E.3 Category A uncertainties

E.3.1 General

Category A uncertainties in measured and normalised electric power and due to climatic variations and the site calibration (if conducted) need to be considered.

E.3.2 Category A uncertainty in electric power

The standard deviation of the distribution of normalized power data in each bin is calculated by the equation:

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$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1} \sum_{j=1}^{N_i} \left(P_i - P_{n,i,j}\right)^2} \quad \text{(E.9)}$$

where

$\sigma_{P,I}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10 min data sets in bin i;

P_i is the normalized and averaged power output in bin i;

$P_{n,i,j}$ is the normalized power output of data set j in bin i.

The standard uncertainty of the normalized and averaged power in the bin is estimated by the equation:

$$s_i = s_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \quad \text{(E.10)}$$

where

$s_{P,i}$ is the category A standard uncertainty of power in bin i;

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i;

N_i is the number of 10 min data sets in bin i.

E.3.3 Category A uncertainties in the site calibration

The residuals between the site calibration corrected and measured wind speed at the wind turbine meteorological mast are used to define the category A uncertainty of the site calibration, s_{sc}. Refer to C.6.1 for the method of derivation.

E.4 Category B uncertainties: Introduction and data acquisition system

E.4.1 Category B uncertainties: Introduction

The category B uncertainties are assumed to be related to the instruments, the data acquisition system, the terrain surrounding the power performance test site, the wind conditions and the uncertainty related to the applied method. If the uncertainties are expressed as uncertainty limits, or have implicit, non-unity coverage factors, the standard uncertainty shall be estimated or they shall be properly converted into standard uncertainties.

Consider an uncertainty expressed as an uncertainty limit ± U. If a rectangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{3}} \quad \text{(E.11)}$$

If a triangular probability distribution is assumed, the standard uncertainty is:

$$\sigma = \frac{U}{\sqrt{6}} \quad \text{(E.12)}$$

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E.4.2 Category B uncertainties: data acquisition system

The uncertainties related to the data acquisition have been included under the treatment for the specific signals. The uncertainty of the electrical power includes a component for data acquisition and the same for wind speed and the other measured signals.

We assume in this annex the data acquisition system to have a standard uncertainty $u_{\mathrm{d},i}$ of 0,1 % of the full range of each measurement channel. However, for the reporting of a specific power performance test the data acquisition uncertainty shall be estimated for the specific test setup, including at least the contributions to the data acquisition uncertainty mentioned in E.4.2.

There may be uncertainties from transmission, signal conditioning, analogue to digital conversion, and data processing in the data acquisition system. The uncertainties may be different for each measurement channel. The standard uncertainty of the data acquisition system for the full range of a certain measurement channel, $u_{\mathrm{d},i}$, can be expressed as:

$$u_{\mathrm{d},i} = \sqrt{u_{\mathrm{d,ST},i}^2 + u_{\mathrm{d,SA},i}^2 + u_{\mathrm{d,SC},i}^2} \tag{E.13}$$

where

$u_{\mathrm{d,ST},i}$ is the uncertainty due to signal transmission in bin i;

$u_{\mathrm{d,SA},i}$ is the uncertainty due to system accuracy in bin i;

$u_{\mathrm{d,SC},i}$ is the uncertainty due to signal conditioning in bin i.

Although the assumption of a standard uncertainty of 0,1 % of the full range of the measurement channel is reasonable in many cases, specific hardware and conditions can cause this to be much higher. In order to ensure that the uncertainty of the data acquisition system is indeed negligible compared to the uncertainty of the sensors (which as a guidance should be interpreted as a factor 10 in magnitude when comparing standard uncertainties) an assessment of the actual uncertainty of the data acquisition system used shall be done.

E.5 Category B uncertainties: Power output

E.5.1 General

The category B uncertainties regarding the power output are based on four different uncertainty components which are introduced here.

The symbol for this uncertainty component is $u_{\mathrm{P},i}$.

The uncertainty of the power measurement has uncertainty contributions from the current and voltage transformers and from the power transducer (or other power measurement device). Uncertainties of these subcomponents are normally stated by their classification.

Finally the uncertainty related to the data acquisition of the power signal shall be added.

E.5.2 Category B uncertainties: Power output – Current transformers

This uncertainty component covers the uncertainty due to the current transformer as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{\mathrm{P,CT},i}$.

In this annex, the current transformers and the power transducer are all assumed to be of class 0,5 which is the minimum acceptable class for a power curve measurement as required by this standard.

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The current transformers of class 0.5 (nominal loads of the current transformers are here designed to match the nominal power, 2 000 kW, and not 125 % of nominal power). They have uncertainty limits, referring to IEC 61689-2, of ± 0,5 % of the current at 100 % load. At 20 % and 5 % loads, though, the uncertainty limits are increased to ± 0,75 % and ± 1,5 % of the current, respectively. For power performance measurements on wind turbines, the most important energy production is produced at a reduced power. Thus, we anticipate the uncertainty limits of ± 0,75 % of the current at 20 % load to be a good average.

The uncertainty distribution for a current transformer is assumed to be rectangular. If current transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.

It is assumed that the uncertainties of the three current transformers are caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each current transformer contributes by one-third to the power measurement, it follows that the uncertainty of all current transformers is proportional to the power as follows:

$$u_{\mathrm{P,CT},i} = \frac{0{,}75\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}43\ \% \cdot P_i\ [\mathrm{kW}] \tag{E.14}$$

E.5.3 Category B uncertainties: Power output – Voltage transformers

This uncertainty component covers the uncertainty due to the voltage transformer as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{\mathrm{P,VT},i}$.

In this annex, the voltage transformers and the power transducer are all assumed to be of class 0.5, which is the minimum acceptable class for a power curve measurement as required by this standard.

The voltage transformers of class 0,5 have uncertainty limits, referring to IEC 61869-3, of ±0,5 % of the voltage at all loads. The uncertainty distribution is assumed to be rectangular.

Voltage transformers are not used in all measurements and the value for this uncertainty components may be set to zero when not used.

If the voltage transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.

The grid voltage is normally rather constant and independent of the wind turbine power. The uncertainties of the three voltage transformers are as for the current transformers assumed to be caused by external influence factors such as air temperature, grid frequency, etc. They are therefore assumed fully correlated (an exception from the general assumption) and are summed linearly. As each voltage transformer contributes by one-third to the power measurement, it follows that the uncertainty of all voltage transformers is proportional to the power as follows:

$$u_{\mathrm{P,VT},i} = \frac{0{,}5\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}29\ \% \cdot P_i\ [\mathrm{kW}] \tag{E.15}$$

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E.5.4 Category B uncertainties: Power Output – Power transducer or other power measurement device

This uncertainty component covers the uncertainty due to the power transducer (or other power measurement device) as covered by the classification of the sensor.

The symbol for this uncertainty component is $u_{\mathrm{P,PT},i}$.

The power transducer of class 0,5, referring to IEC 60688, with a nominal power of 2 500 kW (125 % of the nominal power, 2 000 kW, of the wind turbine) has an uncertainty limit of 12,5 kW. The uncertainty distribution is assumed to be rectangular.

The uncertainty of the power transducer is thus:

$$u_{\mathrm{P,PT},i} = \frac{12{,}5\ \mathrm{kW}}{\sqrt{3}} = 7{,}2\ \mathrm{kW} \tag{E.16}$$

E.5.5 Category B uncertainties: Power output – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the power signal.

The symbol for this uncertainty component is $u_{\mathrm{dP},i}$.

The magnitude of this component has an assumed default value of 0,1 % to 0,2 % of the full range of the data acquisition system.

Considering the electric power range of the measurement channel for a 2 MW turbine to be 3 000 kW and an uncertainty of the data acquisition system of 0,1 % of this range gives a resulting uncertainty of 3 kW.

E.6 Category B uncertainties: Wind speed – Introduction and sensors

E.6.1 Category B uncertainties: Wind speed – Introduction

The wind speed uncertainty consists of three components, each of which again consists of multiple subcomponents. These three components are:

a) the uncertainty related to use of sensing hardware (cups, sonic and remote sensing devices (RSD);
b) the uncertainty related to the flow distortion due to the terrain;
c) the uncertainty related to the methods applied.

The symbol for this uncertainty component is $u_{\mathrm{V},i}$.

These uncertainty components as well as the sub-components will be introduced in the next subclauses.

The sensitivity factor, $c_{\mathrm{V},i}$, is defined in Table E.2.

E.6.2 Category B uncertainties: Wind speed – Hardware

The wind speed uncertainty related to hardware consists of three components, each of which again consists of multiple subcomponents. These three components are:

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a) The uncertainty related to use of sensors placed in a meteorological mast (cup anemometers and sonic anemometers);

b) The uncertainty related to a remote sensing device (RSD);

c) The uncertainty related to a rotor equivalent wind speed (REWS);

The symbol for this uncertainty component is $u_{\mathrm{VHW},I}$.

E.6.3 Category B uncertainties: Wind speed – Meteorological mast mounted sensors

E.6.3.1 General

This uncertainty component covers the uncertainty related to the use of cup anemometers and sonic anemometers in meteorological masts (either top mounted or side mounted).

The symbol for this uncertainty component is $u_{V\mathrm{S},i}$. (V stands for wind speed and S stands for sensors).

This uncertainty component has six sub components:

a) uncertainty related to the calibration of the sensor before start of the power performance test;

b) uncertainty related to the calibration of the sensor during or after the power performance test;

c) the uncertainty related to the operational characteristics as determined by the classification of the sensor;

d) the uncertainty related to the mounting of the sensor;

e) the uncertainty related to the mounting of the lightning finial;

f) the uncertainty related to the data acquisition of the signal from the sensor.

E.6.3.2 Category B uncertainties: Wind speed – Met mast sensors – Pre-calibration

This uncertainty component covers the uncertainty related to calibration of the sensor before the test. This includes the variability of repeated tests for one test facility as well as the variability of repeated tests between various facilities.

The symbol for this uncertainty component is $u_{V\mathrm{S,precal},i}$.

This uncertainty is also discussed in Annex F of this standard.

For a specific power performance test, the values as indicated on the calibration for the sensors employed shall be used for the uncertainty calculation.

E.6.3.3 Category B uncertainties: Wind speed – Met mast sensors – Post-calibration

This uncertainty component covers the uncertainty related to the in-situ calibration and/or the post-calibration of the sensor during and/or after the test.

The symbol for this uncertainty component is $u_{V\mathrm{S,postcal},i}$.

This uncertainty is also discussed in 7.2.2 and Annex K of this standard.

If both an in-situ calibration has been done during the power performance test as well as a post-calibration has been done after the power performance test, the magnitude for this uncertainty component shall be taken from the post-calibration.

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If a post calibration is done, the magnitude of this uncertainty component shall be the maximum difference between the precalibration and post-calibration in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

Please note that due to the inherent uncertainty of the calibration the expectation will be that small differences will occur between the pre-calibration and post-calibration. The best estimate of the calibration value for a specific sensor will be the average of the calibrations done; in the limit of a very large amount of calibrations the average will converge towards the centre of the distribution.

As only the pre-calibration is used to determine the wind speed from the sensor, the maximum difference can therefore be used as an added uncertainty contribution.

If only an in-situ calibration is done according to Annex K, the magnitude of this uncertainty component shall be the maximum value of δ in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

E.6.3.4 Category B uncertainties: Wind speed – Met mast sensors – Classification

This uncertainty component covers the uncertainty related to the operational characteristics of the sensor as determined by the classification of the sensor.

The symbol for this uncertainty component is $u_{V\mathrm{S,class},i}$.

This uncertainty is also discussed in Annex I of this standard.

The magnitude of this uncertainty shall be taken from the classification report. Care shall be taken that the terrain type the sensor is used in matches the terrain type of the classification of the sensor (Class A, B or S).

A reference to the classification report shall be included in the power performance report.

The measured range of the influence parameters used for the classification as per Annex I shall be reported for the same data set used for the power performance report. If upflow is not measured, compliance with the accuracy class shall be argued from the local terrain slopes for the experienced wind directions by fitting a plane to the terrain within a distance of 5 times the measurement height relative to the position of the WME according to IEC 61400-1:2005, 11.9.

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

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

E.6.3.5 Category B uncertainties: Wind speed – Met mast sensors – Mounting

This uncertainty component covers the uncertainty related to the mounting of the sensor.

The symbol for this uncertainty component is $u_{V\mathrm{S,mnt},i}$.

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This uncertainty is also discussed in 7.2.4 and 9.1.2 as well as Annex G of this standard.

This uncertainty component has three default values corresponding to the three mounting arrangements allowed by Annex G (single top-mounted anemometer, side-by-side top-mounted anemometer or side-mounted anemometer).

For a single top-mounted anemometer, the default magnitude for this uncertainty component is 0,5 % of the measured wind speed.

For a side-by-side top-mounted anemometer, the default magnitude for this uncertainty component is 1,0 %.

For a side-mounted anemometer, the default magnitude for this uncertainty component is one the following:

- for not-flow-corrected signals the default magnitude for this uncertainty component is 1,5 % of the measured signal;
- for a flow-corrected signal according to 7.2.4 and 9.1.2 (mast flow distortion correction) the default magnitude for this uncertainty component is the root-sum-square of half the mean correction applied to the wind speed signal and 0,5 % of the measured signal. Wake effects shall be excluded for the correction to be applied.

The same correction principle can also be applied to two top-mounted anemometers in a goal-post configuration, with the same default magnitude for the flow-corrected signal.

E.6.3.6 Category B uncertainties: Wind speed – Met mast sensors – Lightning finial

This uncertainty component covers the uncertainty related to a possible top-mounted lightning finial and its influence on a top-mounted anemometer when the requirements in Clause G.5 for the mounting of the lightning finial cannot be met.

The symbol for this uncertainty component is $u_{V\mathrm{S,lgt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the wind speed signal.

E.6.3.7 Category B uncertainties: Wind speed – Met mast sensors – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the wind speed signal.

The symbol for this uncertainty component is $u_{\mathrm{d}V\mathrm{S},i}$.

This uncertainty is also discussed in E.4.2 of this standard.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the measured wind speed signal.

Considering a wind speed range of 30 m/s of the measurement channel and an uncertainty of the data acquisition system of 0,1 % of this range, the standard uncertainty from data acquisition is 0,03 m/s.

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E.7 Category B uncertainties: Wind speed – RSD

E.7.1 General

This uncertainty component covers the uncertainty related to the use of remote sensing devices for wind speed measurements (LIDAR and SODAR).

The symbol for this uncertainty component is $u_{V\mathrm{R},i}$ (V stands for wind speed and R stands for remote sensing device).

This uncertainty component has six sub components:

a) uncertainty related to the verification of the device;

b) uncertainty related to the in-situ check of the device;

c) the uncertainty related to the operational characteristics of the device as determined by the classification of the device;

d) the uncertainty related to the mounting of the device;

e) the uncertainty related to flow variation in different probe volumes at the same height;

f) the uncertainty related to the monitoring test.

E.7.2 Category B uncertainties: Wind speed – RSD – Calibration

This uncertainty component covers the uncertainty related to the calibration of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,ver},i}$.

This uncertainty is also discussed in Annex L.

Prior to the measurement a calibration according to Annex L shall be undertaken and its uncertainties evaluated ($u_{\mathrm{VR,vrf},i}$) (for details refer to L.4.3). If the uncertainties for the exact measurement height are not available, the uncertainties are recommended to be interpolated. The default magnitude for this uncertainty component is 1,0 % to 3,0 % of the measured wind speed.

E.7.3 Category B uncertainties: Wind speed – RSD – in-situ check

This uncertainty component covers the uncertainty related to the verification of the remote sensing device, only applied for an RSD with a lower than hub height met-mast.

The symbol for this uncertainty component is $u_{V\mathrm{R,isc},i}$ (“isc” stands for in-situ check).

This uncertainty is also discussed in Annex L of this standard.

The in-situ test shall be evaluated as described in Annex K, where the RSD is the main measurement and the anemometer on the monitoring mast is the control anemometer with the same uncertainty limits.

E.7.4 Category B uncertainties: Wind speed – RSD – Classification

This uncertainty component covers the uncertainty related to the classification of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,class},i}$.

This uncertainty is also discussed in Annex L of this standard.

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The uncertainty due to the operational characteristics are coming from the classification report of the RSD which is providing slopes and ranges of environmental variables. There are three ways of calculating the uncertainty due to these variables:

1. The environmental variable is measured during the measurement:

(according to Equation (L.6) of Annex L)

$$u_{VR,\mathrm{class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \left| \bar{x}_{\mathrm{PC},j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)^2} \tag{E.17}$$

where

v_i is the wind speed measured at height i;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of results from a minimum of 3 classification tests;

$\bar{x}_{\mathrm{PC},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the power curve test;

$\bar{x}_{\mathrm{ver},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the performance verification test of the remote sensing device.

2. The environmental variable is NOT measured during the measurement:

$$u_{VR,\mathrm{class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \frac{\max\left(\left| x_{\mathrm{min},j,i} - \bar{x}_{\mathrm{ver},j,i} \right|, \left| x_{\mathrm{max},j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)}{\sqrt{3}} \right)^2} \tag{E.18}$$

where

v_i is the wind speed measured at height i;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of results from a minimum of 3 classification tests;

$x_{\mathrm{min},j,i}$ is the expected lower range limit of not measured environmental variable j in wind speed bin i;

$x_{\mathrm{max},j,i}$ is the expected upper range limit of not measured environmental variable j in wind speed bin i;

$\bar{x}_{\mathrm{ver},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the performance verification test of the remote sensing device.

3. If a fixed range is expected:

$$u_{VR,\mathrm{class},i} = v_i \frac{\text{accuracy class}}{\sqrt{3}} \tag{E.19}$$

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NOTE This equation is inaccurate because the variations of the environmental variable are already included in the uncertainties of cat. A of the power curve.

According to L.4.4, $u_{VR,class}$ becomes equal to zero if the verification test includes the same data as the power curve test.

For more details, see L.4.4 of Annex L.

The default magnitude for this uncertainty component is 1,0 % to 1,5 % of the measured wind speed.

E.7.5 Category B uncertainties: Wind speed – RSD – Mounting

This uncertainty component covers the uncertainty related to the mounting of the remote sensing device.

The symbol for this uncertainty component is $u_{VR,mnt,i}$.

This uncertainty is also discussed in Annex L of this standard.

The uncertainty of the remote sensing device due to non-ideal levelling of the device shall be estimated. The uncertainty is highly dependent on the type of instrument being used.

The default magnitude for this uncertainty component is 0,1 % of the measured wind speed.

E.7.6 Category B uncertainties: Wind speed – RSD – Flow variation

This uncertainty component covers the uncertainty related to the flow variation across the measurement volume of the remote sensing device.

The symbol for this uncertainty component is $u_{VR,flow,i}$.

This uncertainty is also discussed in Annex L of this standard.

The user should consult with the remote sensing device manufacturer for the best method for evaluating the uncertainty for their specific device at the test site.

The following procedure is recommended for a standard use (according to Albers *et al.*, reference [12][25]):

$$u_{VR,flow,i} = \frac{(\tan(\alpha_2) - \tan(\alpha_1)) \cdot v_i}{2 \cdot \tan(\Phi)} \quad \text{(E.20)}$$

α_1 is the upflow angle into the probe volume;

α_2 is the upflow angle out of the probe volume;

Φ is the opening angle of the RSD from the vertical.

As a first estimation for the upflow angles into and out of the probe volume, 1° and –1° respectively, may be used.

25 Figures in square brackets refer to the bibliography.

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This default first estimate results in an uncertainty component of 2 % to 3 % of the measured wind speed (depending on the RSD opening angle), as per L.4.5. Alternatively the method referenced in E.6.3.4 based on terrain slope may be used.

E.7.7 Category B uncertainties: Wind speed – RSD – Monitoring test

This uncertainty component covers the uncertainty related to the result of the monitoring of the remote sensing device.

The symbol for this uncertainty component is $u_{V\mathrm{R,mon},i}$.

This uncertainty is also discussed in Annex L.

Three scenarios are possible and shall be treated as follows:

1. No additional uncertainty needs to be added if the following criterion is met:

$$\sqrt{u^2_{V\mathrm{Rvrf},mh,i} + u^2_{V\mathrm{Rcls},mh,i}} > \left| v_{\mathrm{RSD},mh,i} - v_{\mathrm{MM},i} \right| \tag{E.21}$$

   $u_{V\mathrm{Rvrf},mh,i}$ is the uncertainty of the RSD verification at control mast height in bin i;

   $u_{V\mathrm{Rcls},mh,i}$ is the uncertainty due to operational characteristics of the RSD at control mast height in bin i;

   $v_{\mathrm{RSD},mh,i}$ is the wind speed of the RSD at control mast height in bin i;

   $v_{\mathrm{MM},i}$ is the wind speed of the control mast in bin i

2. If Equation (E.21) is not met and the measurement height of the RSD and the control met mast are equal, the following uncertainty shall be added:

$$u_{V\mathrm{Rmon},i} = \left| v_{\mathrm{RSD},mh,i} - v_{\mathrm{MM},i} \right| - \sqrt{u^2_{V\mathrm{Rvrf},mh,i} + u^2_{V\mathrm{Rcls},mh,i}} \tag{E.22}$$

3. If Equation (E.21) is not met and the measurement heights of the RSD and the control met mast are not the same, $u_{V\mathrm{Rmon},i}$ shall be calculated as follows:

$$u_{\mathrm{added_systematic},j,i} = u_{\mathrm{added_systematic},1,i} \frac{u_{\mathrm{systematic},j,i}}{u_{\mathrm{systematic},1,i}} \tag{E.23}$$

   where

   $u_{\mathrm{added_systematic},j,i}$ is added category B standard uncertainty at measurement height j (not covered by the meteorological mast);

   $u_{\mathrm{added_systematic},1,i}$ is added category B uncertainty at the height of the top of the meteorological mast;

   $u_{\mathrm{systematic},j,i}$ is cumulated other category B uncertainties of the remote sensing device at height j;

   $u_{\mathrm{systematic},1,i}$ is cumulated other category B uncertainties of the remote sensing device at the height of the top of the meteorological mast.

The default magnitude for this uncertainty component is 0,5 % of the measured wind speed.

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E.8 Category B uncertainties: Wind speed – REWS

E.8.1 General

A number of uncertainty components are not related to the wind speed measurement (at least not when applied to a hub height wind speed) but to the use and definition of the rotor equivalent wind speed (REWS). The uncertainty components related to REWS will be covered in this subclause.

The rotor equivalent wind speed according to Equation (5) in 9.1.3.2 includes wind speed measurements at different heights above ground. In order to make uncertainty calculations of the rotor equivalent wind speed feasible, Equations (E.3) and (E.4) are needed. Equation (E.3) and (E.4) are approximations of (E.1) and (E.2) respectively for the case that the category B uncertainty components are independent between different category B uncertainty sources. This approximation is highly violated if uncertainties of wind speed measurements at different height levels are considered as separate category B uncertainties, because the uncertainty components of wind speed measurements at different height levels are well correlated. Thus, Equations (E.3) and (E.4) cannot be applied directly.

In order to overcome this problem, Equations (E.3) and (E.4) shall be applied with such category B components of the rotor equivalent wind speed which can be considered as independent from each other. Subclause E.8.2 provides advice how this can be implemented.

E.8.2 Category B uncertainties: Wind speed – REWS – Wind speed measurement over whole rotor

E.8.2.1 General

This uncertainty component covers the uncertainty of the REWS wind speed based on the multiple wind speed measurements the REWS is based on.

The symbol for this uncertainty component is $u_{\mathrm{REWS,shear},i}$.

This uncertainty is also discussed in Annex P of this standard.

NOTE This uncertainty will be used instead of $u_{\mathrm{V},i}$ in conjunction with E.13.3.

What is very important for this uncertainty component is that the derivation and hence the magnitude is strongly dependent on the various measurement methods as introduced in 7.2. A configuration with a hub-height only meteorological mast will not lead to a REWS implementation, the other measurement configurations are considered in the subclauses below.

Please note that the same symbol is used in each subclause as these configurations are mutually exclusive and depending on the specific measurement setup only one of subclauses E.8.2.2 to E.8.2.4 applies.

E.8.2.2 REWS shear uncertainty – Meteorological mast significantly above hub height

In this configuration the REWS is based on signals from side-mounted cup anemometers or sonic anemometers from multiple measurement heights on a meteorological mast.

In this case Equation (5) in 9.1.3.2 applies and the REWS uncertainty components come from Clause E.6.

The default values come from the combination of the default values in Clause E.6.

The way to combine these components into a REWS uncertainty is explained in E.13.7.

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E.8.2.3 REWS shear uncertainty – RSD + lower-than-hub-height meteorological mast

In this configuration, the REWS is based on signals from an RSD. The data from the meteorological mast is only used to validate the RSD data.

In this case, Equation (5) in 9.1.3.2 applies and the REWS uncertainty components come from Clause E.7.

The default values come from the combination of the default values in Clause E.7.

The way to combine these components into a REWS uncertainty is explained in E.13.7.

E.8.2.4 REWS shear uncertainty – hub height meteorological mast + RSD for shear

In this configuration, the REWS is based on a cup anemometer or sonic anemometer on a hub-height meteorological mast combined with shear data from an RSD.

In this case, Equation (11) in 9.1.3.4 applies and the REWS uncertainty components come from both Clause E.6 as well as Clause E.7.

In this case, we still have a further division: either the RSD signals are considered as absolute wind speed measurements or as relative wind speed measurements, as the treatment is different between these. This depends on the type of equipment used or the available sensitivity & verification test.

For an absolute wind speed the way to combine these components into a REWS uncertainty is explained in E.13.8.

For a relative wind speed the way to combine these components into a REWS uncertainty is explained in E.13.9.

E.8.3 Category B uncertainties: Wind speed – REWS – Wind veer

This uncertainty component covers the uncertainty related to the influence of veer on the Rotor Equivalent Wind Speed.

The symbol for this uncertainty component is $u_{\mathrm{REWS,veer},i}$.

This uncertainty is also discussed in Annex Q of this standard.

The veer measurement is based on signals from side-mounted wind vanes or sonic anemometers from multiple measurement heights on a meteorological mast or on signals from an RSD.

The sub-components for this uncertainty component therefore come from E.12.2 or from E.12.3.

E.9 Category B uncertainties: Wind speed – Terrain

E.9.1 General

This uncertainty component covers the uncertainty related to the flow distortion of the wind speed between measurement point and wind turbine due to the local terrain.

The symbol for this uncertainty component is $u_{V\mathrm{T},i}$ (V stands for wind speed and T stands for Terrain).

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This uncertainty is also discussed in 6.3.4 of this standard.

When the power performance test is done without a site calibration, the default magnitude of this uncertainty component is determined by the distance between the measurement device and the turbine under test. If this distance is between 2 and 3 rotor diameters ($2D$ ≤ distance ≤ $3D$), this default magnitude is 2 % of the measured wind speed for onshore flat terrain and 1 % for offshore. If this distance is between 3 and 4 rotor diameters ($3D$ < distance ≤ $4D$), this default magnitude is 3 % of the measured wind speed for onshore flat terrain and 2 % offshore.

When the power curve test is done with a site calibration, the default magnitude of this uncertainty component is determined by the site calibration measurement.

In this case, this uncertainty component related to the terrain has nine sub components:

a) uncertainty related to the calibration of the anemometers used for the site calibration;
b) uncertainty related to the operational characteristics of the anemometers used for the site calibration;
c) the uncertainty related to the mounting of the anemometers used for the site calibration;
d) the uncertainty related to the data acquisition of the signals from the anemometers used for the site calibration;
e) the uncertainty related to the lightning finial;
f) the uncertainty related to the convergence check (refer to C.7.1);
g) the uncertainty related to the correlation check (refer to C.7.2);
h) the uncertainty related to the change in correction between adjacent bins;
i) the uncertainty related to the removal of the wind direction sensor between site calibration and power curve measurement;
j) the uncertainty related to seasonal variation.

E.9.2 Category B uncertainties: Wind speed – Terrain – Pre-calibration

This uncertainty component covers the uncertainty related to the calibration of the sensors before the site calibration test.

The symbol for this uncertainty component is $u_{\mathrm{VT,precal},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

This uncertainty is virtually the same as $u_{\mathrm{VS,precal},i}$ with the difference that here it is applied to measured wind speeds on two masts.

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

E.9.3 Category B uncertainties: Wind speed – Terrain – Post-calibration

This uncertainty component covers the uncertainty related to the in-situ calibration and/or the post-calibration of the sensor during and/or after the site calibration.

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The symbol for this uncertainty component is $u_{V\mathrm{T,postcal},i}$.

This uncertainty is also discussed in 7.2.2 and Annex K of this standard.

If both an in-situ calibration has been done during the power performance test as well as a post-calibration has been done after the power performance test, the magnitude for this uncertainty component shall be taken from the post-calibration.

If a post calibration is done, the magnitude of this uncertainty component shall be the maximum difference between the precalibration and post-calibration in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

Note that due to the inherent uncertainty of the calibration, the expectation will be that small differences will occur between the pre-calibration and post-calibration. The best estimate of the calibration value for a specific sensor will be the average of the calibrations done; in the limit of a very large amount of calibrations, the average will converge towards the centre of the distribution.

As only the pre-calibration is used to determine the wind speed from the sensor, the maximum difference can therefore be used as an added uncertainty contribution.

If only an in-situ calibration is done according to Annex K, the magnitude of this uncertainty component shall be the maximum value of δ in the wind speed range of 4 m/s to 12 m/s, up to a maximum of 0,2 m/s.

E.9.4 Category B uncertainties: Wind speed – Terrain – Classification

This uncertainty component covers the uncertainty related to the classification of the sensors for the site calibration.

The symbol for this uncertainty component is $u_{V\mathrm{T,class},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

The magnitude of this uncertainty shall be taken from the classification report. Care shall be taken that the terrain type the sensor is used in matches the terrain type of the classification of the sensor (Class A, B or S).

A reference to the classification report shall be included in the site calibration report. If no such reference is included, the default magnitude for the uncertainty shall be a class 3,4A (for non-complex terrain) or a class 4,5B (for complex terrain).

The measured range of the influence parameters used for the classification as per Annex I shall be reported for the same data set used for the site calibration report. If upflow is not measured, compliance with the accuracy class shall be argued from the local terrain slopes for the experienced wind directions, assuming that the vertical angle of the wind is 2/3 of the average terrain slope within 5D of the turbine upwind of the turbine.

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If the measured range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the site calibration is significantly different from the range of influence parameters experienced by the reference sensor on the permanent meteorological mast during the power curve test, an additional uncertainty addition may be required. However, as long as both tests stay within the ranges defined for class A and B, this is considered to be sufficiently covered and no additional uncertainty needs to be taken into account.

E.9.5 Category B uncertainties: Wind speed – Terrain – Mounting

This uncertainty component covers the uncertainty related to the mounting of the sensors during the site calibration.

The symbol for this uncertainty component is $u_{V\mathrm{T,mnt},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

The default magnitude for this uncertainty component is:

a) 0,5 % of the measured wind speed for a single top-mounted anemometer;

b) 1,0 % for a setup with side-by-side top-mounted anemometers;

c) for a side-mounted anemometer, the default magnitude for this uncertainty component is one of the following:

   1) for not-flow-corrected signals the default magnitude for this uncertainty component is 1,5 % of the measured signal;

   2) for a flow-corrected signal according to 7.2.4 and 9.1.2, the default magnitude for this uncertainty component is the root-sum-square of half the mean correction applied to the wind speed signal and 0,5 % of the measured signal. Wake effects shall be excluded for the correction to be applied. This is in lieu of the not-flow-corrected uncertainty and shall not be added to it.

The same correction principle can also be applied to two top-mounted anemometers in a goal-post configuration, with the same default magnitude for the flow-corrected signal.

E.9.6 Category B uncertainties: Wind speed – Terrain – Lightning finial

This uncertainty component covers the uncertainty related to a possible top-mounted lightning finial and its influence on a top-mounted anemometer when the requirements in Clause G.5 for the mounting of the lightning finial cannot be met.

The symbol for this uncertainty component is $u_{V\mathrm{T,lgt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the wind speed signal.

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E.9.7 Category B uncertainties: Wind speed – Terrain – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signals of the wind speed sensors during the site calibration.

The symbol for this uncertainty component is $u_{\mathrm{dVT},i}$.

This uncertainty is also discussed in Clause C.6 of this standard.

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

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the wind speed measurement channel.

E.9.8 Category B uncertainties: Wind speed – Terrain – Change in correction between adjacent bins

This uncertainty component covers the uncertainty related to the change in correction between adjacent bins.

The symbol for this uncertainty component is $u_{\mathrm{VT,coc},i}$ (COC stands for 'change in correction').

Refer to C.7.3 for details of the evaluation of this uncertainty.

E.9.9 Category B uncertainties: Wind speed – Terrain – Removal of WD sensor

This uncertainty component covers the uncertainty related to removal of the wind direction sensor between the site calibration and the power performance test.

The symbol for this uncertainty component is $u_{\mathrm{VT,rmv},i}$.

Refer to C.7.4 for details of the evaluation of this uncertainty.

E.9.10 Category B uncertainties: Wind speed – Terrain – Seasonal variation

This uncertainty component covers the uncertainty related to seasonal variation between the site calibration and the power performance test.

The symbol for this uncertainty component is $u_{\mathrm{VT,sv},i}$ (SV stands for seasonal variation).

This uncertainty is also discussed in C.7.5 of this standard.

This uncertainty shall only be applied if any of these conditions for a wind direction bin differs between site calibration and power performance test by more than the following amounts:

a) 0,05 for wind shear exponent

b) 3 % for turbulence intensity,

c) if upflow is measured, a limit of ± 2° change in vertical upflow is recommended.

If one or more of these conditions is triggered, then the default magnitude for this uncertainty is one third of the magnitude of the site calibration flow correction.

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E.10 Category B uncertainties: Air density

E.10.1 General

This uncertainty component covers the uncertainty related to the influence of air density on the power curve.

The symbol for this uncertainty component is $u_{\mathrm{AD},i}$.

The air density is derived from measurements of the air temperature, the humidity and the air pressure.

The air density uncertainty consists of four components:

- the uncertainty related to the use of a temperature sensor and the data acquisition;
- the uncertainty related to the use of a pressure sensor and the data acquisition;
- the uncertainty related to the use of a relative humidity (RH) sensors and the data acquisition, or the lack of such a sensor;
- the uncertainty due to the air density correction.

These uncertainty components as well as the subcomponents will be introduced in Clause E.10.

E.10.2 Category B uncertainties: Air density – Temperature introduction

This uncertainty component covers the uncertainty related to the measurement of the temperature.

The symbol for this uncertainty component is $u_{T,i}$.

This uncertainty component has four sub-components:

a) uncertainty related to the calibration of the temperature sensor;
b) uncertainty related to the radiation shielding of the temperature sensor;
c) uncertainty related to the mounting of the temperature sensor;
d) uncertainty related to the data acquisition of the signal from the temperature sensor.

The equations for the sensitivity factors for temperature are:

Sensitivity for temperature for a measurement on wind turbine with active power control:

$$c_{T,i} = -\frac{c_{V,i} v_i}{3\rho_i}\left(\frac{\rho_i}{T_i} + \frac{\phi_i}{T_i}\left(\frac{1}{R_0} - \frac{1}{R_{\mathrm{w}}}\right) 0{,}0000205 \cdot \exp\left(0{,}0631846 T_i\right)\right) \quad \text{(E.24)}$$

where

$c_{T,i}$ is the sensitivity factor for temperature in bin i;
$c_{v,i}$ is the sensitivity factor for wind speed in bin i;
v_i is the average wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
Φ_i is the average relative humidity (range 0 % to 100 %) in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK];

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R_w is the gas constant of water vapour 461,5 [J/kgK].

Sensitivity for temperature for a measurement on a stall regulated wind turbine:

$$c_{T,i} = \frac{P_i}{\rho_i}\left(\frac{\rho_i}{T_i} + \frac{\phi_i}{T_i}\left(\frac{1}{R_0} - \frac{1}{Rw}\right)\cdot 0{,}0000205 \cdot 0{,}0631846 \cdot \exp\left(0{,}0631846 \cdot T_i\right)\right) \quad \text{(E.25)}$$

where

$c_{T,i}$ is the sensitivity factor for temperature in bin i;

P_i is the sensitivity factor for wind speed in bin i;

ρ_i is the is the average air density in bin i;

T_i is the average temperature in bin i;

Φ_i is the average relative humidity (range 0 % to 100 %) in bin i;

R_0 is the gas constant of dry air 287,05 [J/kgK];

R_w is the gas constant of water vapour 461,5 [J/kgK].

E.10.3 Category B uncertainties: Air density – Temperature – Calibration

This uncertainty component covers the uncertainty related to calibration of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{cal},i}$.

The default magnitude for this uncertainty component is 0,4 °C to 0,6 °C.

E.10.4 Category B uncertainties: Air density – Temperature – Radiation shielding

This uncertainty component covers the uncertainty related to the radiation shielding of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{shield},i}$.

The default magnitude for this uncertainty component is 1,5 °C to 2,5 °C.

E.10.5 Category B uncertainties: Air density – Temperature – Mounting

This uncertainty component covers the uncertainty related to the mounting of the temperature sensor.

The symbol for this uncertainty component is $u_{T,\mathrm{mnt},i}$.

The default magnitude for this uncertainty component is 0,25 °C to 0,4 °C.

E.10.6 Category B uncertainties: Air density – Temperature – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the temperature sensor.

The symbol for this uncertainty component is $u_{\mathrm{d}T,i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the full range of the measurement channel. With an assumed temperature range of 40 °C this comes to 0,04 °C.

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E.10.7 Category B uncertainties: Air density – Pressure introduction

This uncertainty component covers the uncertainty related to the measurement of the pressure.

The symbol for this uncertainty component is $u_{B,i}$.

This uncertainty component has three sub-components:

a) uncertainty related to the calibration of the pressure sensor;
b) uncertainty related to the mounting of the pressure sensor;
c) uncertainty related to the data acquisition of the signal from the pressure sensor.

The equation for the sensitivity factors for pressure are:

Sensitivity for pressure for a measurement on wind turbine with active power control:

$$c_{B,i} = \frac{c_{V,i} v_i}{3 \rho_i T_i R_0} \tag{E.26}$$

where

$c_{B,i}$ is the sensitivity factor for temperature in bin i;
$c_{v,i}$ is the sensitivity factor for wind speed in bin i;
v_i is the average wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK].

Sensitivity for pressure for a measurement on a stall regulated wind turbine

$$c_{B,i} = -\frac{P_i}{\rho_i T_i R_0} \tag{E.27}$$

where

$c_{B,i}$ is the sensitivity factor for temperature in bin i;
P_i is the sensitivity factor for wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK].

E.10.8 Category B uncertainties: Air density – Pressure – Calibration

This uncertainty component covers the uncertainty related to the calibration of the pressure sensor.

The symbol for this uncertainty component is $u_{B,\mathrm{cal},i}$.

The default magnitude for this uncertainty component is 2 hPa to 4 hPa.

E.10.9 Category B uncertainties: Air density – Pressure – Mounting

This uncertainty component covers the uncertainty related to the mounting of the pressure sensor.

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The symbol for this uncertainty component is $u_{B,\mathrm{mnt},i}$.

The default magnitude for this uncertainty component is determined by the height difference for which the signal from the pressure sensor is corrected. Using ISO 2533 the pressure related to this height difference can be calculated. The default magnitude for the uncertainty related to this pressure correction is 10 % of the correction.

For a sensor installed at a height of 2 m and a hub height of 100 m, the difference is 98 m which gives a pressure difference of 11,7 hPa. The uncertainty would then be 1,17 hPa.

E.10.10 Category B uncertainties: Air density – Pressure – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the pressure sensor.

The symbol for this uncertainty component is $u_{\mathrm{d}B,i}$.

The default magnitude for this uncertainty component is 0,1 % of the full range of the measurement channel for pressure. Considering a pressure range of 100 hPa of the measurement channel this gives 0,1 hPa.

E.10.11 Category B uncertainties: Air density – Relative humidity introduction

This uncertainty component covers the uncertainty related to the measurement of the relative humidity.

The symbol for this uncertainty component is $u_{\mathrm{RH},i}$.

The relative humidity is not required to be measured. In that case, a default value of 50 % shall be assumed with an uncertainty of 100 % (from 0 % to 100 %).

In case the humidity is measured, this uncertainty component has three sub-components:

a) uncertainty related to the calibration of the humidity sensor;
b) uncertainty related to the mounting of the humidity sensor;
c) uncertainty related to the data acquisition of the signal from the humidity sensor;

The equations for the sensitivity factors for relative humidity are:

Sensitivity for relative humidity for a measurement on wind turbine with active power control:

$$c_{\mathrm{RH},i} = -\frac{c_{v,i} v_i}{3\rho_i T_i}\left(\frac{1}{R_0} - \frac{1}{R_w}\right) \cdot 0{,}0000205 \cdot \exp(0{,}0631846 \cdot T_i) \qquad \text{(E.28)}$$

where

$c_{\mathrm{RH},i}$ is the sensitivity factor for temperature in bin i;
$c_{v,i}$ is the sensitivity factor for wind speed in bin i;
v_i is the average wind speed in bin i;
ρ_i is the is the average air density in bin i;
T_i is the average temperature in bin i;
R_0 is the gas constant of dry air 287,05 [J/kgK];
R_w is the gas constant of water vapour 461,5 [J/kgK].

Sensitivity for relative humidity for a measurement on a stall regulated wind turbine

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$$c_{\mathrm{RH},i} = \frac{P_i}{\rho_i T_i}\left(\frac{1}{R_0} - \frac{1}{R_w}\right)\cdot 0{,}0000205 \cdot \exp(0{,}0631846 \cdot T_i) \quad \text{(E.29)}$$

where

$c_{\mathrm{RH},i}$ is the sensitivity factor for temperature in bin i;

P_i is the sensitivity factor for wind speed in bin i;

ρ_i is the is the average air density in bin i;

T_i is the average temperature in bin i;

R_0 is the gas constant of dry air 287,05 [J/kgK];

R_w is the gas constant of water vapour 461,5 [J/kgK].

E.10.12 Category B uncertainties: Air density – Relative humidity – Calibration

This uncertainty component covers the uncertainty related to the calibration of the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{RH,cal},i}$.

The default magnitude for this uncertainty component is 1 % to 2 %.

E.10.13 Category B uncertainties: Air density – Relative humidity – Mounting

This uncertainty component covers the uncertainty related to the mounting of the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{RH,mnt},i}$.

The default magnitude for this uncertainty component is 0,1 % to 0,2 % of the measured value.

E.10.14 Category B uncertainties: Air Density – Relative humidity – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the humidity sensor.

The symbol for this uncertainty component is $u_{\mathrm{dRH},i}$.

The default magnitude for this uncertainty component is 0,1 % of the full range of the measurement channel for relative humidity.

E.10.15 Category B uncertainties: Air density – Correction

This uncertainty component covers the uncertainty related to the air density correction.

The symbol for this uncertainty component is $u_{\mathrm{AD,method},i}$.

As part of the data analysis, a normalisation from measured air density to a reference air density is performed. This normalisation is related to an uncertainty component, in part because of the uncertainties in the measured temperature, pressure and relative humidity but also because one of the underlying assumptions upon which the normalisation formula is based is increasingly inaccurate the larger the air density difference is on which the air density normalisation is applied.

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For a stall-regulated wind turbine with constant pitch and constant rotational speed, this uncertainty shall be evaluated by bin averaging the air density normalised power output and the measured power output against the wind speed at hub height. Half of the deviation of the normalised and measured power output per wind speed bin shall be considered as the standard uncertainty of the air density normalisation in that wind speed bin.

For a wind turbine with active power control, the uncertainty of the air density normalisation shall be evaluated by bin averaging the measured wind speed against the wind speed normalised for the air density. Half of the deviation of the normalised and measured wind speed shall be considered as the standard uncertainty of the air density normalisation in that wind speed bin.

In this example using a wind turbine with active power control, the wind speed deviations per wind speed bin are listed in Table E.9.

E.11 Category B uncertainties: Method

E.11.1 General

The specific method used to measure or analyse a power curve can also contribute to the uncertainty of the result. As much as possible these have been included with the category B uncertainties they are related to. Therefore the uncertainty related to the air density correction is included under air density and the uncertainty related to the flow distortion correction is included under the wind speed sensors.

However, some of the uncertainties related to the method cannot easily be attributed to a specific component and these have been grouped under the header 'Method'.

The symbol for this uncertainty component is $u_{M,i}$.

E.11.2 Category B uncertainties: Method – Wind conditions

E.11.2.1 General

Although this uncertainty is not directly discussed elsewhere in this standard, it is strongly related to the definition of the power curve as given in Clause 5 of this standard.

As per the definition the power curve according to this standard is a climate specific power curve. The wind conditions in terms of wind shear, wind veer, turbulence and upflow have a direct influence upon the power performance of a wind turbine.

As an example, let's assume that a power curve is measured for a specific set of wind conditions, namely shear = 0,1; wind veer is 10°, turbulence is 10 % and upflow is +2°. The measured power curve would then be reported together with these values and no further uncertainty needs to be introduced.

However, mostly we will not experience constant values for these parameters during a power curve measurement and during the power curve measurement each of these parameters will reflect a range of values that the turbine has been subjected to. As part of this example, let's assume that shear ranges from 0 to 0,3, wind veer from 0° to 20°, turbulence from 3 % to 20 % and upflow from 0° to 5°. As the measurement progresses, we are in fact sampling from many different power curves. As we have no control over these input variables, the next power curve measurement at the same site (be it immediately after the first measurement or a year later to catch the same part of the annual season) will be somewhat different from the first power curve measured. This is the basic argument for adding an uncertainty component related to the wind conditions.

From this perspective, we have the following considerations:

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a) If one or more of the four parameters that determine the wind conditions have not been measured, the power curve cannot be reported accurately. The uncertainty related to this can only be estimated by assuming possible values and ranges for the missing parameters and estimating the potential influence on the power performance of the turbine.

b) For the parameters that have been measured more information is available, but not necessarily all information sufficient to characterise the power performance in detail. For example:

- A parameter measured on three points across the rotor may still not give a full picture for the areas that have not been measured.
- The wind conditions (e.g. shear) are measured two to four rotor diameters away from the turbine and in most cases without further data to which extent the conditions at the measurement location reflects the conditions at the turbine location. Note that the uncertainty of the hub height wind speed correlation is considered in E.9.1.
- A similar argument goes for the horizontal dimension of the rotor; the measurement to a large extent only characterises the changes of these parameters with height (if even that) but not the horizontal variability of the measured parameters.

In the light of these arguments a practical approach has been adopted. For nine or more measurement heights for one of these parameters, the assumption has been made that no further uncertainty needs to be added. For fewer measurement heights, an additional increase in uncertainty will be added.

This means that some of the above points are not addressed at all in the current uncertainty analysis; this will be incorporated in a future revision of this standard once sufficient details have been clarified to do so.

c) If one or more of these parameters have been measured, it may be possible to normalise the power curve using this information, as explained in Annex M, Annex P and Annex Q.

The uncertainties related to points a) and b) are covered in this subclause, whereas the uncertainty related to the normalisations is covered further down.

Many of the influences here will be expressed as an uncertainty on wind speed. The experience values that the default estimates are based on are often expressed in terms of AEP. As a practical approach, the choice has been made to express this as an uncertainty through wind speed.

E.11.2.2 Category B uncertainties: Method – Wind conditions – Shear

E.11.2.2.1 General

The symbol for this uncertainty component is $u_{\mathrm{M,shear},i}$.

The default magnitude for this uncertainty component can be found in the two subclauses below.

E.11.2.2.2 Half rotor wind shear measurement coverage

This uncertainty estimation applies to a power curve with a hub height wind speed definition and without Annex P normalization. As wind turbine power curves are influenced by wind shear, the uncertainty of the measured power curve due to wind shear shall be conservatively estimated and taken into account even if no wind shear measurement is performed. For this, a wind shear correction factor according to Equation (9) and (10) in 9.1.3.3 shall be calculated under the following assumptions:

a) Assuming 20 virtual wind speed measurements equally distributed over the rotor height range, resulting in 20 weighting factors.

b) Assuming one power law for the lower rotor half and another power law for the upper rotor half. Based on these power laws, the wind speed relative to hub height shall be calculated

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for each virtual measurement height. The wind shear exponent applied for the lower rotor half shall be determined from the measurements for each 10 minute data point. The wind shear exponent for the upper rotor half shall be assumed to be half the value used for the lower rotor half. In case of negative shear values, also half of these values shall be assumed for the upper rotor half.

The standard uncertainty of the measured power curve in terms of the wind speed due to not measuring the wind shear shall be assumed for the i -th wind speed bin as:

$$u_{\mathrm{M,shear},i} = \frac{1}{\sqrt{3}} |f_r - 1| v_{\mathrm{h},i} \tag{E.30}$$

where

f_r is the wind shear correction factor as calculated in 9.1.3.3;

$v_{\mathrm{h},i}$ is the wind speed at hub height in bin i.

Examples of estimated standard uncertainties of power curve measurements in terms of the wind speed due to the absence of wind shear measurements are shown in Table E.3. The respective uncertainty increases with the rotor diameter and decreases with the hub height.

Table E.3 – Example of standard uncertainties due to absence of a wind shear measurement

H	D	$u_{\mathrm{M,shear},i} / v_{\mathrm{H}}$
[m]	[m]	[%]
60	60	3,0
60	80	3,9
100	80	2,4
120	80	2,0
100	120	3,5
150	120	2,4
Wind shear exponents of 0,5 and 0 have been assumed for the lower and upper rotor half, respectively.		

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E.11.2.2.3 Full rotor wind shear measurement coverage

This uncertainty estimation applies to:

a) a power curve with a rotor equivalent wind speed definition;

b) a hub height wind speed power curve to which the normalization in Annex P is applied.

The calculation of the rotor equivalent wind speed according to Equation (5) in 9.1.3.2 assumes a constant wind speed for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed. This uncertainty shall be estimated by fitting a power law through each pair of wind speed measurements of successive measurement heights (z_{m}). The wind speed according to this power law shall be calculated for at least 10 height levels equally distributed between each pair of measurement heights. The summation according to Equation (5) shall be repeated with all height levels covered by the power law assumption and measurement heights. The percentage deviation of the resulting rotor equivalent wind speed compared to the rotor equivalent wind speed using only the measured wind speeds shall be assumed as the (percentage) standard uncertainty of the wind speed due to the limited number of measurement heights.

The estimation of the standard uncertainty due to the limited number of measurement heights shall be performed on the basis of the bin averages of the wind speed measurements at the different height levels as function of the wind speed finally applied for the power curve evaluation.

NOTE The 10-min data sets are necessary for the calculation.

E.11.2.3 Category B uncertainties: Method – Wind conditions – Wind veer

E.11.2.3.1 General

This uncertainty component covers the uncertainty related to fewer than nine measurement heights for wind veer.

The symbol for this uncertainty component is $u_{\mathrm{M,veer},i}$.

The default magnitude for this uncertainty component can be determined using the three subclauses below.

E.11.2.3.2 No veer measurement

A wind veer correction factor according to Equation (Q.1) shall be calculated under the following assumptions:

a) Assuming wind speeds to be equal to 1 at all measurement heights. Then Equation (Q.1) transforms to a wind veer correction factor.

b) Assuming 20 virtual wind direction measurements equally distributed over the rotor height range, resulting in 20 weighting factors.

c) Assuming homogenous wind veer over the entire rotor height range as large as can be reasonably expected for the test site. If no reasonable assumptions about extreme wind veer are possible for the test site, a wind veer of 40°/100 m shall be assumed.

The standard uncertainty of the measured power curve in terms of the wind speed due to not measuring the wind veer shall be assumed for the i -th wind speed bin as:

$$u_{\mathrm{M,veer},i} = \frac{1}{\sqrt{3}} \left| f_r - 1 \right| v_{\mathrm{h},i} \tag{E.31}$$

where

f_r is the wind veer correction factor as calculated above;

$v_{\mathrm{h},i}$ is the wind speed at hub height in bin i.

Examples of power curve measurement estimated standard uncertainties in terms of the wind speed due to the absence of wind veer measurements are shown in Table E.4. The respective uncertainty increases with the rotor diameter.

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Table E.4 – Example of standard uncertainties due to absence of a wind veer measurement

D	$U_{M,veer}/\ v_h$
[m]	[%]
20	0,04
40	0,1
60	0,3
80	0,6
100	0,9
120	1,2
140	1,7
160	2,1
180	2,7
200	3,2
An extreme wind veer of 40°/100 m has been assumed for the calculations.	

E.11.2.3.3 Half rotor veer measurement

The calculation of the rotor equivalent wind speed according to Equation (Q.1) assumes a constant wind direction for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed.

The uncertainty related to a veer measurement across half a rotor shall be estimated using the same procedure as used for the veer across a full rotor (see E.11.2.3.4), with the change that the wind veer across the full rotor is 2,5 times that measured across the half rotor.

E.11.2.3.4 Full rotor veer measurement

The calculation of the rotor equivalent wind speed according to Equation (Q.1) assumes a constant wind direction for each measurement height. This assumption leads to an uncertainty of the evaluation of the rotor equivalent wind speed. This uncertainty shall be estimated by assuming a linear increase of the wind veer between each pair of wind speed measurements of successive measurement heights. The wind speed according to this assumption shall be calculated for at least 10 height levels equally distributed between each pair of measurement heights. The summation according to Equation (Q.1) shall be repeated with all height levels covered by the wind veer profile assumption and measurement heights and by assuming a constant wind speed for all heights. The percentage deviation of the resulting rotor equivalent wind speed to the rotor equivalent wind speed using only the measured wind directions, shall be assumed as (percentage) standard uncertainty of the wind speed due to the limited number of wind direction measurement heights.

The estimation of the uncertainty due to the limited number of wind direction measurement heights shall be performed on the basis of the bin averages of the wind direction measurements at the different height levels as function of the wind speed finally applied for the power curve evaluation.

NOTE The 10-min data sets are necessary for the calculation.

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E.11.2.4 Category B uncertainties: Method – Wind conditions – Upflow

This uncertainty component covers the uncertainty related to fewer than nine measurement heights for upflow. This uncertainty component shall be applied for sites that do not meet the requirements of Annex B.

The symbol for this uncertainty component is $u_{\mathrm{M,upflow},i}$.

The default magnitude for this uncertainty component can be found in Table E.5.

Table E.5 – Uncertainty contributions due to lack of upflow knowledge

Number of measurement heights	[% of wind speed]
0 (no upflow measurement)	0,3 to 0,5
1 (at hub height only)	0,15 to 0,25
2 (lower rotor area)	0,08 to 0,12
3	0,03 to 0,07
5	0,015 to 0,025
7	0,005 to 0,015

Please note that this is a very different uncertainty component for upflow than is considered in the classification of the wind speed sensor where also upflow is included. In that case we are looking at the inaccurate measurement of the horizontal wind speed due to the presence of a vertical wind speed component. Here we consider the influence of the upflow on the turbine's performance. Although we define a horizontal wind speed, the turbine's performance still varies when a vertical component is present.

E.11.2.5 Category B uncertainties: Method – Wind conditions – Turbulence intensity

This uncertainty component covers the uncertainty related to not having a measurement for hub height turbulence.

The symbol for this uncertainty component is $u_{\mathrm{M,ti},i}$.

For turbulence we do not consider other measurement heights as Clause 5 of this standard defined the power curve only for hub height turbulence. This is a required signal. The reason this is still included as an additional uncertainty components is that the measurement configuration with a lower-than-hub height meteorological mast only has a hub height turbulence measured by a remote sensing device. The turbulence as measured by a remote sensing device is significantly different from the turbulence as measured by a sonic or cup anemometer. Hence the additional uncertainty.

The default magnitude for this uncertainty component can be found in Table E.6.

Table E.6 – Uncertainty contributions due to lack of turbulence knowledge

Number of measurement heights	[% of wind speed]
0 (no accurate TI due to RSD)	0,3 % to 0,5 %

E.11.3 Category B uncertainties: Method – Seasonal effects

This uncertainty component covers the uncertainty related to the influence of seasonal effects on the power curve. Note that some seasonal variations contribute in the wind speed

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uncertainty as they influence the wind profile characteristics (shear, turbulence, etc.). These variations are treated separately.

Some other contributions, such as blade accretion from bugs and/or dirt on the blades (e.g. during a warm and dry period), increase the blade surface roughness and deteriorate the blade aerodynamic performance. Therefore, for the same kinetic energy in the wind, the turbine production will be lower when blades are dirty. These contributions are combined in the uncertainty component $u_{\mathrm{M,sfx},i}$.

Clearly, these contributions do not influence the wind profile characteristics and therefore, strictly speaking, are effects on the electrical power. However, with the purpose to quantify the contribution to the AEP variation, this uncertainty component is more conveniently expressed as uncertainty in the wind speed.

A default magnitude of 0,7 % on the wind speed is suggested, yet the magnitude of this component will vary with the site location and the year period of the performance test and where possible it should be estimated from experience or AEP variation data from the specific site.

E.11.4 Category B uncertainties: Method – Turbulence normalisation (or the lack thereof)

This uncertainty component covers the uncertainty related to the turbulence normalisation of the power curve

The symbol for this uncertainty component is $u_{\mathrm{M,tinorm},i}$.

This uncertainty is also discussed in Annex M and 9.1.6.

The turbulence normalisation given in Annex M is designed to handle effects of the 10 min data averaging on the evaluated power curve. There are further effects of the turbulence intensity on wind turbine power curves, which could, for instance, be due to direct impact of the turbulence intensity on the aerodynamics or due to the 3-dimensional character of turbulence. In the end, the turbulence intensity normalisation is a strongly simplified approach for characterising short term wind speed fluctuations. Thus, there is a remaining uncertainty of the evaluated power curve due to possible turbulence effects, even if the turbulence normalisation procedure is applied. The turbulence normalisation often removes about half of the observed effect of the turbulence intensity on measured wind turbine power curves. Thus, the following steps should be performed in order to calculate the uncertainty of the turbulence normalisation:

a) The final bin-averaged power curve shall be evaluated on the basis of the turbulence normalised power output and on the basis of the non-turbulence normalised power output.

b) the deviation of these two power curves shall be assumed to be the maximum uncertainty of the turbulence-normalised power curve per wind speed bin resulting from the turbulence normalisation. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the power curves divided by $\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties of the power performance measurement for the determination of the total standard uncertainty according to Annex D.

In the absence of turbulence normalisation, the uncertainty due to turbulence effects on the power curve should be calculated as described in Clause M.5.

E.11.5 Category B uncertainties: Method – Cold climate

This uncertainty component covers the uncertainty related to the influence of measurement in cold climate on the classification of the anemometers.

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The symbol for this uncertainty component is $u_{M,cc,i}$.

This uncertainty is also discussed in Annex O of this standard.

If an extended temperature range is required, the uncertainty component for the sensor classification shall be based on a class S classification report; this is covered by the uncertainty component $u_{VS,class,i}$.

Although ice detection is recommended, it cannot be avoided that snow and ice will accrete on the mounting structure and thus influence the measured wind speed. This aspect is covered by the uncertainty component as discussed here.

Please note that these considerations already should be considered for 'normal' class B measurements, as class B extends to –10 °C and most snow and ice occurs around 0 °C. If a measurement is exposed to more than a few days of snow and/or ice, this additional uncertainty component shall be applied. Otherwise this components can be set to zero.

The default magnitude of this uncertainty component is 0,5 % to 1 % on wind speed.

E.12 Category B uncertainties: Wind direction

E.12.1 General

There is an influence of the wind direction uncertainty on the power curve through the site calibration as well as a smaller effect. Based on the magnitude of the wind direction uncertainty compared to the site calibration bin size, some data will be incorrectly assigned to a bin. For a bin size of 10° and a wind direction uncertainty of 5°, roughly 39 % of the data in a bin has been wrongly assigned. Although this will tend to average out, it can have an effect for small measurement sectors and large differences between adjacent bins. A similar argument goes for the filtering on the power curve measurement sector, but to a lesser extent.

These uncertainties shall only apply if the wind direction sensor or its mounting is changed for sites on which a site calibration was performed.

This background is the main reason why the standard requires that the wind direction uncertainty is assessed to ensure that it stays below 5°.

The influence from the wind direction on the power curve and AEP is not quantifiably established and no sensitivity factors have been developed.

As the wind direction uncertainty shall be reported, Clause E.12 gives the minimum uncertainty components that shall be considered for the wind direction uncertainty. An estimate of the magnitude of these components is not given, but shall be included for a reported power curve.

E.12.2 Category B uncertainties: Wind direction – Vane or sonic

E.12.2.1 Category B uncertainties: Wind direction – Vane or sonic – Calibration

This uncertainty component covers the uncertainty related to the calibration of the wind direction sensor.

The symbol for this uncertainty component is $u_{WV,cal,i}$.

The resolution of the wind direction sensor is also included here and this value divided by $2\sqrt{3}$ shall be taken as a minimum value.

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No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.2 Category B uncertainties: Wind direction – Vane or sonic – North mark

This uncertainty component covers the uncertainty related to the accurate determination of the sensors north mark in relation to the boom on which the sensor is installed.

The symbol for this uncertainty component is $u_{\mathrm{WV,nm},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.3 Category B uncertainties: Wind direction – Vane or sonic – Boom orientation

This uncertainty component covers the uncertainty related to establishing the direction of the boom with regards to the North reference, i.e. magnetic or true.

The symbol for this uncertainty component is $u_{\mathrm{WV,bo},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.4 Category B uncertainties: Wind direction – Vane or sonic – Operational effects

This uncertainty component covers the uncertainty related to the influence of the mast on the free stream wind direction at the point of measurement.

The symbol for this uncertainty component is $u_{\mathrm{WV,oe},i}$.

As the wind will flow around the mast, the wind direction as measured by the sensor may not be the free flow wind direction. This effect is covered under this uncertainty component.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.5 Category B uncertainties: Wind direction – Vane or sonic – Magnetic declination angle

This uncertainty component covers the uncertainty related to the difference between magnetic north and true north.

The symbol for this uncertainty component is $u_{\mathrm{WV,mda},i}$ (MDA stands for magnetic declination angle).

The correction from magnetic north to true north is also related to an uncertainty.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.2.6 Category B uncertainties: Wind direction – Vane or sonic – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the wind direction sensor.

The symbol for this uncertainty component is $u_{\mathrm{dWV},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

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E.12.3 Category B uncertainties: Wind direction – RSD

E.12.3.1 Category B uncertainties: Wind direction – RSD – Verification

This uncertainty component covers the uncertainty related to the verification of the wind direction sensor.

The symbol for this uncertainty component is $u_{\mathrm{WR,ver},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.2 Category B uncertainties: Wind direction – RSD – Monitoring

This uncertainty component covers the uncertainty related to the data acquisition of the signal from the wind direction monitoring by the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{WR,mon},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.3 Category B uncertainties: Wind direction – RSD – Flow variation

This uncertainty component covers the uncertainty related to the flow variation in different probe volumes.

The symbol for this uncertainty component is $u_{\mathrm{WR,fv},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.4 Category B uncertainties: Wind direction – RSD – Alignment

This uncertainty component covers the uncertainty related to accuracy of the alignment of the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{WR,align},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.5 Category B uncertainties: Wind direction – RSD – Magnetic declination angle

This uncertainty component covers the uncertainty related to the correction from magnetic north to true north.

The symbol for this uncertainty component is $u_{\mathrm{WR,mda},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

E.12.3.6 Category B uncertainties: Wind direction – RSD – Data acquisition

This uncertainty component covers the uncertainty related to the data acquisition of the signal of the RSD device.

The symbol for this uncertainty component is $u_{\mathrm{dWR},i}$.

No default value is given but this uncertainty component shall be assessed and reported.

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E.13 Combining uncertainties

E.13.1 General

In Clause E.13, the equations and further considerations to combine uncertainty components to an aggregate level will be presented and discussed. An example is the calculation of the site calibration uncertainty based on the uncertainty components of the site calibration uncertainty.

E.13.2 Combining Category B uncertainties in electric power ($u_{P,i}$)

The standard uncertainty of the electric power for each bin, $u_{P,i}$, is calculated by combining the standard uncertainties from the power transducer, the current and voltage transformers and the data acquisition system:

$$u_{P,i} = \sqrt{u_{P,CT,i}^2 + u_{P,VT,i}^2 + u_{P,PT,i}^2 + u_{dP,i}^2} \quad \text{(E.32)}$$

where

$u_{P,i}$ is the uncertainty on the power measurement;

$u_{P,CT,i}$ is the uncertainty related to the current transformers;

$u_{P,VT,i}$ is the uncertainty related to the voltage transformers;

$u_{P,PT,i}$ is the uncertainty related to the power transducers;

$u_{dP,i}$ is the uncertainty related to the data acquisition of the power signal.

Considering the default magnitudes for these uncertainty components as given in Clause E.5 the standard uncertainty from the electric power sensor for each bin is:

$$\begin{aligned} u_{P,i} &= \sqrt{(0{,}43\% \cdot P_i[\text{kW}])^2 + (0{,}29\% P_i[\text{kW}])^2 + (7{,}2\text{kW})^2 + (0{,}1\% \cdot 3\,000\,\text{kW})^2} \\ &= \sqrt{(0{,}53\% \cdot P_i[\text{kW}])^2 + (7{,}8\,\text{kW})^2} \end{aligned} \quad \text{(E.33)}$$

E.13.3 Combining uncertainties in the wind speed measurement ($u_{V,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed, $u_{V,i}$:

$$u_{V,i} = \sqrt{u_{VHW,i}^2 + u_{VT,i}^2 + u^2{}_{AD,method,i}} \quad \text{(E.34)}$$

where

$u_{VHW,i}$ is the uncertainty on the hardware used and is one of $u_{VS,i}$, $u_{VR,i}$ or $u_{REWS,I}$;

$u_{VT,i}$ is the uncertainty related to the flow distortion from the terrain;

$u_{AD,method,i}$ is the uncertainty related to the air density correction.

E.13.4 Combining uncertainties in the wind speed measurement from cup or sonic ($u_{VS,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from cup or sonic, $u_{VS,i}$:

$$u_{VS,i} = \sqrt{u_{VS,precal,i}^2 + u_{VS,postcal,i}^2 + u_{VS,class,i}^2 + u_{VS,mnt,i}^2 + u_{VS,lgt,i}^2 + u_{dVS,i}^2} \quad \text{(E.35)}$$

where

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$u_{VS,precal,i}$ is the uncertainty related to the calibration of the sensor before the start of the power performance test;

$u_{VS,postcal,i}$ is the uncertainty related to the calibration of the sensor during or after the power performance test;

$u_{VS,class,i}$ is the uncertainty related to the classification of the sensors;

$u_{VS,mnt,i}$ is the uncertainty related to the mounting of the sensors;

$u_{VS,lgt,i}$ is the uncertainty related to the flow distortion from lighting finial;

$u_{dVS,i}$ is the uncertainty related to the data acquisition of the wind speed signal.

E.13.5 Combining uncertainties in the wind speed measurement from RSD ($u_{VR,i}$)

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from an RSD device, $u_{VR,i}$:

$$u_{VR,i} = \sqrt{u^2_{VR,ver,i} + u^2_{VR,isc,i} + u^2_{VR,class,i} + u^2_{VR,mnt,i} + u^2_{VR,flow,i} + u^2_{VR,mon,i}} \quad \text{(E.36)}$$

where

$u_{VR,ver,i}$ is the uncertainty due to the verification test;

$u_{VR,isc,i}$ is the uncertainty due to the in-situ test;

$u_{VR,class,i}$ is the uncertainty related to the classification of the RSD;

$u_{VR,mnt,i}$ is the uncertainty related to the mounting of the RSD;

$u_{VR,flow,i}$ is the uncertainty related to the flow variation across the measurement volume of the RSD;

$u_{VR,mon,i}$ is the uncertainty related to the monitoring of the RSD.

E.13.6 Combining uncertainties in the wind speed measurement from REWS $u_{REWS,i}$

The following uncertainty components are combined to calculate the category B uncertainty for a wind speed measurements expressed as a rotor equivalent wind speed, $u_{REWS,i}$:

$$u_{REWS,i} = \sqrt{u^2_{REWS,shear,i} + u^2_{REWS,veer,i}} \quad \text{(E.37)}$$

where

$u_{REWS,i}$ is the uncertainty of the rotor equivalent wind speed (REWS);

$u_{REWS,shear,i}$ is the uncertainty due to the influence on REWS from the shear measurement across the rotor;

$u_{REWS,veer,i}$ is the uncertainty due to the influence on REWS from the veer measurement across the rotor.

The value of $u_{REWS,shear,i}$ is taken from one of the following:

– $u_{veq,i}$ (from E.13.7),
– $u_{veq,final,i}$ (from E.13.8),
– or determined through $u_{fr,RSD,k,i}$ (from E.13.9).

The value of $u_{REWS,veer,i}$ is taken from $u_{veq,i}$ (from E.13.10).

The wind speed uncertainty components that are included in the REWS uncertainty are based on Equation (5) of 9.1.3.2 or Equation (11) of section 9.1.3.4. Equation (6) in 9.1.3.2 (which would also influence Equation (11)) implies that there is an uncertainty component related to establishing the correct measurement height. As this is considered to be insignificant for a meteorological mast measurement and is included in a LIDAR calibration as per Annex L, the only concern is with SODAR measurements especially for higher wind speeds when 'beam

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bending' may occur. In case this is experienced during a measurement this shall be included as a further uncertainty component.

E.13.7 Combining uncertainties in the wind speed measurement for REWS for either a meteorological mast significantly above hub height or an RSD with a lower-than-hub-height meteorological mast

The following uncertainty components are combined to calculate the category B uncertainty for wind speed measurements from an RSD device.

The rotor equivalent wind speed shall be considered as a single wind speed measurement. The total standard uncertainty of the rotor equivalent wind speed in the wind speed bin i can then be expressed by:

$$u^2_{v_{\mathrm{eq}},i} = \sum_{k=1}^{M}\sum_{l=1}^{M} u_{v_{\mathrm{eq}},k,i}\, u_{v_{\mathrm{eq}},l,i}\, \rho_{k,l,i} \tag{E.38}$$

where

M is the number of uncertainty components of v_{eq};

i is the wind speed bin referring to bin averaging of power curve;

$u_{v_{\mathrm{eq}},k,i}$ is the standard uncertainty sub-component k of v_{eq} in wind speed bin i;

$u_{v_{\mathrm{eq}},l,i}$ is the standard uncertainty sub-component l of v_{eq} in wind speed bin i;

$\rho_{k,l,i}$ is the correlation coefficient between the uncertainty component k height m and n in wind speed bin i.

Please note that the sensitivity factors are expressly not included here as they are included in the equation below.

The uncertainty components of v_{eq} in wind speed bin i shall be calculated from the uncertainty components of the wind speed measurements in single measurement heights by the method of error propagation:

$$u^2_{v_{\mathrm{eq}},k,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{m,i}\, u_{v_m,k,i}\, c_{n,i}\, u_{v_n,k,i}\, \rho_{m,n,k,i} \tag{E.39}$$

where

L is the number of measurement heights across the rotor;

$u_{v_m,k,i}$ is the standard uncertainty sub-component k of wind speed measurement at height m in wind speed bin i;

$u_{v_n,k,i}$ is the standard uncertainty sub-component k of wind speed measurement at height n in wind speed bin i;

$c_{m,i}$ is the sensitivity factor of v_{eq} on wind speed at height m in wind speed bin i;

$c_{n,i}$ is the sensitivity factor of v_{eq} on wind speed at height n in wind speed bin i;

$\rho_{m,n,k,i}$ is the correlation coefficient between the uncertainty component k height m and n in wind speed bin i.

The sensitivity factors $c_{m,i}$ and $c_{n,i}$ are gained from the definition of the rotor equivalent wind speed by error propagation as:

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$$c_{m,i} = \frac{\partial v_{\mathrm{eq},i}}{\partial v_{m,i}} = \frac{A_m}{A}\left(\frac{v_{m,i}}{v_{\mathrm{eq},i}}\right)^2 \tag{E.40}$$

where

A_m is the rotor segment attributed to wind speed measurement at height m according to Equation (6) in 9.1.3.2;

A is the rotor swept area;

$v_{m,i}$ is the wind speed at height m in wind speed bin i;

$v_{\mathrm{eq},i}$ is the equivalent wind speed in bin i.

For the application of Equation (E.40), the wind speed measured at the different measurement heights $v_{m,i}$ shall be bin averaged as function of the wind speed finally applied for the power curve evaluation (air density normalised and wind shear corrected wind speed).

Equation (E.39) in combination with Equation (E.40) simplifies if either full correlation or no correlation between the uncertainty components at different measurement heights is assumed. The correlation coefficients suggested in Table E.7 should be applied for the calculation of the uncertainties of v_{eq}. Lower correlation coefficients shall be used only if they are evident.

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Table E.7 – Suggested assumptions for correlations of measurement uncertainties between different measurement heights[26]

Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
Wind shear measurement by cup anemometers		
Wind tunnel calibration	1	Calibration in same wind tunnel is required; high correlation of uncertainties of calibrations of different cup anemometers
Cup anemometer classification	1	Anemometers at different heights measure under very similar climatic conditions
Cup anemometer mounting	1, 0	1, if boom mounted and same boom configuration; 0, if one anemometer top mounted and the other boom mounted
Data acquisition system	0	Different input channels applied
Site effects due to distance between the reference meteorological mast and the test wind turbine	1	As a first approximation, the site effects may be assumed to be identical for the rotor height range.
Uncertainty due to limited number of measurements over rotor height range	1	To a first approximation, this uncertainty is fully correlated between the measurement heights
Wind shear measurement by remote sensing device		
Verification test	1	Normally, very similar conditions of reference sensors at different heights present. Sensitivity of accuracy of remote sensing device on measurement height may be ignored.
Sensitivity analysis / classification	1	Classification performed under very similar conditions at different heights. Dependency of sensitivity of remote sensing device on environmental conditions on measurement height may be ignored.
Uncertainty resulting from control with meteorological mast	1	Same uncertainty assumed for all heights
Uncertainty due to flow variation in different probe volumes at same height	1	Normally, quite similar effect expected at different measurement heights. Sensitivity of error on measurement height may be ignored.
Mounting	1	Similar effect of system mounting in different measurement heights
Site effects due to distance between the measurement and the test wind turbine	1	As a first approximation, the site effects may be assumed to be identical for the rotor height range.
Uncertainty due to limited number of measurements over rotor height range	1	To a first approximation, this uncertainty is fully correlated between the measurement heights

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26 An additional uncertainty of the determination of the wind speed results from the air density normalisation. This component is produced after the rotor averaging of wind speeds and must be added for the final evaluation of wind speed uncertainties.

NOTE If one assumes that for all components the correlation coefficient is equal to 1 and all components for each height is the same, this procedure simplifies to the extent that the uncertainty calculation can be done as described in Clause E.6 using $v_{\mathrm{eq},i}$ instead of v_i. For fixed values (such as the calibration), this value can be used for $v_{\mathrm{eq}} v_{\mathrm{eq},i}$.

E.13.8 Combining uncertainties in the wind speed measurement for REWS for a hub height meteorological mast + RSD for shear using an absolute wind speed

The uncertainty of the wind speed measurement at hub height by means of a cup or sonic anemometer and the uncertainty of the wind shear measurement by the remote sensing device can be considered as being independent from each other. Error propagation on Equation (11) of 9.1.3.4 leads then to the following equation for the uncertainty of the final rotor equivalent wind speed:

$$u^2_{v_{\mathrm{eq}},\mathrm{final},i} = f^2_{r,X,i} u^2_{v_h,i} + v^2_{h,i} u^2_{f_{r,X},i} \tag{E.41}$$

where

$u_{v_{\mathrm{eq}},\mathrm{final},i}$ is the standard uncertainty of final rotor equivalent wind speed in bin i;

$f_{r,X,i}$ is the wind shear correction factor in wind speed bin i;

$v_{h,i}$ is the wind speed measured at hub height in bin i by cup or sonic anemometer

u_{v_h},i is the standard uncertainty of $v_{h,i}$ in wind speed bin i;

$u_{f_{r,X}},i$ is the standard uncertainty of $f_{r,X,i}$ in wind speed bin i.

The uncertainty of the wind shear correction factor is (error propagation on Equation (9) and (10) of 9.1.3.3):

$$u^2_{f_{r,X},i} = \frac{1}{v^2_{h,X,i}} u^2_{v_{\mathrm{eq},X},i} + \frac{v^2_{\mathrm{eq},X,i}}{v^4_{h,X,i}} u^2_{v_{h,X},i} - 2\frac{v_{\mathrm{eq},X,i}}{v^3_{h,X,i}} u_{v_{\mathrm{eq},X},i} u_{v_{h,X},i} \rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},i} \tag{E.42}$$

where

$v_{h,X,i}$ is the wind speed measured by remote sensing device in bin i;

$u_{v_{h,X}},i$ is the standard uncertainty of $v_{h,X,i}$;

$v_{\mathrm{eq},X,i}$ is the rotor equivalent wind speed as measured with the remote sensing device in bin i;

$u_{v_{\mathrm{eq},X}},i$ is the standard uncertainty of $v_{\mathrm{eq},X,i}$ in bin i;

$\rho_{u_{v_{\mathrm{eq}}},u_{v_{h,X}},i}$ is the correlation coefficient between uncertainty components $u_{v_{\mathrm{eq},X},i}$ and $u_{v_{h,X},i}$ in bin i.

Considering that $v_{\mathrm{eq},X,i}$ and $v_{h,X,i}$ both have the same types of uncertainty sub components as given in Table E.7 and assuming that these sub components are independent from each other, Equation (E.42) is equal to:

$$u^2_{f_{r,X},i} = \sum_{k=1}^{M} \frac{1}{v^2_{h.X.i}} u^2_{v_{\mathrm{eq},X},k,i} + \frac{v^2_{\mathrm{eq},X,i}}{v^4_{h,X,i}} u^2_{v_{h,X},k,i} - 2\frac{v_{\mathrm{eq},X,i}}{v^3_{h,X,i}} u_{v_{\mathrm{eq},X},k,i} u_{v_{h,X},k,i} \rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i} \tag{E.43}$$

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where

$u_{v_{\mathrm{eq},X},k,i}$ is the standard uncertainty component k of rotor equivalent wind speed as measured with the remote sensing device in bin i, to be analysed according to Equation (E.39);

$u_{v_{h,X},k,i}$ is the standard uncertainty component k of hub height wind speed as measured with the remote sensing device in bin i;

$\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}$ is the correlation coefficient between standard uncertainty components $u_{v_{\mathrm{eq},X},k,i}$ and $u_{v_{h,X},k,i}$ in bin i;

M is the number of uncertainty components of $v_{\mathrm{eq},X}$ and $v_{h,X}$.

For the application of Equation (E.43), $v_{h,X,i}$ and $v_{\mathrm{eq},X,i}$ are gained from bin averaging the rotor equivalent wind speed and the hub height wind speed measured by the remote sensing device as function of the wind speed finally applied for the power curve evaluation (air density and wind shear normalised wind speed). The correlation coefficients between the standard uncertainty components of the rotor equivalent wind speed and the hub height wind speed measured by the remote sensing device $\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}$ shall be estimated from the results of the verification test and sensitivity test/classification of the remote sensing device. In some cases, the assumption of correlation coefficients close to 1 can be justifiable.

Equation (E.43) in combination with Equation (E.41) and Equation (E.39) allows evaluating all standard uncertainty components of the final rotor equivalent wind speed. These sub components shall be implemented in Equations (E.3) and (E.4).

According to Equation (E.41), the total uncertainty of the final rotor equivalent wind speed is larger than the uncertainty of the wind speed measured at hub height by the cup or sonic anemometer (at least as soon as the wind shear correction factor exceeds 1). The uncertainty is increased due to the uncertainty of the wind shear correction factor. According to Equation (E.43), this additional uncertainty vanishes if the uncertainties of the rotor equivalent wind speed and the wind speed measured at hub height by the remote sensing device are fully correlated ($\rho_{u_{v_{\mathrm{eq},X}},u_{v_{h,X}},k,i}=1$) and if the rotor equivalent wind speed is equal to the wind speed at hub height measured by the remote sensing device.

NOTE Assuming all correlation coefficients are equal to 1 and $u_{v_{\mathrm{eq},X},k,i}$ is equal to $u_{v_{h,X},k,i}$ (see E.13.7) the equation for $u^2_{f_{r,X},i}$ simplifies as follows:

$$u_{f_{r,X},i} = \left(\frac{v_{h,X,i} - v_{\mathrm{eq},X,i}}{v^2_{h,X,i}}\right) \sqrt{\sum_{k=1}^{M} u^2_{v_{h,X},k,i}} \qquad \text{(E.44)}$$

where

$v_{h,X,i}$ is the wind speed measured by remote sensing device in bin i;

$u_{vh,X,k,i}$ is the standard uncertainty of component k of either $v_{h,X,i}$ or $v_{\mathrm{eq},X,i}$;

$v_{\mathrm{eq},X,i}$ is the rotor equivalent wind speed as measured with the remote sensing device in bin i.

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E.13.9 Combining uncertainties in the wind speed measurement for REWS for a hub height meteorological mast and RSD for shear using a relative wind speed

A sensitivity analysis and verification test of the remote sensing device for wind shear measurements instead of for absolute wind speed measurements may be available. This means that the accuracy of the remote sensing device in terms of wind shear measurements is verified by the verification test, and that the sensitivity of the wind shear measurement on environmental variables is tested for the classification of the remote sensing device. If such a sensitivity analysis and verification test of the remote sensing device is present, it is useful for the evaluation of uncertainties to introduce a relative wind speed measurement as performed by the remote sensing device:

$$v_{r,\mathrm{RSD},m} = \frac{v_{m,\mathrm{RSD}}}{v_{h,\mathrm{RSD}}} \tag{E.45}$$

where

$v_{r,\mathrm{RSD},m}$ is the relative wind speed measured by remote sensing device at m -th height relative to hub height wind speed measured by remote sensing device;

$v_{h,\mathrm{RSD}}$ is the wind speed measured by remote sensing device at hub height;

$v_{m,\mathrm{RSD}}$ is the wind speed measured by remote sensing device at m-th height.

The wind shear correction factor as defined in Equation (9) in 9.1.3.3 can then be rewritten as

$$f_{r,\mathrm{RSD}} = \left(\sum_{m=1}^{L} \frac{A_m}{A} v_{r,\mathrm{RSD},m}^3 \right)^{\frac{1}{3}} \tag{E.46}$$

where

A_m is the rotor segment attributed to wind speed measurement at m-th height according to Equation (5) in 9.1.3.2;

A is the rotor swept area;

L is the number of measurement heights in the height area of the rotor.

Equation (E.41) can then be applied for assessing the uncertainty of the final rotor equivalent wind speed with the uncertainty components of the wind shear correction factor in wind speed bin i gained from:

$$u^2_{f_{r,\mathrm{RSD}},k,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{v_{r,\mathrm{RSD}},m,i} u_{v_{r,\mathrm{RSD}},m,k,i} c_{v_{r,\mathrm{RSD}},n,i} u_{v\mathrm{RSD},n,k,i} \rho_{r,m,n,k,i} \tag{E.47}$$

where

L is the number of measurement heights in the height area of the rotor;

$u_{v_{r,\mathrm{RSD}},m,k,i}$ is the standard uncertainty component k of relative wind speed measurement at m-th height in wind speed bin i;

$u_{v_{r,\mathrm{RSD}},n,k,i}$ is the standard uncertainty component k of relative wind speed measurement at n-th height in wind speed bin i;

$c_{v_{r,\mathrm{RSD}},m,i}$ is the sensitivity factor of $f_{r,\mathrm{RSD}}$ on relative wind speed at m-th height in wind speed bin i;

$c_{v_{r,\mathrm{RSD}},n,i}$ is the sensitivity factor of $f_{r,\mathrm{RSD}}$ on relative wind speed at n-th height in wind speed bin i.

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The sensitivity factors $c_{v_{r,\mathrm{RSD},m,i}}$ and $c_{v_{r,\mathrm{RSD},n,i}}$ are:

$$c_{v_{r,\mathrm{RSD},m,i}} = \frac{\partial f_{r,\mathrm{RSD},i}}{\partial v_{r,\mathrm{RSD},m,i}} = \frac{A_m}{A}\left(\frac{v_{r,\mathrm{RSD},m,i}}{f_{r,\mathrm{RSD},i}}\right)^2 \tag{E.48}$$

The same uncertainty components as given in Table E.7 shall be applied, but in terms of the remote sensing device relative wind speed measurements rather than in terms of absolute wind speed measurements. In addition, the same correlation coefficients of uncertainty components between two measurement heights as shown in Table E.7 shall be assumed for the relative wind speed measurements, unless evidence exists that other values are present.

The wind speed measured at hub height by the cup or sonic anemometer v_h, the wind shear correction factor $f_{r,\mathrm{RSD}}$ and the relative wind speeds $v_{r,\mathrm{RSD}}$ measured by the remote sensing device shall be bin averaged against the final wind speed applied for the power curve evaluation for the application of Equations (E.41), (E.47) and (E.48) (wind shear corrected and air density normalised wind speed).

E.13.10 Combining uncertainties in the wind speed measurement from REWS due to wind veer across the whole rotor $u_{\mathrm{REWS,veer},i}$

The rotor equivalent wind speed (taking consideration wind veer according to Annex Q) is dependent on wind speeds and wind directions across the rotor height range. Often, the uncertainties of wind direction and wind speed measurements can be considered as being independent from each other. Then Equation (E.38) in E.13.7 transforms to:

$$u^2_{v_{\mathrm{eq}},i} = \sum_{k=1}^{M} u^2_{v_{\mathrm{eq}},k,i} + \sum_{l=1}^{N} u^2_{v_{\mathrm{eq}},l,i} \tag{E.49}$$

where

M is the number of uncertainty sub-components of v_{eq} related to wind speed measurements;

i is the wind speed bin referring to bin averaging of power curve;

$u_{v_{\mathrm{eq}},k,i}$ is the standard uncertainty sub-component k of v_{eq} related to wind speed measurements in wind speed bin i;

N is the number of uncertainty sub-components of v_{eq} related to wind direction measurements;

$u_{v_{\mathrm{eq}},l,i}$ is the standard uncertainty sub-component l of v_{eq} related to wind direction measurements in wind speed bin i.

The left term in this equation covers all wind speed measurement uncertainties of the rotor equivalent wind speed and shall be treated according to Clause E.8, while the sensitivity factors given in Equations (E.39) and (E.49) shall be multiplied by the third power of $\cos(\phi_m)$, where m is the wind direction difference to hub height at the m^{th} measurement height. This factor shall also be introduced in Equation (E.46) for the definition of the wind shear correction factor.

The right term in this Equation (E.49) covers all wind direction measurement uncertainties of the rotor equivalent wind speed. As is explained in E.8.1, a difficulty in assessing this uncertainty is related to the fact that the uncertainties of the wind direction measurements at the different height levels are correlated with each other. Similar to Equation (E.39), the sub wind direction uncertainty components of v_{eq} in wind speed bin i shall be calculated from the uncertainty components of the wind direction measurements in single measurement heights by the method of error propagation:

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$$u^2_{v_{\mathrm{eq}},l,i} = \sum_{m=1}^{L}\sum_{n=1}^{L} c_{m,i}u_{v_m,l,i}c_{n,i}u_{v_n,l,i}\rho_{m,n,l,i} \tag{E.50}$$

where

L is the number of measurement heights in the height area of the rotor;

$u_{v_m,l,i}$ is the standard uncertainty sub-component l of wind direction measurement at m-th height relative to hub height in wind speed bin i;

$u_{v_n,l,i}$ is the standard uncertainty sub-component l of wind direction measurement at n-th height relative to hub height in wind speed bin i;

$c_{m,i}$ is the sensitivity factor of v_{eq} on wind direction at height m relative to hub height in wind speed bin i;

$c_{n,i}$ is the sensitivity factor of v_{eq} on wind direction at height n relative to hub height in wind speed bin i;

$\rho_{m,n,l,i}$ is the correlation coefficient between standard uncertainty component l of wind direction measurement at height m and height n relative to hub height in wind speed bin i (wind speed bin referring to the power curve).

The sensitivity factors $c_{m,i}$ and $c_{n,i}$ are gained from the definition of the rotor equivalent wind speed by consideration of wind veer by error propagation as:

$$c_{m,i} = \frac{\partial v_{\mathrm{eq},i}}{\partial \varphi_{m,i}} = -\sin(\varphi_{m,i})\cos^2(\varphi_{m,i})\frac{A_m}{A}\frac{v^3_{m,i}}{v^2_{\mathrm{eq},i}} \tag{E. 51}$$

where

A_m is the rotor segment attributed to wind speed measurement at m-th height according to Equation (5) in 9.1.3.2;

A is the rotor swept area;

$\varphi_{m,i}$ is the wind direction at m-th height relative to wind direction at hub height in wind speed bin i;

$v_{m,i}$ is the wind speed at height m in wind speed bin i;

$v_{\mathrm{eq},i}$ is the equivalent wind speed in bin i.

For the application of Equation (E.40), the relative wind directions $\Phi_{m,i}$ and wind speeds $v_{m,i}$ measured at the different measurement heights shall be bin averaged as function of the wind speed finally applied for the power curve evaluation (air density normalised, wind shear and wind veer corrected wind speed).

Equation (E.50) in combination with Equation (E.51) simplifies if full correlation, no correlation or anti-correlation between the uncertainty components at different measurement heights is assumed. The correlation coefficients suggested in Table E.8 shall be applied for the calculation of the uncertainties in terms of wind direction of v_{eq}. Lower correlation coefficients shall be used only if they are evident and relevant data is reported.

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Table E.8 – Suggested correlation assumptions for relative wind direction measurement uncertainties at different measurement heights

Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
Relative wind direction measurement by vanes or sonic anemometers		
Wind tunnel calibration of vanes used at height m, n and hub height	0,5	The uncertainty of the calibration of single vanes is basically correlated. But as the wind direction differences relative to hub height at heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Influence of met mast on wind direction measurements at heights m,n and hub height	0,5; 1	If the vanes at the two heights m and n are mounted in the same wat relative to the same mast structure, the uncertainties are fully correlated across the two heights m and n. However, the uncertainty itself gets 0 if the vane at hub height is also influenced in the same way by the met mast. If the vanes at the two heights m and n are mounted different relative to the mast structure, or if the mast structure differs much at two heights m and n, the uncertainties and these two heights can be considered as being uncorrelated. But as the wind direction difference relative to hub height at the two heights m and n includes the direction measurement at hub height, a correlation coefficient of 0,5 is suggested for this case.
Northing of wind direction measurement at height m, n and hub height	0,5	The uncertainty of the northing of single vanes is basically uncorrelated. But as the wind direction relative to hub height at the two heights m and n includes the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Data acquisition system (DAS) used to monitor the vanes at height m,n and hub height	0,5	The uncertainty of the DAS channels of single vanes is often basically uncorrelated. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested.
Relative wind direction measurement by remote sensing device		
Wind tunnel calibration of reference vanes used for verification tests at heights m, n and hub height	0,5; 1	These uncertainties of the reference measurement of the verification tests are basically uncorrelated at two heights m and n. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested. An exception is the case of using the same verification test at two height m and n (e.g. if the mast used for the verification test does not cover the entire range of the rotor). Then the uncertainties are fully correlated across the two heights m and n. However, the uncertainty itself gets 0 if the same verification is also applied for hub height.
Northing of reference vanes used for verification tests at heights m, n and hub height	0,5; 1	
Data acquisition system (DAS) used to monitor reference vanes applied for verification tests at heights m, n and hub height	0,5; 1	
Mean deviation of RSD measurement and reference measurement during verification tests at heights m, n and hub height	0,5; 1	
Statistical uncertainty of verification tests at height m, n and hub height	0,5; 1	
Uncertainty of verification tests at height m, n and hub height due to a possible misalignment of the RSD	1	The uncertainty is fully correlated across the heights m and n. However, the respective uncertainty is zero for all heights m and n as the misalignment error cancels out when evaluating the difference

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Component	Correlation coefficient of uncertainties between different measurement heights	Explanation
		of the wind direction at height m and n relative to hub height.
Uncertainty of verification tests at height m, n and hub height caused by the assumption of equal wind conditions across the probe volumes of the RSD.	1	These uncertainties are highly correlated across the heights m and n. However, the respective uncertainties are close to zero as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Uncertainty of verification tests at height m, n and hub height due to a possible separation of the centre of the measurement volume of the RSD and the position of the reference mast	1	
Uncertainty due to sensitivity of RSD measurements and environmental variables.	1	
Possible misalignment of the RSD at the power curve test	1	This uncertainties is fully correlated across the heights m and n. However, the respective uncertainties is zero for all heights m and n as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Assumption of equal wind conditions across the probe volumes of the RSD at heights m, n and hub height	1	This uncertainties is highly correlated across the heights m and n. However, the respective uncertainties are close to zero as the influence on the wind direction measurement at height m (or n) and hub height cancels out when evaluating the difference of the wind directions.
Monitoring wind with a met mas at the power curve test	0,5; 1	If the monitoring met mast covers the two heights m and n with different vanes, the uncertainties of the monitoring are basically uncorrelated at two heights m and n. But as the wind direction differences relative to hub height at the two heights m and n include the direction measurement at hub height, a correlation coefficient of 0,5 is suggested in this case. If the monitoring mast provides only one measurement height that can be used to check the RSD measurement at the heights m and n, the uncertainty is fully correlated across the heights m and n. However, the respective uncertainty is then close to zero for all heights m and n as the uncertainty cancels out when evaluating the difference of the wind direction at height m (or n) and hub height.

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E.13.11 Combining uncertainties in the wind speed measurement from flow distortion due to site calibration $u_{VT,i}$

The following uncertainty components are combined to calculate the category B uncertainty for a site calibration, $u_{VT,i}$:

$$u_{VT,i,j} = \sqrt{u^2_{VT,precal,i,j} + u^2_{VT,postcal,i,j} + u^2_{VT,class,i,j} + u^2_{VT,mnt,i,j} + u^2_{VT,lgt,i,j} + u^2_{VT,coc,i,j} + u^2_{VT,rmv,i,j} + u^2_{VT,sv,i,j} + u^2_{dVT,i,j} + s^2_{VT}} \quad \text{(E.52)}$$

where

$u_{VT,i,j}$ is the uncertainty from the site calibration;

$u_{VT,precal,i,j}$ is the uncertainty related to the calibration of the anemometers;

$u_{VT,postcal,i,j}$ is the uncertainty related to the post calibration or in-situ calibration of the anemometers;

$u_{VT,class,i,j}$ is the uncertainty related to the classification of the sensors;

$u_{VT,mnt,i,j}$ is the uncertainty related to the mounting of the sensors;

$u_{VT,lgt,i,j}$ is the uncertainty due to a possible lightning finial on a top mounted anemometer;

$u_{VT,coc,i,j}$ is the uncertainty related to the change of correction value between bins;

$u_{VT,rmv,i,j}$ is the uncertainty related to the removal of the wind direction sensor between site calibration and power performance test;

$u_{VT,sv,i,j}$ is the uncertainty related to the seasonal variation between site calibration and power performance test;

$u_{dVT,i,j}$ is the uncertainty related to the data acquisition of the wind speed signal;

s_{VT} is the category A standard uncertainty of the site calibration, see C.6.1.

To obtain the uncertainty in one wind speed bin across all the directional sectors the weighted average shall be used:

$$u_{VT,i} = \frac{\sum_j u_{VT,i,j} N_{i,j}}{\sum_j N_{i,j}} \tag{E.53}$$

where $N_{i,j}$ is number of power curve data sets for wind speed bin i and wind direction bin j.

E.13.12 Combining uncertainties for the temperature measurement $u_{T,i}$

The following uncertainty components are combined to calculate the category B uncertainty for temperature, $u_{T,i}$:

$$u_{T,i} = \sqrt{u_{T,cal,i}^2 + u_{T,shield,i}^2 + u_{T,mnt,i}^2 + u_{dT,i}^2} \tag{E.54}$$

where

$u_{T,i}$ is the uncertainty of the temperature measurement;

$u_{T,cal,i}$ is the uncertainty related to the calibration of the temperature sensor;

$u_{T,shield,i}$ is the uncertainty related to the shielding of the temperature sensor;

$u_{T,mnt,i}$ is the uncertainty related to the mounting of the temperature sensor;

$u_{dT,i}$ is the uncertainty related to the data acquisition of the temperature signal.

If we make the following assumptions:

- The standard uncertainty of the temperature sensor is 0,5 °C.
- The shielding of the temperature sensor is 2 °C.
- The standard uncertainty due to mounting effects of the temperature sensor is dependent on the vertical distance from the hub height. With the temperature sensor mounted within 10 m of hub height a standard uncertainty of 1/3 °C is assumed.
- Considering a temperature range of 40 °C of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the air temperature in each bin is:

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$$u_{T,i} = \sqrt{(0{,}5\text{K})^2 + (2{,}0\text{K})^2 + (0{,}3\text{K})^2 + (0{,}1\,\% \cdot 40\text{K})^2} = 2{,}1\,\text{K} \quad \text{(E.55)}$$

E.13.13 Combining uncertainties for the pressure measurement $u_{B,i}$

The following uncertainty components are combined to calculate the category B uncertainty for pressure, $u_{B,i}$:

$$u_{B,i} = \sqrt{u_{B,cal,i}^2 + u_{B,mnt,i}^2 + u_{dB,i}^2} \quad \text{(E.56)}$$

where

$u_{B,i}$ is the uncertainty of the pressure measurement;

$u_{B,cal,i}$ is the uncertainty related to the calibration of the pressure sensor;

$u_{B,mnt,i}$ is the uncertainty related to the mounting of the pressure sensor;

$u_{dB,i}$ is the uncertainty related to the data acquisition of the pressure signal.

If we make the following assumptions:

- The pressure sensor to have a standard uncertainty of 3,0 hPa. It is assumed that the pressure is corrected to the hub height according to ISO 2533 (which, for a standard atmosphere and a height difference of 98 m between the sensor and the hub, is 11,7 hPa). The standard uncertainty due to deployment is estimated to be 10 % of the correction, which is 1,17 hPa.
- Considering a pressure range of 100 hPa of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the air pressure is:

$$u_{B,i} = \sqrt{(3{,}0\text{hPa})^2 + (1{,}17\text{hPa})^2 + (0{,}1\,\% \cdot 100\text{hPa})^2} = 3{,}2\,\text{hPa} \quad \text{(E.57)}$$

E.13.14 Combining uncertainties for the humidity measurement $u_{RH,i}$

The following uncertainty components are combined to calculate the category B uncertainty for humidity, $u_{RH,i}$:

$$u_{RH,i} = \sqrt{u_{RH,cal,i}^2 + u_{RH,mnt,i}^2 + u_{dRH,i}^2} \quad \text{(E.58)}$$

where

$u_{RH,i}$ is the uncertainty of the relative humidity measurement;

$u_{RH,cal,i}$ is the uncertainty related to the calibration of the relative humidity sensor;

$u_{RH,mnt,i}$ is the uncertainty related to the mounting of the relative humidity sensor;

$u_{dRH,i}$ is the uncertainty related to the data acquisition of the relative humidity signal.

If we make the following assumptions:

- The relative humidity sensor to have a standard uncertainty of 1 %;
- The mounting of the sensor to be 0,1 %;
- Considering a pressure range of 100 % of the measurement channel and a standard uncertainty of the data acquisition system of 0,1 % of this range.

Then the numerical calculation for the standard uncertainty of the relative humidity is:

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$$u_{\mathrm{RH},i} = \sqrt{(1{,}0\,\%)^2 + (0{,}1\%)^2 + (0{,}1\,\% \cdot 100\,\%)^2} = 1{,}0\,\% \tag{E.59}$$

E.13.15 Combining uncertainties for the method related components $u_{M,i}$

The following uncertainty components are combined to calculate the category B uncertainty for related to the methodology, $u_{\mathrm{M},i}$:

$$u_{\mathrm{M},i} = \sqrt{u^2_{\mathrm{M,shear},i} + u^2_{\mathrm{M,veer},i} + u^2_{\mathrm{M,upflow},i} + u^2_{\mathrm{M,ti},i} + u^2_{\mathrm{M,sfx},i} + u^2_{\mathrm{M,tinorm},i} + u^2_{\mathrm{M,cc},i}} \tag{E.60}$$

where

$u_{\mathrm{M},i}$ is the uncertainty related to the applied methodology;

$u_{\mathrm{M,shear},i}$ is the uncertainty related to missing information regarding shear across the whole rotor;

$u_{\mathrm{M,veer},i}$ is the uncertainty related to missing information regarding wind veer across the whole rotor;

$u_{\mathrm{M,upflow},i}$ is the uncertainty related to missing information regarding upflow across the whole rotor;

$u_{\mathrm{M,ti},i}$ is the uncertainty related to missing information regarding turbulence when no hub-height meteorological mast wind speed signal is available;

$u_{\mathrm{M,sfx},i}$ is the uncertainty related to the unquantifiable seasonal effects on the turbine;

$u_{\mathrm{M,tinorm},i}$ is the uncertainty related to turbulence normalisation;

$u_{\mathrm{M,cc},i}$ is the uncertainty related to the measurement in a cold climate.

E.13.16 Combining uncertainties for the wind direction measurement with wind vane or sonic anemometer $u_{WV,i}$

The following uncertainty components are combined to calculate the category B uncertainty for the wind direction measurement with wind vane or sonic anemometer, $u_{\mathrm{WV},i}$:

$$u_{\mathrm{WV},i} = \sqrt{u^2_{\mathrm{WV,cal},i} + u^2_{\mathrm{WV,nm},i} + u^2_{\mathrm{WV,bo},i} + u^2_{\mathrm{WV,oe},i} + u^2_{\mathrm{WV,mda},i} + u^2_{\mathrm{dWV},i}} \tag{E.61}$$

where

$u_{\mathrm{WV},i}$ is the uncertainty related to the wind direction measured with a mast mounted wind direction sensor (wind vane or sonic anemometer);

$u_{\mathrm{WV,cal},i}$ is the uncertainty related to the calibration of the wind direction sensor;

$u_{\mathrm{WV,nm},i}$ is the uncertainty related to north marking of the wind direction sensor;

$u_{\mathrm{WV,bo},i}$ is the uncertainty related to the boom orientation on which the wind direction sensor is mounted;

$u_{\mathrm{WV,oe},i}$ is the uncertainty related to the influence of the meteorological mast on the wind direction measurement;

$u_{\mathrm{WV,mda},i}$ is the uncertainty related to the magnetic declination angle;

$u_{\mathrm{dWV},i}$ is the uncertainty related to the data acquisition of the signal from the wind direction sensor.

E.13.17 Combining uncertainties for the wind direction measurement with RSD $u_{WR,i}$

The following uncertainty components are combined to calculate the category B uncertainty for the wind direction measurement with RSD, $u_{\mathrm{WR},i}$:

$$u_{\mathrm{WR},i} = \sqrt{u^2_{\mathrm{WR,ver},i} + u^2_{\mathrm{WR,class},i} + u^2_{\mathrm{WR,mon},i} + u^2_{\mathrm{WR,fv},i} + u^2_{\mathrm{WR,align},i} + u^2_{\mathrm{WR,mda},i} + u^2_{\mathrm{dWR},i}} \tag{E.62}$$

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where

$u_{WR,i}$ is the uncertainty related to the wind direction measured with an RSD;

$u_{WR,ver,i}$ is the uncertainty related to the verification test of the RSD;

$u_{WR,class,i}$ is the uncertainty related to the classification of the RSD;

$u_{WR,mon,i}$ is the uncertainty related to the monitoring of the RSD;

$u_{WR,fv,i}$ is the uncertainty related to the variation in wind flow across to measured volume;

$u_{WR,align,i}$ is the uncertainty related to the alignment of the RSD;

$u_{WR,mda,i}$ is the uncertainty related to the magnetic declination angle;

$u_{dWR,i}$ is the uncertainty related to the data acquisition of the signal from the wind direction sensor.

E.13.18 Combined category B uncertainties

The category B uncertainties in each bin are combined as:

$$u_i = \sqrt{u_{P,i}^2 + c_{v,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2} \quad \text{(E.63)}$$

E.13.19 Combined standard uncertainty – Power curve

The combined standard uncertainties of each bin of the power curve are found by combining the category A uncertainty with all the category B uncertainties.

$$u_{c,i} = \sqrt{S_i^2 + u_i^2} = \sqrt{S_i^2 + u_{P,i}^2 + c_{v,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2} \quad \text{(E.64)}$$

E.13.20 Combined standard uncertainty – Energy production

The combined standard uncertainty of AEP is found by combining individually the category A and B uncertainties bin-wise. This may be accomplished according to the full formulation of Equation (E.4) and shown in Equation (E.65) or the simplified and conservative formulation of Equation (E.5), shown in Equation (E.65):

$$u_{AEP} = N_h \sqrt{\sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} \left(\sum_{i=1}^{N} f_i \, c_{k,i} \, u_{k,i}\right)^2} \quad \text{(E.65)}$$

$$u_{AEP} = N_h \sqrt{\sum_{i=1}^{N} f_i^2 s_i^2 + \left(\sum_{i=1}^{N} f_i \, u_i\right)^2} \quad \text{(E.66)}$$

where

f_i is the relative occurrence of wind speed between V_{i-1} and V_i: $F(V_i) - F(V_{i-1})$ within bin i.

E.14 Relevance of uncertainty components under specified conditions

As per the Guide to expression of uncertainty in measurement, in some cases an uncertainty component may be evaluated and found to be insignificant and therefore not be included in the evaluation of the uncertainty of the measurement result.

In this standard, various uncertainty components only should be assigned a zero value in specific cases or when a specific set of conditions have been met. An example is the uncertainty of $u_{VT,coc,i,j}$ which relates to the uncertainty applied in a site calibration when wind direction bins with a change in correction factor larger than 2 % compared to the neighbouring

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bin are not eliminated from the data set (see C.7.3 d). Only when the decision is made not to remove such bins does $u_{VT,coc,i,j}$ get a value, otherwise it has value zero.

It is up to the user of this standard to determine in which cases an uncertainty component can be deemed irrelevant and hence set to zero. This should be documented (including the justification) to ensure reproducibility of the uncertainty calculation.

E.15 Reference tables

Table E.9 – Uncertainties from air density normalisation

Bin No. i	Air density normalized wind speed $V_{n\,i}$ m/s	Wind speed before normalization (un-normalized) $V_{un\,i}$ m/s	Difference of normalised and un-normalized wind speed $V_{ni} - V_{un\,i}$ m/s	Uncertainty due to air density normalization $u_{PI,i}$ m/s
4	2,03	2,025	0,008	0,004
5	2,51	2,501	0,013	0,007
6	3,03	3,015	0,014	0,007
7	3,52	3,501	0,016	0,008
8	4,02	4,000	0,022	0,011
9	4,53	4,503	0,028	0,014
10	5,00	4,976	0,029	0,014
11	5,55	5,523	0,031	0,016
12	6,03	5,991	0,035	0,017
13	6,56	6,503	0,055	0,028
14	7,01	6,970	0,041	0,021
15	7,55	7,485	0,061	0,031
16	8,04	7,979	0,065	0,032
17	8,57	8,503	0,064	0,032
18	9,08	8,999	0,080	0,040
19	9,58	9,494	0,090	0,045
20	10,10	10,007	0,091	0,045
21	10,61	10,501	0,113	0,056
22	11,10	10,982	0,122	0,061
23	11,60	11,475	0,121	0,060
24	12,11	11,986	0,125	0,062
25	12,64	12,504	0,139	0,070
26	13,17	13,034	0,134	0,067
27	13,59	13,467	0,123	0,061
28	14,18	14,020	0,157	0,079
29	14,62	14,479	0,140	0,070
30	15,07	14,916	0,149	0,075
31	15,76	15,611	0,151	0,075
32	16,09	15,941	0,147	0,073
33	16,83	16,680	0,150	0,075
34	17,03	16,926	0,100	0,050
35	17,81	17,586	0,226	0,113

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Bin No. i	Air density normalized wind speed $V_{n\,i}$ m/s	Wind speed before normalization (un-normalized) $V_{un\,i}$ m/s	Difference of normalised and un-normalized wind speed $V_{ni} - V_{un\,i}$ m/s	Uncertainty due to air density normalization $u_{PI,i}$ m/s
36	18,19	18,052	0,135	0,068
37	18,5	0,152 2	0,135	0,068
38	19	0,152 1	0,135	0,068
39	19,5	0,153 9	0,135	0,068
40	20	0,154 1	0,135	0,068
41	20,5	0,150 5	0,135	0,068
42	21	0,151 2	0,135	0,068
43	21,5	0,154 8	0,135	0,068
44	22	0,153	0,135	0,068
45	22,5	0,153 3	0,135	0,068
46	23	0,155 7	0,135	0,068
47	23,5	0,156 7	0,135	0,068

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Table E.10 – Sensitivity factors

	Power curve (database B)		Sensitivity factors		
Bin No. i	Wind speed V_i m/s	Electric power P_i kW	Wind speed $c_{V,i}$ kW/m/s	Air temperature $c_{T,i}$ kW/K	Air pressure $c_{B,i}$ kW/hPa
4	2,13	–3,64	1,712	0,013	0,004
5	2,49	–3,65	0,014	0,013	0,004
6	2,99	–3,78	0,269	0,013	0,004
7	3,51	–2,19	3,062	0,008	0,002
8	3,99	–0,43	3,645	0,001	0,000
9	4,50	6,04	12,825	0,021	0,006
10	4,98	27,70	44,664	0,096	0,027
11	5,52	67,39	74,049	0,234	0,067
12	5,98	111,30	94,430	0,386	0,110
13	6,51	160,95	95,019	0,558	0,159
14	7,01	209,42	95,472	0,727	0,207
15	7,50	261,96	107,566	0,909	0,259
16	8,00	327,63	131,992	1,137	0,323
17	8,50	395,23	136,290	1,372	0,390
18	8,99	462,01	134,677	1,603	0,456
19	9,49	556,06	187,824	1,930	0,549
20	10,00	629,80	145,079	2,186	0,622
21	10,47	703,06	155,957	2,440	0,694
22	11,00	786,55	157,358	2,729	0,776
23	11,50	836,48	100,000	2,903	0,826
24	11,99	893,52	116,327	3,101	0,882
25	12,49	928,61	70,200	3,223	0,917
26	13,03	956,44	51,481	3,319	0,944
27	13,50	971,30	31,702	3,371	0,959
28	14,00	980,92	19,200	3,404	0,968
29	14,48	988,17	15,208	3,429	0,976
30	15,00	993,46	10,192	3,448	0,981
31	15,49	993,71	0,408	3,449	0,981
32	15,99	995,70	4,000	3,455	0,983
33	16,54	996,22	0,909	3,457	0,983
34	17,02	996,42	0,417	3,458	0,984
35	17,48	996,48	0,217	3,458	0,984
36	17,95	996,50	0,000	3,458	0,984
37	18,49	995,71	0,556	3,457	0,983
38	18,97	996,6	0,833	3,459	0,984
39	19,42	996,1	1,111	3,457	0,983
40	19,96	994,1	3,704	3,450	0,981
41	20,51	987,4	12,182	3,427	0,975
42	20,88	996,9	25,676	3,460	0,984

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Table E.11 – Category B uncertainties

Bin No. i	Electric power $u_{P,i}$ kW	Wind speed $u_{V,i}$ m/s	Wind speed $c_{V,i} \cdot u_{V,i}$ kW	Air temperature $u_{T,i}$ K	Air temperature $c_{T,i} \cdot u_{T,i}$ kW	Air pressure $u_{B,i}$ hPa	Air pressure $c_{B,i} \cdot u_{B,i}$ kW
4	6,29	0,19	0,33	2,09	0,03	3,18	0,01
5	6,29	0,19	0,00	2,09	0,03	3,18	0,01
6	6,29	0,19	0,05	2,09	0,03	3,18	0,01
7	6,29	0,19	0,60	2,09	0,02	3,18	0,01
8	6,29	0,20	0,71	2,09	0,00	3,18	0,00
9	6,29	0,20	2,53	2,09	0,04	3,18	0,02
10	6,29	0,20	8,85	2,09	0,20	3,18	0,09
11	6,30	0,20	14,82	2,09	0,49	3,18	0,21
12	6,32	0,20	19,04	2,09	0,81	3,18	0,35
13	6,35	0,20	19,34	2,09	1,17	3,18	0,51
14	6,39	0,21	19,58	2,09	1,52	3,18	0,66
15	6,44	0,21	22,28	2,09	1,90	3,18	0,82
16	6,52	0,21	27,66	2,09	2,37	3,18	1,03
17	6,62	0,21	28,87	2,09	2,86	3,18	1,24
18	6,74	0,21	28,86	2,09	3,35	3,18	1,45
19	6,93	0,22	40,71	2,09	4,03	3,18	1,75
20	7,09	0,22	31,82	2,09	4,57	3,18	1,98
21	7,28	0,22	34,61	2,09	5,10	3,18	2,21
22	7,51	0,22	35,38	2,09	5,70	3,18	2,47
23	7,65	0,23	22,77	2,09	6,06	3,18	2,63
24	7,82	0,23	26,81	2,09	6,48	3,18	2,81
25	7,93	0,23	16,41	2,09	6,73	3,18	2,92
26	8,02	0,24	12,20	2,09	6,93	3,18	3,00
27	8,07	0,24	7,61	2,09	7,04	3,18	3,05
28	8,10	0,24	4,67	2,09	7,11	3,18	3,08
29	8,13	0,25	3,75	2,09	7,16	3,18	3,10
30	8,14	0,25	2,55	2,09	7,20	3,18	3,12
31	8,14	0,25	0,10	2,09	7,20	3,18	3,12
32	8,15	0,26	1,03	2,09	7,22	3,18	3,13
33	8,15	0,26	0,24	2,09	7,22	3,18	3,13
34	8,15	0,26	0,11	2,09	7,22	3,18	3,13
35	8,15	0,27	0,06	2,09	7,22	3,18	3,13
36	8,15	0,27	0,00	2,09	7,22	3,18	3,13
37	8,15	0,28	0,15	2,09	7,22	3,18	3,13
38	8,15	0,28	0,23	2,09	7,22	3,18	3,13
39	8,15	0,28	0,32	2,09	7,22	3,18	3,13
40	8,15	0,29	1,07	2,09	7,21	3,18	3,12
41	8,12	0,29	3,54	2,09	7,16	3,18	3,10
42	8,15	0,29	7,54	2,09	7,23	3,18	3,13

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Annex F
(normative)

Wind tunnel calibration procedure for anemometers

F.1 General requirements

The general requirements for the calibration of anemometers are summarized as follows:

a) the calibration of the anemometer shall be carried out in a wind tunnel that is suitable for the calibration of anemometers;

b) the calibration facility shall be recognised by IECRE or accredited in accordance with ISO/IEC 17025, being the main standard for testing and calibration laboratories;

c) all transducers and measuring equipment relevant for the calibration of anemometers shall have traceable calibrations according to ISO/IEC 17025. Calibration certificates and reports shall contain all relevant traceability information;

d) the reference wind speed shall be measured with a pitot-static tube that shall be of NPL type with ellipsoidal head according to ISO 3966. The pitot-static tube shall be calibrated for appropriate wind speed ranges, and be documented. The reference wind speed may alternatively be measured by LDA (Laser Doppler Anemometry) with well documented uncertainties;

e) consistency of the experimental set-up shall be verified by at least daily comparative calibrations of the facility's "quality control anemometer";

f) flow quality shall be verified as required in Clause F.2;

g) the repeatability of the calibration shall be verified as required in Clause F.2;

h) anemometer calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO Guide 98-3:2008.

F.2 Requirements to the wind tunnel

The presence of the anemometer shall not substantially affect the flow field in the wind tunnel. During measurements the anemometer will to some extent be influenced by wind tunnel blockage and boundary effects. The blockage area ratio (*BR)* – defined as the ratio of the anemometer projected area, perpendicular to flow direction, (including its mounting system and projected area of a spinning rotor) to the total test section area – shall not exceed 0,05. Blockage effects shall always be accounted for according to F.4.3.

It is recommended that the wind tunnel test section has a height of at least 1,0 m and a width of at least 1,0 m.

The flow in the cross sectional area, where the anemometer will be located, shall be uniform. Flow uniformity should be measured using velocity sensing devices, i.e. pitot tubes, hot wires or Laser Doppler Velocimetry to measure flow profiles in longitudinal, transversal and vertical direction. Over the calibration wind speed range, the maximum difference in the mean velocity between any two points inside the measurement volume shall be less than 0,2 %. The mean value shall be calculated during at least five minutes and the measurement volume shall cover the active volume of the anemometer with 50 % margin in all directions as per Figure F.1. Uniformity shall be tested over a period of at least 5 minutes for wind speeds at approximately 4 m/s, 8 m/s, 12 m/s and 16 m/s each.

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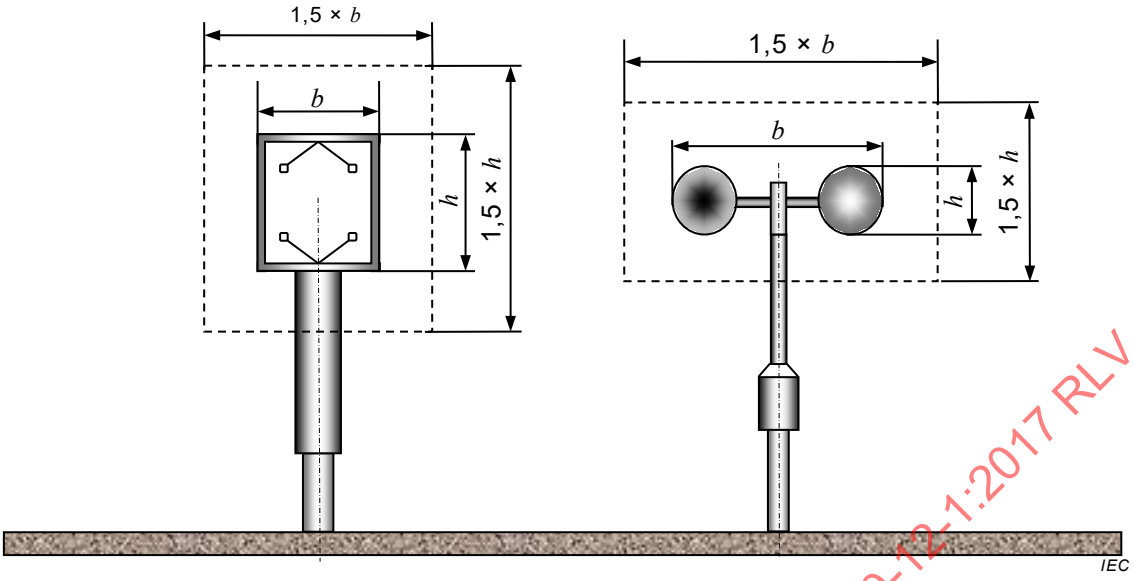

Figure F.1 – Definition of volume for flow uniformity test – The volume will also extend 1,5 x *b* in depth (along the flow)

The stability of the flow shall be measured in the middle of the volume of which uniformity was verified. The flow can be considered stable if 10 consecutive 30 s means are within 0,5 % of their average value.

Cup anemometers are very sensitive to horizontal wind gradients. Different horizontal wind gradients can be seen depending on pollution of nets and smoothing devices. Therefore, it is useful to check the horizontal wind gradient by using two identical pitot tubes. They shall be placed at the exact position where the anemometer will be placed with their heads spanning approximately the area covered by the cup anemometers rotating cups. A set of measurements shall be made and the linear regression between the dynamic pressures measured by the two pitot tubes shall be calculated. The difference in wind speed shall be less than 0,2 % over a period of at least 5 minutes. The influence due to the presence of the anemometer type to be calibrated (including mounting tube) on the flow speed measured by the pitot tube shall be verified to be less than ± 0,2 %.

The axial turbulence intensity in wind speed at the anemometer's position shall be below 2 %. The turbulence intensity shall include longitudinal wind speed fluctuations with frequencies of up to 10 Hz. The data for turbulence measurements shall be acquired for a duration of 60 s per wind speed at a sampling rate of at least 20 Hz. Turbulence assessment shall be performed for at least the flow speeds 7 m/s, 10 m/s and 13 m/s with a device that is suitable to measure wind speed fluctuations with a cut-off frequency of at least 20 Hz. Deviations from the above requirements shall be assessed through suitable tests and be considered in the uncertainty evaluation.

The wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position, shall be appraised using pitot tubes for a speed range of 4 m/s to 16 m/s.

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 facility shall prove, through proficiency testing, that its results are comparable with other anemometer calibration facilities, according to ISO 17043.

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F.3 Instrumentation and calibration set-up requirements

Dedicated external signal conditioning equipment such as frequency to voltage converters, etc. shall be calibrated in isolation from the anemometer, so allowing the anemometer's calibration to be derived and reported in isolation from the signal conditioning equipment.

The resolution of the data acquisition system shall be at least 0,02 m/s. Care shall also be exercised in the case of an analogue voltage instrument, to ensure that the signal is adequately buffered to prevent its attenuation by low impedance logging equipment.

Mounting arrangements can have dramatic effects on instrument performance, particularly if the ratio of tube diameter to rotor diameter is high. Therefore, during calibration, the anemometer shall be mounted on top of a tube in order to minimize flow distortion and only one anemometer may be calibrated at a time. This tube shall be of the same diameter as the one on which the anemometer will be mounted in service in the free atmosphere. It is recommended that the vertical distance between the anemometer rotor relative to the upper and lower boundaries of the wind tunnel test section should not be less than 0,5 m. In case of a directional sensitive anemometer with respect to horizontal flow, a reference orientation has to be defined and documented and referred to during calibration. The anemometer shall be positioned at the test section perpendicular to the flow field of the wind tunnel as accurate as possible. The maximum deviation of the anemometer mounting tube is 0,2°. An example of a typical cup anemometer tilt response is shown in Figure J.1.

It is important to ensure that the anemometer is not influenced by the presence of any reference wind speed measurement equipment. Conversely, the presence of the anemometer shall not affect the flow in the region of the reference instrument. If flow distortion effects are encountered, then the pitot tube shall be repositioned. This effect can be assessed by removing and then reinstating the anemometer and afterwards the reference instrument, and ascertaining whether the output of the remaining instrument changes.

The pitot static tubes shall be positioned in the test section aligned with the mean flow direction. The maximum misalignment allowed is 0,5°.[27]

During calibration, the anemometer output signal shall be examined to ensure that it is not subject to interference or noise.

F.4 Calibration procedure

F.4.1 General procedure cup and sonic anemometers

The anemometer shall run in for minimum 5 min at about 10 m/s before the calibration procedure begins. Calibration shall be performed under both rising and falling wind speed in the range of 4 m/s to 16 m/s at a calibration interval of 1 m/s or less[28]. If heating is switched on during calibrations, it shall be noted in the calibration certificate.

The sampling frequency shall be at least 1 Hz and the sampling interval at least 30 s. This sampling interval can be increased when low resolution anemometers are calibrated. It is important to ensure that anemometer and reference wind speed readings span the same period of time. Before collecting data at each wind speed, adequate time shall be allowed for stable flow conditions to become established, see Clause F.2. This may take 1 min, but will vary from facility to facility.

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27 Missalignment of pitot static tubes may lead to a bias in differential pressure measurement! An alignment to within 0.5°of the mean flow direction assures a bias in differential pressure reading of less than 0,1 % for the NPL type Pitot tube (see ISO 3966:2008, Figure A.5).

28 1 m/s intervals can also be realized with the allowance for 2 m/s jumps, for example 4 m/s, 6 m/s, 8 m/s, 10 m/s, 12 m/s, 14 m/s, 16 m/s, 15 m/s, 13 m/s, 11 m/s, 9 m/s, 7 m/s, 5 m/s.

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F.4.2 Procedure for the calibration of sonic anemometers

Sonic anemometers are designed to measure 2D or 3D wind components. For the purpose of power performance measurements sonic anemometers shall be set up for measurement of horizontal wind speed preferably internally or by post processing.

During calibration the complete sonic anemometer shall be placed in the wind tunnel test section. The active part of the sonic anemometer shall be located within the test section volume. The yaw alignment shall be set at the reference calibration yaw direction, see Clause F.3. It is often advantageous to set a yaw alignment that imposes the least flow disturbance from the supports of the acoustic transceivers.

The setup parameters of the sonic during its calibration shall be documented in the calibration certificate or alternatively in an annex of the calibration certificate. The calibration holds only for identical settings of the sensor and identical signal output format.

For this test, the sonic anemometer shall be calibrated at variable wind speeds according to F.4.1. Calibrations of additional yaw position (i.e. yaw angle for max. flow disturbance from the supports) may be performed if desired. Calibrations of additional yaw positions should be performed at 10 m/s as a quality control of compliance with classification results.

Status signal of the sonic anemometer (if available) shall be monitored during the calibrations. The status signal shall be used to exclude erroneous data.

F.4.3 Determination of the wind speed at the anemometer position

Air density ρ shall be calculated on the basis of the mean wind tunnel air temperature T, relative humidity Φ and barometric pressure B, using Equation (F.1) (standard uncertainty less than 10^{-3} kg/m^3):

$$\rho = \frac{1}{T}\left(\frac{B}{R_0} - \phi P_{\mathrm{w}}\left(\frac{1}{R_0} - \frac{1}{R_{\mathrm{w}}}\right)\right) \tag{F.1}$$

where

B is the barometric pressure [Pa];

T is the absolute temperature [K];

Φ is the relative humidity (range 0 to 1);

R_0 is the gas constant of dry air [287,05 J/kgK];

R_{w} is the gas constant of water vapour [461,5 J/kgK];

P_{w} is the vapour pressure [Pa].

Vapour pressure P_{w} depends on mean air temperature.

$$P_{\mathrm{w}} = 0{,}0000205 \cdot \exp\left(0{,}0631846 \cdot T\right) \tag{F.2}$$

The mean flow speed at anemometer position is calculated from mean differential pressure

Δp_{ref} at reference position using the equation:

$$\bar{v} = f\left(k_{\mathrm{b}}, k_i, k_{\mathrm{p}}, \bar{v}_{\mathrm{p}}, \ldots\right) a k_{\mathrm{c}} \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{2\Delta p_{\mathrm{ref},i}}{\rho}} \tag{F.3}$$

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where

α is the pitot static tube head coefficient;

k_c is the wind tunnel calibration factor, which gives the relation between the conditions at the reference measurement position and those at the anemometer position;

$f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ is a correction function due to interference between the anemometer including its mounting tube and the wind tunnel flow;

k_b is the interference correction factor due to blockage;

k_i is the correction factor due to interference between the anemometer (including mounting tube) and test section enclosure, also including flow effects due to mounting tubes extending through the enclosure;

k_p is the correction factor due to interference caused by the anemometer (including mounting tube) on the velocity measured by the pitot tube;

$\bar{v}$ is the average wind speed at the anemometer position;

$\bar{v}_p$ is the average wind speed at the reference position;

n is the number of samples within the sampling interval.

The correction function $f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ should be equal to one for a test section without an anemometer and its supporting tube. The influence of the correction function on the calibration results shall be assessed and included in the calibration facility setup report and uncertainty calculation.

F.5 Data analysis

A linear regression analysis shall be carried out on the calibration data for the estimation of the following regression parameters: Offset, slope, regression coefficient, standard uncertainty. The wind speed values shall be regressed upon the anemometer outputs.

If the correlation coefficient, r, for the data is less than 0,999 95 then it shall be checked if it is caused by anemometer non-linearity or due to other reasons. In case of anemometer non-linearity, it shall be documented in the certificate.

F.6 Uncertainty analysis

It is important to identify the uncertainty of the horizontal wind speed incident upon the anemometer. It is required that an uncertainty analysis is carried out in accordance with the ISO/IEC Guide 98:2008 comprising both category A and category B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall take account of:

a) flow speed measurement uncertainty (pitot tubes, transducers, air density evaluation, etc.);

b) wind tunnel calibration factor;

c) wind tunnel correction factors through the correction function $f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ defined in Equation (F.3);

d) the influence of wind tunnel cross section size shall be assessed as part of the uncertainty analysis;

e) measurement of anemometer output;

f) the influence of non-vertical anemometer alignment shall be considered for each anemometer type in the uncertainty assessment;

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g) statistical uncertainty due to short term scatter of the anemometer output (variation of the indicated anemometer signal, i.e. fluctuation of the angular rotor velocity, bias from signal generation, sampling bias, over the averaging time);

h) uncertainty due to the difference between the result of the wind tunnel performing the calibration and the average result of other wind tunnels as determined through proficiency testing to the extent not covered by other uncertainty components;

i) uncertainty due to linearization of calibration expression.

F.7 Reporting format

The relevant documentation shall provide information on the procedure followed and the facility used for calibrating the anemometers (report on the calibration facility setup and on the individual anemometer calibration. The calibration facility setup report shall contain the following information as a minimum:

a) description of the wind tunnel (including test section, settling chamber, flow straighteners, fan arrangement);

b) sketch of the wind tunnel showing the positions of anemometer and pitot tube(s) in the test section;

c) flow quality measurements;

d) blockage effect assessment;

e) influence of mounting height of the anemometer;

f) influence of bottom plate;

g) influence of mounting position into reference measurement;

h) influence of the correction function;

i) turbulence measurements;

j) instrumentation certificates;

k) measurement procedure;

l) data evaluation procedure;

m) repeatability documentation of the anemometer calibration;

n) uncertainty analysis;

o) deviations from these requirements.

The calibration report of an anemometer shall as a minimum contain the following information:

1) make, type and serial number of the tested anemometer and cup serial number if transported separately;

2) specification of yaw orientation during calibration (yaw sensitive devices);

3) tube diameter of the mounting system;

4) make, type and serial number of external converters;

5) name and address of the customer;

6) signatures from the persons who carried out the calibration, checked the results and approved their issue;

7) name of the wind tunnel;

8) environmental conditions during calibration (air temperature, air pressure and humidity);

9) regression parameters (offset, slope, regression coefficient);

10) uncertainty due to linearization (scatter of residuals);

11) uncertainty due to the correction function $f\left(k_{\mathrm{b}}, k_i, k_{\mathrm{p}}, \bar{v}_{\mathrm{p}}, \ldots\right)$;

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12) tabular and graphical presentation (deviations from linear regression line amplified) of all calibration points and regression results;

13) uncertainty associated to each measuring point;

14) reference to the corresponding calibration facility set up report;

15) date of the calibration;

16) photo showing the anemometer and the mounting in the wind tunnel.

F.8 Example uncertainty calculation

As it is practically impossible to measure the flow velocity at the place of the anemometer and as the sensor in the wind tunnel experiences a significantly smaller flow field as in the free atmosphere, corrections are necessary. The optimization of the wind tunnel in terms of the corrections as well as the determination of the correction factor is crucial for the calculation of the measurement uncertainty.

Ideally, the uncertainty calculation should be applied independently to each wind speed calibration condition used in a calibration test. For this example, take a notional calibration point of 10 m/s using a wind tunnel rated at 25 m/s.

Table F.1 deals with each uncertainty source; first with those of category B.

To avoid repetition, a detailed assessment of barometric pressure measurement has been left out, as it can be dealt with in the same way as temperature measurement.

Table F.1 – Example of evaluation of anemometer calibration uncertainty

Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i\, c_i$ m/s
u_f, wind tunnel correction factor, f	An uncertainty on the correction factor $f(k_b, k_i, k_p, \bar{v}_p, \ldots)$ based on investigation of calibration influence factors.			
u_t, wind tunnel calibration factor, k_c	Wind tunnel calibration can be carried out by using two pitot tubes, one at the permanent reference position and one at the location to be occupied by the test anemometer. By swapping the two pitot systems, all category B errors can be eliminated, and standard regression analysis can be applied to yield a correction factor (the intercept being forced through the origin) and a related category A standard uncertainty. Assume the correction has a value of 1,02 and the standard uncertainty is 0,01.	0,01	C_t = 0,5 v/k_c = 0,5 x 10/1,02 = 4,90 m/s	0,049
u_B, blockage correction factor, k_b	If a solid object is positioned in the flow of the wind tunnel, the flow will be affected depending on the relation between object size and wind tunnel area. Conditional on the spatial dimensions of the specimen, a raise in the flow velocity occurs in a closed measurement section because of the continuity. In an open measurement section, the current will be widened, which is equivalent to a speed reduction. Assuming the blockage effect is known the uncertainty value of 0,1 % is appropriate. The calibration facility setup report shall present the calculations applied and estimated value of the correction factor and the associated uncertainty.	0,001	C_f = v/k_b =10 m/s/1,001 ≈ 10 m/s	0,01

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Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i\ c_i$ m/s
u_{ki}, position correction factor, k_i	An anemometer needs a certain free space (depending on the size of the mounting pipe and the anemometer) below and above it, to experience the same flow conditions as in free atmosphere. Therefore the centre of the measurement section is not necessarily the best position for the specimen. If the wind tunnel is small and thus the mounting pipe is too short, an error of up to 2 % may occur. Only from a certain lengths of the mounting pipe, the influence begins to decrease. This free length amounts to approximately 50 cm above the base plate. Assuming the position effect is known, the uncertainty value of 0,1 % may be appropriate.	0,001	$C_P = v/k_p$ =10 m/s/1,001 ≈ 10 m/s	0,01
u_p, position correction factor, k_p	The flow around the anemometer exerts some influence on the flow around the reference pitot tube. Assuming the influence effect is known, the uncertainty value of 0,1 % of the effect may be appropriate.	0,001		
u_{FD}, flow correction factor, k_{FD}	Mostly, anemometers are mounted on measurement masts of considerable length – a situation which cannot be reproduced in the wind tunnel. If an anemometer is mounted on a tube stub and if this stub is mounted in a wind tunnel with an open measurement section, the current can evade downward. This means a loss of impetus for the anemometer and thus a systematic error. By installing a base-plate, this loss can be considerably reduced. Assuming a base-plate is installed, the standard uncertainty value of 0,1 % is appropriate otherwise the influence has to be examined.	0,001	$C_{FD} = v/k_{FD}$ =10 m/s/1,001 ≈ 10 m/s	0,01
$u_{p,t}$ pressure transducer, $K_{p,t}$	The calibration certificate for the pressure transducer shows a maximum uncertainty of 0,5 Pa in the range from 0 Pa to 500 Pa.	0,5 Pa	$c_{p,t} = 0,5\ v/K_{p,t}$ = 0,5 × 10/5 000 = 0,001	0,000 5
$u_{p,s}$ pressure transducer signal conditioning gain, $K_{p,s}$ and $u_{p,d}$ pressure transducer data sampling conversion $K_{p,d}$	The calibration of the equipment used to measure the pressure transducer output shows a maximum uncertainty of 0,000 15 V in the range from 0 V to 10 V.	0,000 15 V	$c_{p,s} = 0,5\ v/K_{p,s}$ = 0,5 × 10/0,01 = 500	0,010
$u_{T,t}$ ambient temperature transducer, $K_{T,t}$ $u_{T,s}$ temperature signal conditioning gain, $K_{T,s}$ and $u_{T,d}$ temperature signal digital conversion, $K_{T,d}$	The calibration of the equipment used to measure the temperature shows a maximum uncertainty of 0,1 °C in the range from 10 °C to 30 °C.	0,1 °C	$c_{T,t} = 0,5\ v/K_{T,t}$ n/a	0,001
u_h pitot tube	The head coefficient of a pitot tube depends	0,000 997	$C_h = –0,5\ v/C_h$	0,005

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Error source u_i	Discussion	Value u_i	Sensitivity value c_i	$u_i\ c_i$ m/s
head coefficient, C_h	upon the angle of attack of the wind. Two error sources are possible, one related to the accuracy with which the pitot tube is set up in alignment with the mean flow direction, and the other due to turbulent variations in instantaneous flow direction. Assume the nominal head coefficient, C_h, is 0,997, and assume also that it is possible to deduce that the standard deviation on angle of attack is 2°. Relevant ISO standards suggest this will give rise to a 0,1 % change in head coefficient.		= –0,5 × 10/0,997 = –5,015	
u_{pcal} pitot tube calibration	From the calibration certificate of the pitot tube, an uncertainty of 0,25 % in the range of 4 m/s to 16 m/s may be used.	0,002 5	C_{ph} = –0,5 v/C_h = –0,5 × 10/0,997 = –5,015	
$u_{B,t}$ sensitivity of barometer, $K_{B,t}$, $u_{B,s}$ signal conditioning gain on barometer, $K_{B,s}$ and $u_{B,d}$ digital conversion of barometer signal, $K_{B,d}$	The calibration of the barometer shows a maximum uncertainty of 0,5 hPa in the range from 900 hPa to 1 100 hPa.	0,5 hPa	$c_{B,t}$ = –0,5 $v/k_{B,t}$	
s_A statistical uncertainty in the mean of the wind speed time series	Assume the turbulence intensity is 2 %, and that 2 Hz sampling over 30 s is used, giving 60 samples. The standard uncertainty in the mean value of 10 m/s is then given by $\sqrt{1/60 \cdot 0{,}02 \cdot 10}$	0,026	1	0,026
u_p, humidity correction to density, k_p or u_φ, relative humidity, φ	The calibration of the relative humidity measurement equipment shows an uncertainty of less than 2 % in the range 10 to 95 %. A value of 2 % is selected for the calculation. $c_\varphi = \frac{\partial \bar{v}}{\partial k_p} \cdot \frac{\partial k_p}{\partial \varphi} = \frac{1}{2} \frac{\bar{v}}{k_p} 0{,}378 \frac{P_w}{B}$ At 15 °C, P_w = 1 700 Pa and assuming B = 1013 mbar = 101 300 Pa, k_p is evaluated as 0,997 and c_φ (at 10 m/s) is 0,032.	u_φ = 0,02 %RH	c_P = 0,032	0,001

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The combined standard uncertainty can be obtained by taking the root mean square of the contributory uncertainties in the right hand column. For the values which have been dealt with, this amounts to 0,06 m/s.

The example shows that category B error is liable to dominate. Extending the calibration period can help reduce the category A uncertainty, but will have no effect on category B. Furthermore, category B error sources, although not correlated with one another for a particular wind speed, are fully self-correlated across wind speeds, meaning that good apparent calibrations (good straight lines) can be obtained, whilst still retaining significant uncertainty.

Annex G
(normative)

Mounting of instruments on the meteorological mast

G.1 General

Appropriate arrangement of instruments on the meteorological mast is important for accurate wind turbine testing. The arrangement of anemometers for power performance tests shall include a primary hub height anemometer and a control anemometer. The purpose of the control anemometer is to provide a means of in-situ consistency checking of the primary hub height anemometer as described in Annex K. Before using an anemometer classified for power performance tests, it is recommended that the geometry of the anemometer is checked with the geometry description that corresponds to the anemometer type on which the classification was made. In particular, the anemometer shall be located to minimize flow distortions, especially from mast and boom influences. When minimal flow distortion across a wide wind direction range is required, then this is obtained with a single top-mounted anemometer. However, a side-by-side arrangement of two top-mounted anemometers provides redundancy and a robust method of anemometer consistency checking with only marginally increased flow distortion if both adequate horizontal separation and a stable mounting structure for the anemometers are achieved. When anemometers are mounted on side booms at elevations below the meteorological mast top, flow distortion from both the meteorological mast and the boom is significant and shall be taken into account. Irrespective of the type of mounting arrangement, care shall be taken to ensure that the boom structure is sufficiently stable to avoid significant vibrations. Those other instruments on the meteorological mast which are required to be mounted close to hub height (control anemometer, wind vanes, temperature and pressure sensors) should be mounted in a way that avoids interference with the primary anemometer.

G.2 Single top-mounted anemometer

To achieve negligible flow distortion of the wind speed measurements over a wide wind direction range, a single top-mounted anemometer is the ideal configuration. Where this configuration is adopted all provisions of this section shall be met. However, careful consideration should be given to whether sufficiently robust anemometer consistency checks against a lower elevation anemometer can be achieved with this configuration. This is particularly the case where the meteorological mast is of large cross-sectional area and as a consequence the lower anemometer is subject to more significant meteorological mast interference effects than the top-mounted anemometer or in cases where large variations in wind shear are experienced.

The anemometer shall be supported such that the anemometer cups[29] are at least 1,5 m above the meteorological mast and any other sources of flow disturbance and such that no parts of the support structure or meteorological mast shall extend outside of a 11:1 half cone[30] whose vertex is coincident with the anemometer cups. The anemometer shall be mounted on a round vertical tube of the same (± 0,1 mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer. The combined length of the tube and anemometer (measured to the anemometer cups) shall be at least 0,75 m. Furthermore the anemometer shall be held steady, which may necessitate the mounting of the small-diameter vertical tube concentric with another tube of larger

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29 Where the anemometer is an allowable type of anemometer other than a cup anemometer (e.g. an ultrasonic anemometer), then “cups” should be interpreted as “sensor measuring elements” throughout this annex.

30 The cone is defined such that the base of the cone is of diameter equal to the characteristic width (maximum width of the mast or protrusions for a distance of 4 m below the cups) of the mast and the height of the cone equals 11 times the radius of the cone base.

diameter to provide a stable structure. This additional tube cannot be of greater diameter than the anemometer body for a height of 1,5 m below the cups. The bracket connecting the anemometer to the vertical tube shall be compact, smooth, and symmetrical. Where the anemometer is designed for internal cable routing in the support tube, then the cable shall be routed inside the vertical tube. For other configurations (e.g. pig tail), then the cable should be spirally wound around the vertical tube (approximately 3 turns/m or similar to that used during calibration and classification). The anemometer should be calibrated with the same cable attachment and routing configuration as is to be used in the field. The anemometer (and mounting tube) inclination from vertical shall be less than 2°. It is recommended that this is verified by measurement. No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside of the 11:1 half cone to a distance of at least 4 m below the anemometer cups. In this case, the control anemometer for the top-mounted anemometer shall be a side-mounted anemometer located at least 4 m and no more than 6 m below the top-mounted anemometer and otherwise satisfying the requirements for side-mounted anemometers in Clause G.4. Figure G.1 shows an example of a top-mounting configuration.

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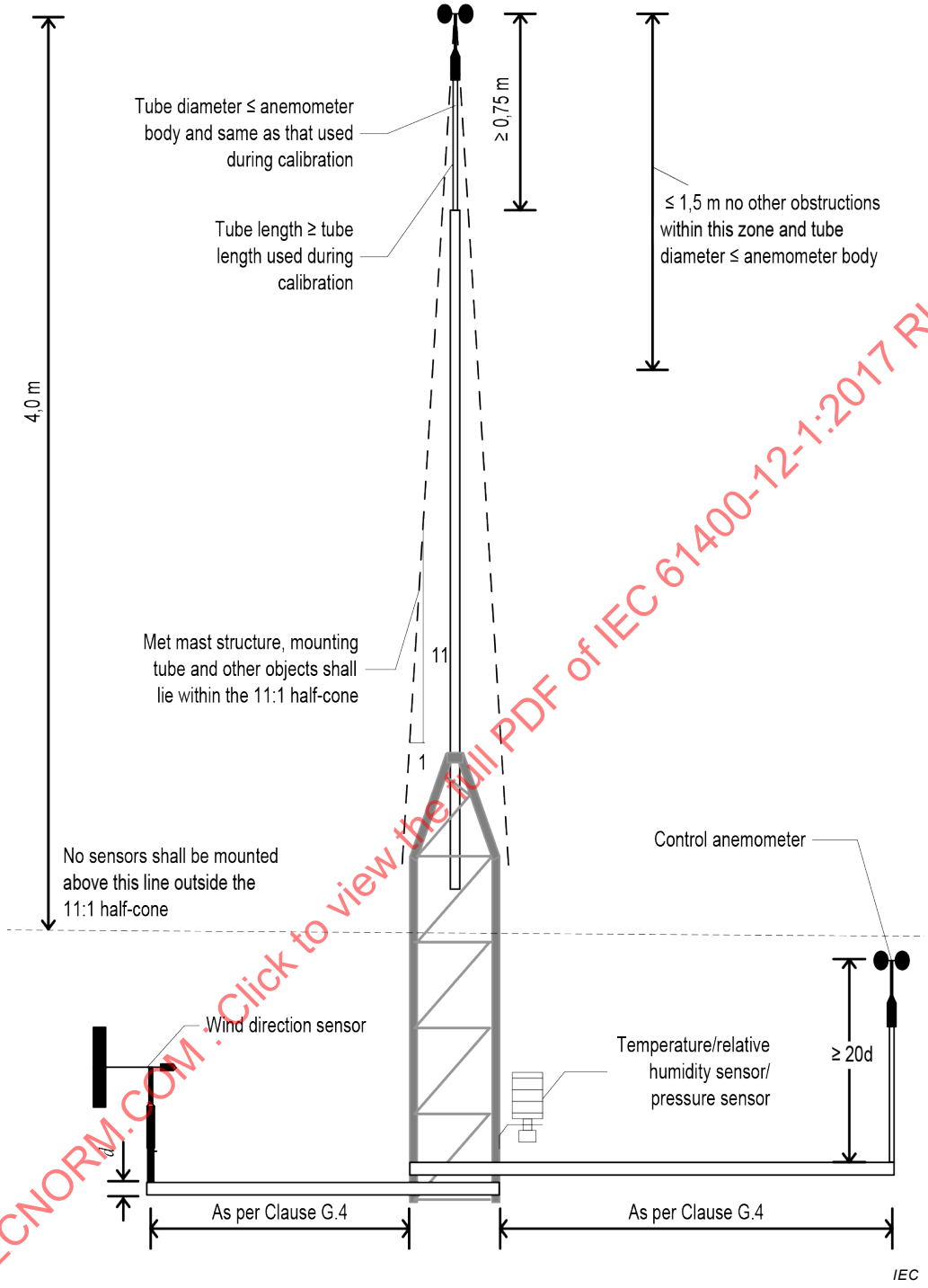

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Figure G.1 – Example of a top-mounted anemometer and requirements for mounting

G.3 Side-by-side top-mounted anemometers

In the side-by-side arrangement all mounting conditions in Clause G.2 shall be met in addition to those specified here. The anemometer cups shall be mounted above the boom by a minimum of 20 times the boom diameter, but 25 times the boom diameter is recommended. The boom, consisting of both the horizontal portion and vertical stems, shall be of round cross-section. The anemometers shall be separated by at least 2,5 m and no more than 4,0 m. No parts of the meteorological mast shall extend beyond a 11:1 half cone whose vertex is coincident with the midpoint between the cups of the two top-mounted anemometers (the top boom itself is excluded from this requirement provided that it meets the foregoing

dimensional criteria). No other instruments shall be positioned closer than 1,5 m to the anemometer cups nor outside the 11:1 half cone to a distance of at least 4 m below the anemometer cups. Figure G.2 shows an example of a side-by-side configuration. It is recommended that the boom is mounted concentric with the meteorological mast axis or centrally on the upwind side of the meteorological mast. The influence of one anemometer on the other shall be assessed and the measurement sector restricted such that the overall uncertainty of the wind speed measurement remains within the desired limits. The uncertainty due to flow distortion from other instruments, the meteorological mast and booms shall be determined.

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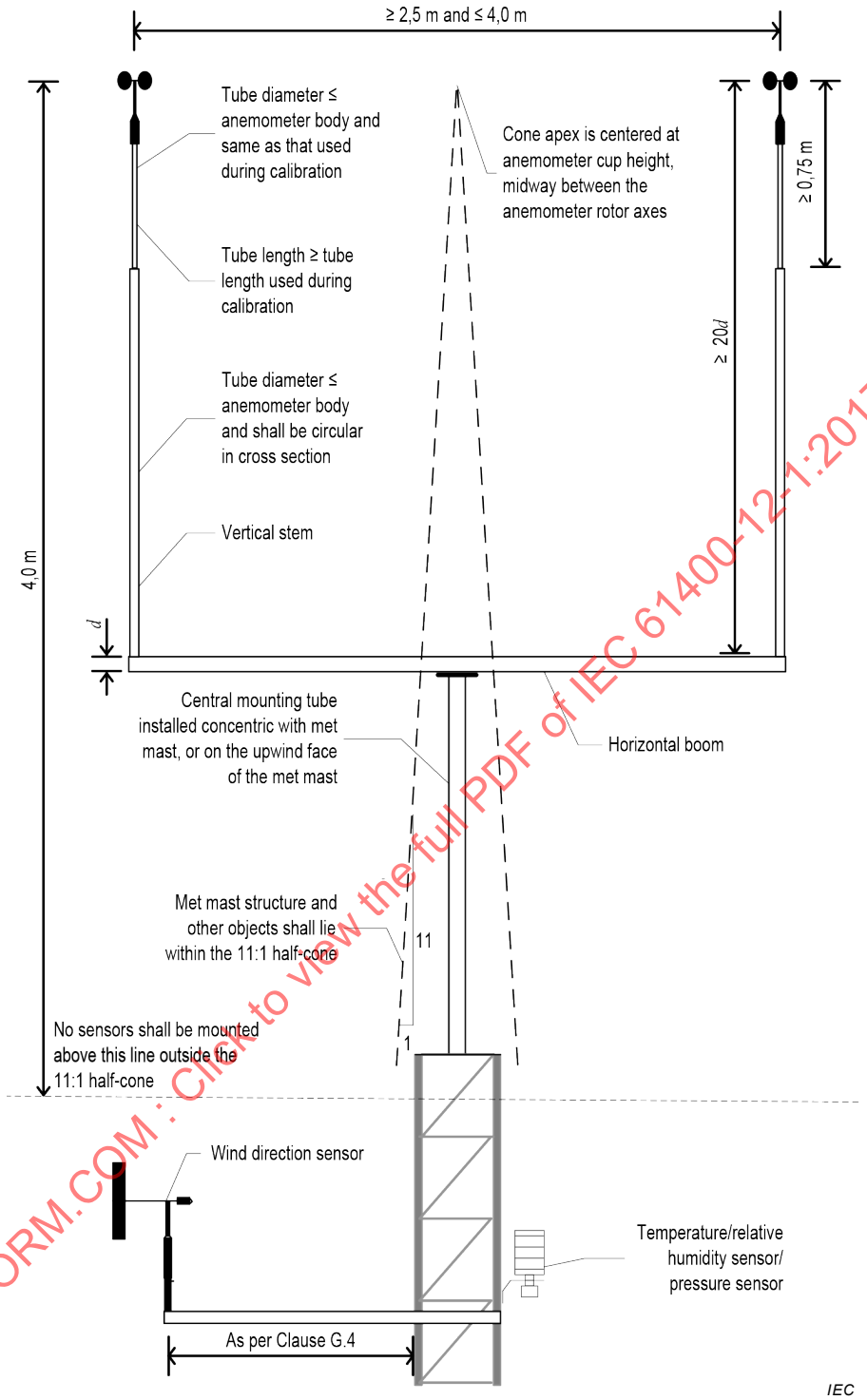

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Figure G.2 – Example of alternative top-mounted primary and control anemometers positioned side-by-side and wind vane and other instruments on the boom

G.4 Side-mounted instruments

G.4.1 General

Side-mounted instruments such as anemometers and wind direction sensors are influenced by flow distortion from the meteorological mast, boom and guy wires. The influence of a round tubular boom is 0,5 % at a separation distance of 20 boom diameters above the boom. Flow distortion at the anemometer cup location due to booms should be kept below 0,5 %. The

anemometer shall be mounted on a round vertical tube of the same (± 0,1 mm) outer diameter as used during calibration (and classification), but of no larger diameter than the body of the anemometer. Wind direction sensors should be mounted at a distance from the meteorological mast of no less than half of that recommended for anemometers. There shall be at least 20 boom diameter vertical separation from side-mounted instruments to booms above. This separation requirement applies where a side-mounted anemometer is being used as a control anemometer for another side-mounted anemometer at a different height as well as to the case where side-mounted anemometers at different heights are being used for wind shear measurement. In the case where the side-mounted anemometer is being used as a control anemometer to another side-mounted anemometer, the vertical separation to the primary instrument shall be in the range 4 m to 6 m where the side booms are on the same side of the mast as each other and pointing in the same direction. Alternatively the control anemometer side boom may be mounted at the same height as the other side-mounted anemometer but pointing in a different direction such that the flow distortion requirements at both anemometer locations are satisfied within the measurement sector.

An anemometer operating in the wake of the meteorological mast is highly disturbed. Measurements obtained in this condition shall not be used in the power performance analysis. Flow distortion upstream of the meteorological mast can be significant. Adequate separation shall be allowed between the anemometer and the meteorological mast to keep meteorological mast flow distortion below 1 %. Guidance for appropriate anemometer to meteorological mast separation is given in G.4.2 and G.4.3.

Wakes from meteorological mast guys can have a strong influence on anemometers over surprisingly long distances. Location of anemometers downstream of guys shall be avoided.

It is largely up to the user to determine what degree of disturbance and hence uncertainty is acceptable, but a suitable aim should be to avoid meteorological mast and boom induced flow distortions greater than 1 % and 0,5 %, respectively.

Meteorological masts can either be of cylindrical or lattice construction. The required separation of the anemometer from the meteorological mast depends upon the type of meteorological mast and solidity.

G.4.2 Tubular meteorological masts

An approximation of the flow disturbance in the vicinity of a tubular meteorological mast can be obtained from Figure G.3. This figure shows an iso-speed plot of the flow around a tubular meteorological mast from a Navier-Stokes analysis. The least disturbance can be seen to occur if facing the wind at 45°. More generally, it can be seen that there is a retardation of the flow upwind of the meteorological mast, acceleration around it, and a wake behind it. Due to the complexity of the flow in the mast wake influenced region, Figure G.3 is to be considered accurate only for the upwind zone of least disturbance as indicated by the green shading in the figure.

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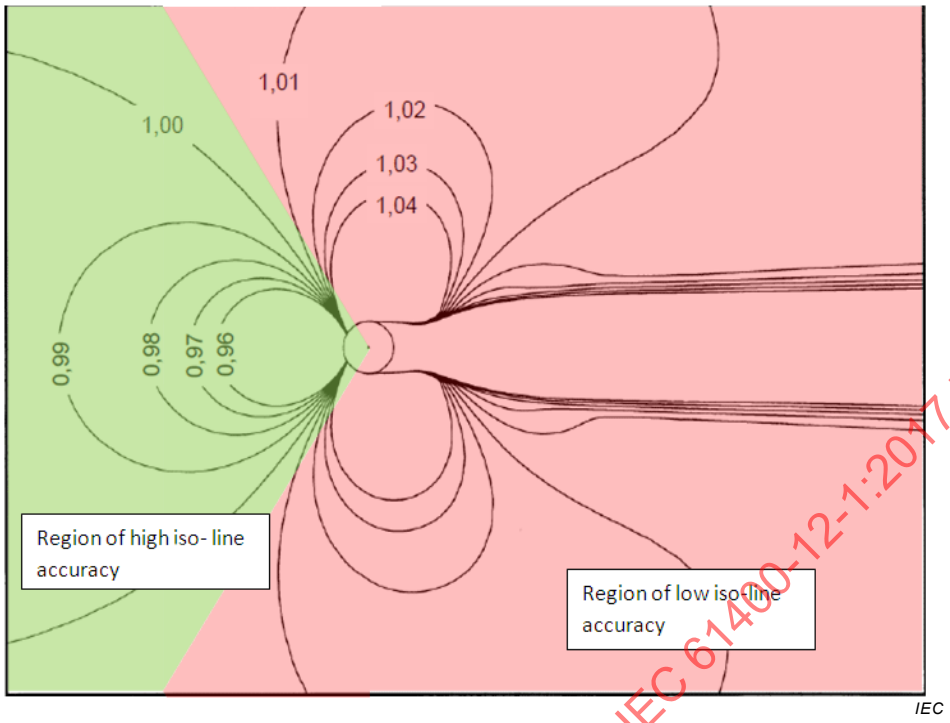

NOTE The speed is normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computations for which the green shaded region on the left is considered accurate and the red shaded region on the right inaccurate due to inaccuracies modelling flow in and behind the separation zone.

Figure G.3 – Iso-speed plot of local flow speed around a cylindrical meteorological mast

It is evident from Figure G.3 that for an anemometer mounted within the ±45° sector relative to the wind direction on the upwind side of the meteorological mast that the greatest distortion of the wind speed relative to free stream occurs when the anemometer is directly upwind of the meteorological mast. Figure G.4 shows the relative wind speed as a function of distance upwind of the meteorological mast[31].

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31 Note that wind speed distortion may be higher than shown in Figure G.4 if winds approach from angles greater than 45° from the anemometer – mast alignment.

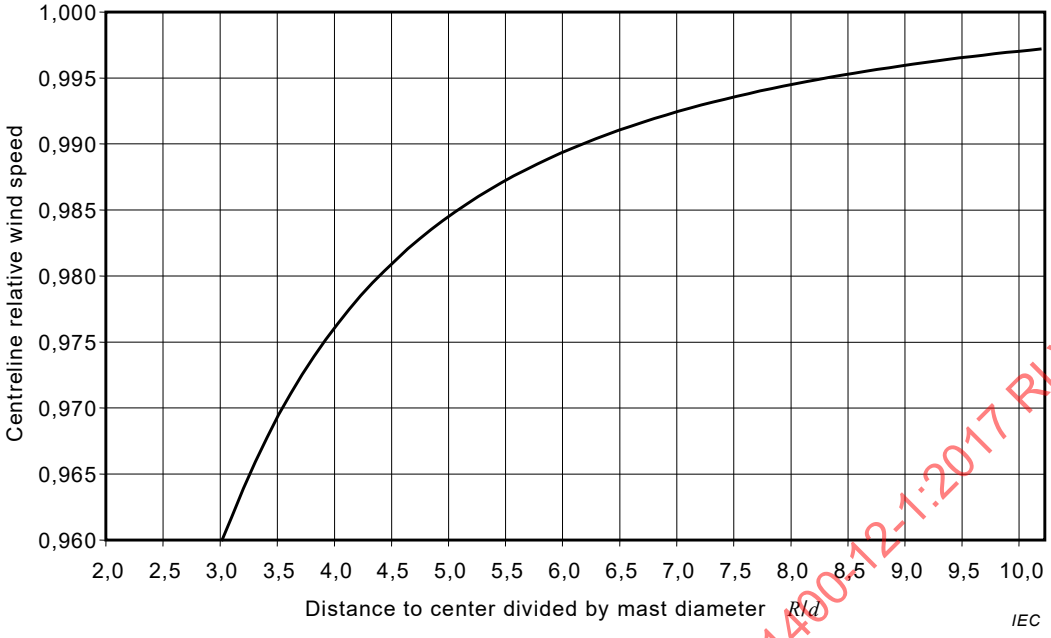
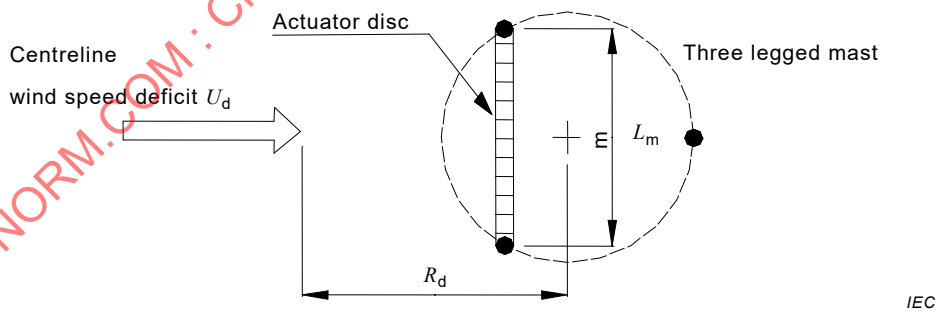


Figure G.4 – Centreline relative wind speed as a function of distance R_d from the centre of a tubular meteorological mast and meteorological mast diameter d

A 99,5 % relative wind speed is seen to occur at R_d/d of 8,2. The corresponding value for a 99 % relative wind speed is 6,1.

G.4.3 Lattice meteorological masts

Analysis of the flow around a lattice structure can be based upon a combination of actuator disc and Navier-Stokes theory and analysis. The degree to which flow is disturbed by the meteorological mast is a function of the solidity of the meteorological mast, the drag of the individual members, the orientation of the wind and the separation of the measurement point from the meteorological mast. Figure G.5 shows the dimensions of interest on a top-view of a triangular lattice meteorological mast.



NOTE The figure shows the centreline wind speed deficit, the actuator disc representation of the meteorological mast with the leg distance L_m and distance R_d from the centre of the meteorological mast to the point of observation.

Figure G.5 – Representation of a three-legged lattice meteorological mast

The flow distortion is a function of the assumed thrust coefficient, C_T, which in turn depends upon the solidity of the meteorological mast and the drag on the individual members. C_T can

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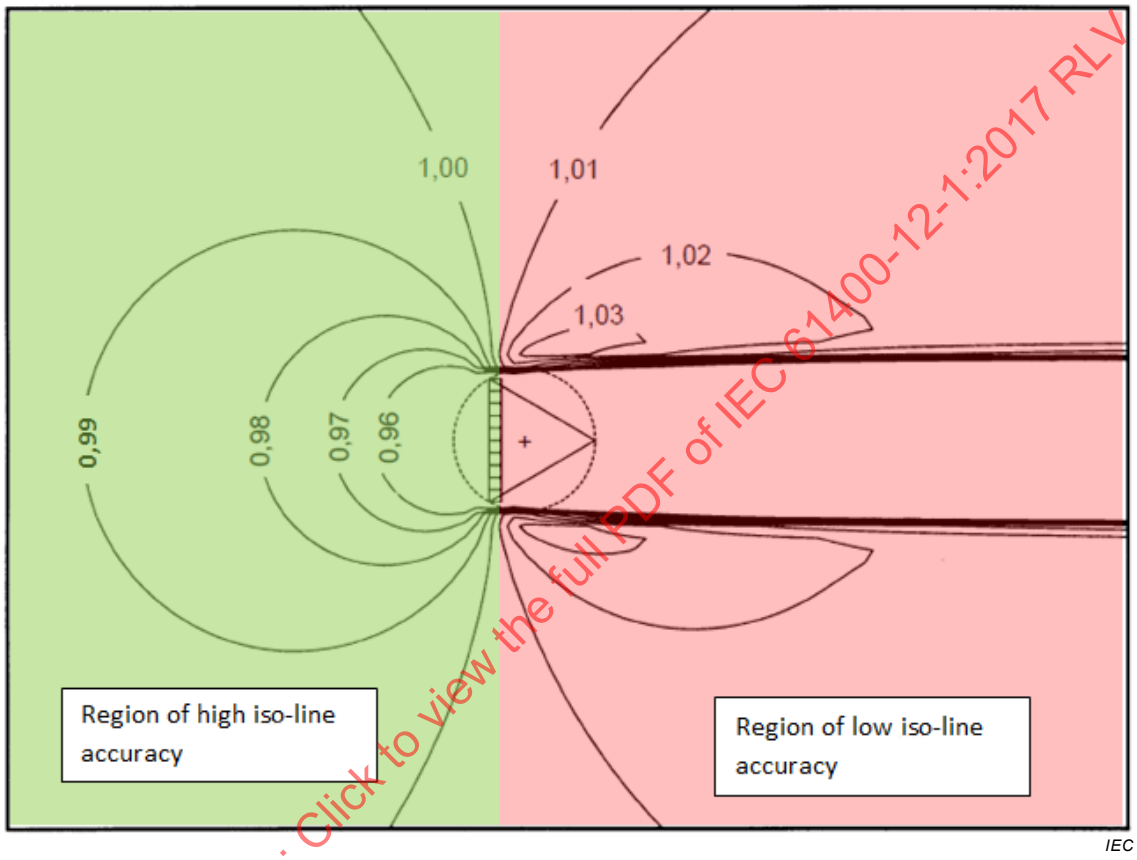
be regarded as the total drag force per unit length of the mast, divided by the dynamic pressure and the leg distance L_m[32].

Figure G.6 shows the computed flow around a lattice meteorological mast having a C_T of 0,5. At typical distances of the anemometer $R_d > 2$ times the meteorological mast leg distance , this flow disturbance is very little affected by meteorological mast orientation (whether the face or a corner is oriented into the wind), and it can therefore be assumed to be the same. However, Figure G.6 is to be considered accurate only for the upwind zone of least disturbance as indicated by the green shading in the figure.



NOTE The speed is normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computation and actuator disc theory for which the green shaded region on the left is considered accurate and the red shaded region on the right inaccurate due to inaccuracies modelling flow in and behind the separation zone.

Figure G.6 – Iso-speed plot of local flow speed around a triangular lattice meteorological mast with a C_T of 0,5

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32 The leg distance shall represent the face width. For significant leg diameters (leg diameter > 5 % of face width) one leg diameter should be added to the distance between the leg centres to get the leg distance.

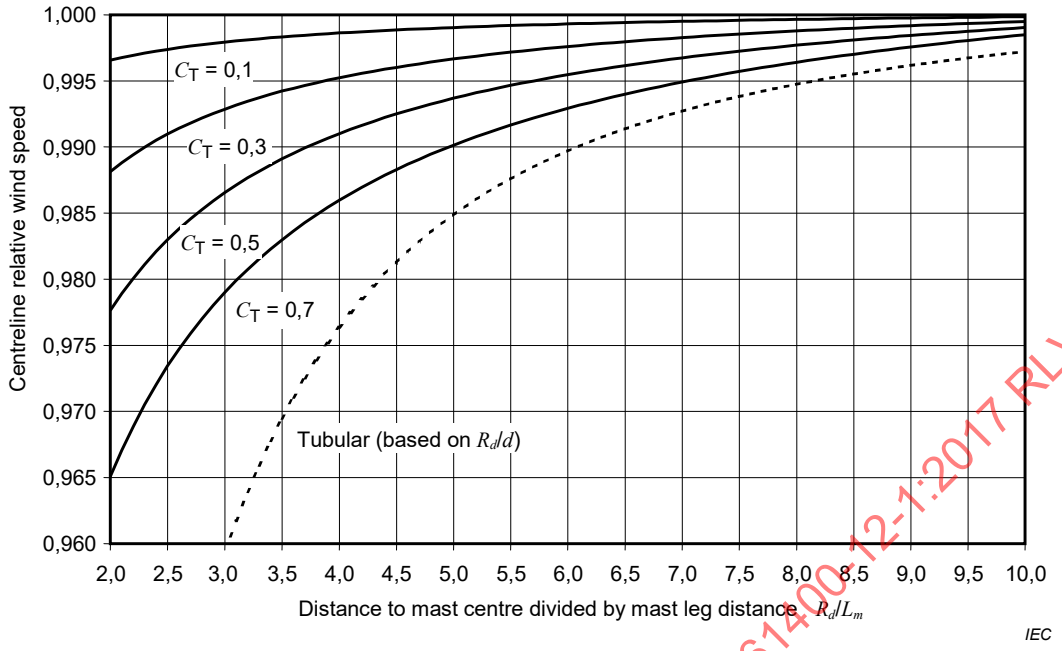

Figure G.7 – Centreline relative wind speed as a function of distance R_d from the centre of a triangular lattice meteorological mast of leg distance L_m for various C_T values

When the flow direction is perpendicular to a meteorological mast face, minimum distortion is obtained when the anemometer is placed at an angle of 90° to the flow direction. Otherwise, the flow distortion may be determined by considering the upwind deficit as a function of distance. Figure G.7 shows the computed centreline relative wind speeds for lattice towers having various C_T values. Note, however, that wind speed distortion may be higher than shown in Figure G.7 if winds approach from angles greater than 100° from the anemometer boom alignment.

The equation below may be used to estimate the centreline wind speed deficit U_d as a function of C_T and R_d/L_m:

$$U_d = 1 - \left(0{,}062C_T^2 + 0{,}076C_T\right) \cdot \left(\frac{L_m}{R_d} - 0{,}082\right) \quad \text{(G.1)}$$

C_T can be estimated from local building codes or, within the ranges specified, from Table G.1. In this table, the solidity S is defined as the ratio of the projected area of all structural members on the side of the meteorological mast to the total exposed area.

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Table G.1 – Estimation method for C_T for various types of lattice mast

Type of mast	Plan section	Expression for C_T	Valid range
Square cross-section, members with sharp edges		$4{,}4(1 - S)S$	$0{,}1 < S < 0{,}5$
Square cross-section, round members		$2{,}6(1 - S)S$	$0{,}1 < S < 0{,}3$
Triangular cross-section, round members		$2{,}1(1 - S)S$	$0{,}1 < S < 0{,}3$

Alternatively, if the desired maximum centreline wind speed deficit is specified, the distance R_d may be obtained from the following equation:

$$R_d = \frac{L}{\frac{1-U_d}{(0{,}062C_T^2 + 0{,}076C_T)} + 0{,}082} \quad \text{(G.2)}$$

For a lattice meteorological mast with a C_T of 0,5 and a 99,5 % centreline wind speed deficit, R_d shall be 5,7 times the meteorological mast leg distance L_m. A wind speed deficit of 99 % will reduce the distance R_d to 3,7 times the meteorological mast leg distance.

The above equations and charts represent somewhat idealised meteorological mast geometry and flow conditions. It should be noted that the flow interference will be significantly more complex in those cases where secondary support structures such as lattice work, cross-bracing, cable ladders, flanges and attachment brackets are also present at or near the height level of the anemometer or where the flow direction is not parallel to the meteorological mast cross section axis of symmetry. Figure G.8 illustrates the CFD derived flow (from the left) where the relative position and hence influence of the cross-bracing on the flow distortion changes with height. Note that the distortion is asymmetric but that the optimum location for minimum flow distortion is still at 90° to the flow direction.

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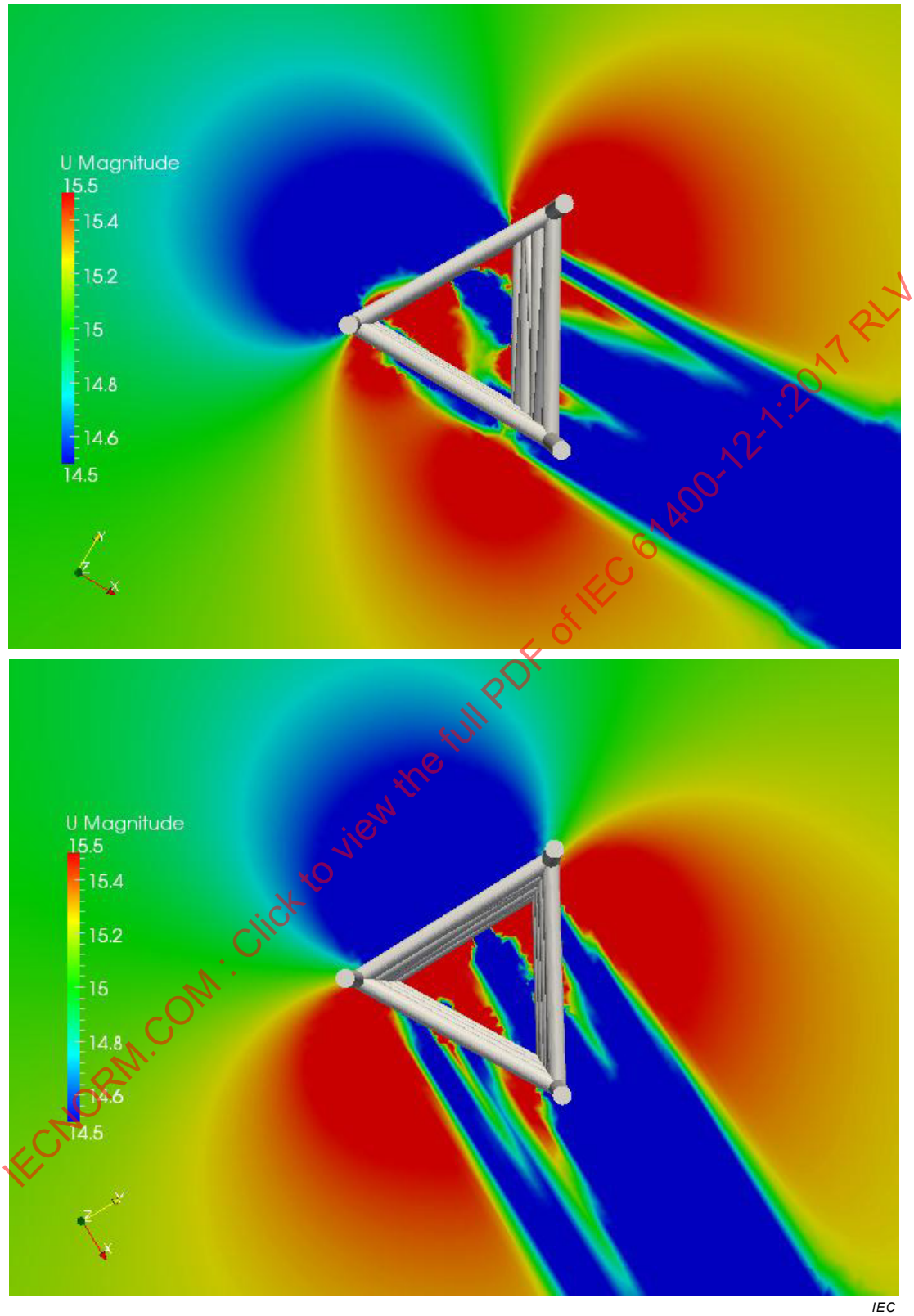

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Figure G.8 – 3D CFD derived flow distortion for two different wind directions around a triangular lattice meteorological mast (C_T = 0,27) – For flow direction see the red arrow lower left in each figure

G.5 Lightning protection

A lightning finial (attractor) can protect the top-mounted instruments. If lightning protection is installed, a number of precautions shall be taken. The lightning finial should be mounted at the top of the meteorological mast in such a way that:

a) the anemometer is separated horizontally by at least 30 times the finial diameter from the finial;

b) the anemometer is not in the wake of the finial when the wind is in the measurement sector;

Where these conditions cannot be met, then the flow distortion on the anemometer shall be assessed and an additional uncertainty shall be added.

G.6 Mounting of other meteorological instruments

The control anemometer should be located as close to the primary anemometer as possible, whilst still satisfying the minimum separation requirements of Clauses G.2 to G.4, in order to provide a good correlation between the two instruments during the test. This correlation should be validated to ensure that the primary anemometer does not change its calibration during the test. However, the control anemometer shall not interfere with the primary anemometer and shall also be free of flow disturbance from other instruments.

The wind direction sensor shall be mounted 4 m to 10 m below the primary anemometer. It shall be mounted so that flow distortion effects are minimized with respect to the measurement sector. The horizontal separation of the wind direction sensor from the meteorological mast should be at least half that required for an anemometer.

Except in the case where a meteorological mast shorter than hub height is being used in conjunction with a remote sensing device, temperature, humidity and pressure sensors shall be located within 10 m 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 Clauses G.2 and G.3. The temperature sensor shall be mounted in a radiation shield. The pressure sensor may be mounted in a weatherproof box. However, care should be taken to ensure that the box is properly vented so that pressure readings are not influenced by the pressure distribution around the box.

If the meteorological mast available for the power performance test is shorter than hub height (specifically when a shorter meteorological mast is used in conjunction with a remote sensing device as defined in Annex L), temperature, humidity and pressure sensors shall be located at a height within 1,5 m to 10 m of the primary anemometer. Atmospheric pressure shall be adjusted to hub height following this standard. Furthermore, the air temperature shall be adjusted to hub height assuming that the atmosphere varies according to ISO 2533:1975. Alternatively a temperature sensor shall be mounted on the wind turbine nacelle. The sensor shall be mounted at least 1 m above the nacelle and upwind of any existing ventilation systems.

Examples of suitable arrangements for other meteorological instruments and top-mounted anemometers are shown in Figure G.1 and Figure G.2.

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Annex H
(normative)

Power performance testing of small wind turbines

H.1 General

Small wind turbines (as defined by IEC 61400-2) require special provisions for power performance testing. In particular, wind turbines used to charge batteries shall be tested in a way that is representative of normal operation but that reduces or eliminates the influence of the particular battery configuration and condition used during testing, and wind turbines that use inverters for grid connection shall be tested in conjunction with those inverters to give results representative of normal operation. In all cases the relevant power is useful power to the consumer, thus power is the power injected into the grid for grid connected wind turbines, similarly power delivered to the batteries for battery charging wind turbines. When testing a small wind turbine, all requirements described in this standard shall be met with the following additions and changes.

H.2 Definitions

Maximum power, P_{60}: maximum one-minute average power output a wind turbine in normal steady-state operation will produce (peak instantaneous power output can be higher).

Reference power: the averaged power level in the 11 m/s wind speed bin.

Reference annual energy production: The AEP measured at 5 m/s annual average wind speed, Rayleigh distributed, using the sea level density corrected power curve.

H.3 Wind turbine system definition and installation

With respect to 6.2, the following is required:

a) When characterising battery charging performance, the wind turbine generator system shall include the wind turbine, wind turbine tower, wind turbine controller, wiring between the wind turbine and the load, and charge controller, which is a voltage protection device that reduces wind turbine power output when batteries are fully charged. It may include a dump load that is used to dissipate energy from the wind turbine when the batteries are fully charged. The wind turbine generator system does not include a battery bank because it is considered part of the load. Other energy storage devices may be substituted for batteries throughout this clause;

b) when characterising system output to a grid, the wind turbine generator system shall include the wind turbine, wind turbine tower, wind turbine controller, wiring between the wind turbine and the load, and any additional controllers. In addition, the system may include a voltage inverter. If a transformer is installed between the voltage inverter and the grid, it may be considered as either part of the wind turbine generator system or the load. If the grid-connected wind turbine system incorporates a battery bank and/or dump load, it shall be considered part of the system;

c) the wind turbine shall be connected to an electrical load that is representative of the load for which the wind turbine is designed. In the case of battery charging applications, the load consists of a battery bank, a voltage regulator, and a means to dissipate the power that passes through the voltage regulator (or dump load). In the ideal test set-up, the battery bank does not store energy produced by the wind turbine. Rather all wind turbine output is routed through the voltage regulator. Therefore, the battery bank may be smaller than typically recommended for the wind turbine as long as voltage at the connection of the wind turbine to the load can be maintained within the specifications stated below;

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d) the wind turbine shall be installed using the manufacturer's specified mounting system. If a wind turbine is not supplied with a specific mounting system, the wind turbine generator should be mounted at a hub height of at least 10 m;

e) in order to minimize differences in results due to wiring between the wind turbine and the load, the total wire run length, measured from the base of the tower to the load, shall be at least 8 rotor diameters. Wiring between the small wind turbine and the load shall be in accordance with the manufacturer's specifications for this wire run length. If the specifications provide for a range of wire sizes, wires shall be sized as close as possible to the average of that range. If no specifications are provided, the wiring shall be sized so that voltage drop between the wind turbine generator and the load is equivalent to 10 % of nominal voltage at rated power;

f) the voltage regulator shall be capable of maintaining voltage at the connection of the wind turbine to load within 10 % of the settings given in Table H.1 over the full range of power output of the wind turbine. The 1-minute average of the load voltage shall be within 5 % of the settings given in Table H.1 to be included in the usable data set.

H.4 Meteorological mast location

With respect to 6.3.2 the following is required:

a) If it is more practical to mount the anemometer on a long boom that is connected to the wind turbine tower, a separate meteorological mast is not required. To minimize the flow distortion on the small wind turbine rotor from the wake from the anemometer, the wind vane and their mounting hardware, all such components shall be located at least 3 m away from any part of the wind turbine rotor. In addition, the anemometer mounting should be configured to minimize its cross-sectional area above the level that is 1,5 rotor diameters below hub height. The boom shall be installed such that structural vibrations are not introduced into the wind speed signal;

b) for vertical axis wind turbines hub height is defined as the height of the centroid of the swept area of the wind turbine rotor;

c) for vertical axis wind turbines the distance between wind turbine and meteorological mast is illustrated in Figure H.1.

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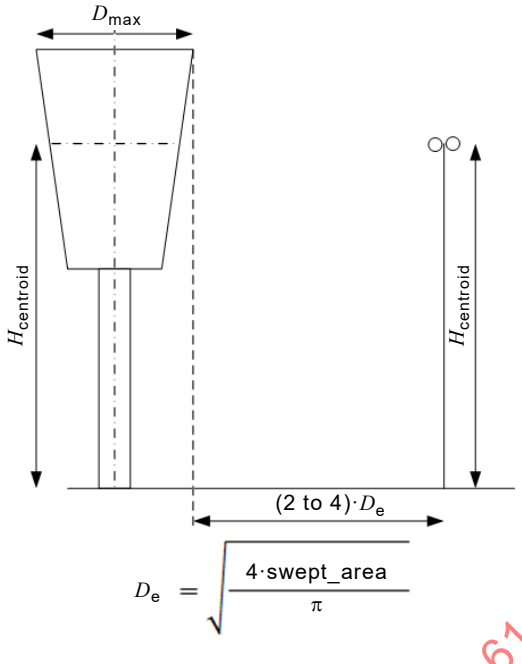

Figure H.1 – Definition of hub height and meteorological mast location for vertical axis wind turbines

H.5 Test equipment

a) In 7.1 when measuring DC outputs for battery charging wind turbines with a swept area of 40 m^2 or less, the use of measurement equipment with an accuracy of 2 % or better is permitted for the purposes of measuring current and power, rather than the 0,5 % accuracy referred to in 7.1;

b) in 7.1: wind turbine output power shall be measured at the connection to the load as defined in Clause H.3;

c) also in 7.1: in addition to electric power, voltage at the connection to the load shall be measured to ensure compliance with the requirements listed in Clause H.3;

d) also in 7.2.2: the anemometer mounting guidance provided in Annex G should be followed. If deviations are made the reason for doing so needs to be documented in the test report and additional uncertainty shall to be added to the analysis. In extreme cases, it is permissible to temporarily use an anemometer other than the control anemometer if it can be demonstrated that a good correlation exists between the control anemometer and this third anemometer. Additional uncertainty will have to be used in the analysis to accommodate for the uncertainties in the correlation;

e) also in 7.2.3: anemometer shall be mounted at the top of a meteorological mast at hub height ± 2 % relative to the ground at the meteorological mast;

f) in 7.2.6: no wind shear needs to be measured;

g) in 7.4: measurement of relative humidity and correction for it is optional;

h) also in 7.4: the air temperature sensor, air pressure sensor, and humidity sensor, if used, shall be mounted so that they are at least 1,5 rotor diameters vertical distance from hub height and within 100 m horizontal distance of the hub;

i) in 7.7: monitoring of small wind turbine status is recommended but is not mandatory.

H.6 Measurement procedure

a) in 8.2: if the wind turbine's charge controller reduces wind turbine output at the optional high voltage setting, the charge controller may be adjusted to a higher voltage. If the

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charge controller is adjusted, the test report shall document the settings before and after adjustment. Any other adjustments to the wind turbine's controls shall be clearly reported;

b) in 8.3: pre-processed data shall be of 1 min duration. All subsequent references to 10-min data sets in the standard shall apply to 1 min data sets when testing small wind turbines;

c) in 8.4: add bullet for data rejection

– 1 min average of the load voltage is not within 5 % of the settings given in Table H.1;

d) in 8.5: the database shall be considered complete when it has met the following criteria:

1) each wind speed bin between 1 m/s below cut-in and 14 m/s shall contain a minimum of 10 min of sampled data;

2) the total database contains at least 60 h of data with the small wind turbine within the wind speed range defined in bullet 1);

3) in the case of furling wind turbines, the database should include completed wind speed bins characterizing performance when the wind turbine is furled.

e) it is recommended that additional performance data be obtained to quantify the effect that changes of battery bank voltage have on wind turbine performance. These additional power curves should be obtained by setting the battery bank voltage to the optional low and high settings listed in Table H.1, and by obtaining at least 30 h of data using 1-min pre-averaging. When reporting these power curves, the tables and graphs shall clearly indicate that they show performance at optional low and high voltage settings and shall indicate those voltage settings. It is recommended that a single graph be used to show the variation of power with wind speed and battery bank voltage.

Table H.1 – Battery bank voltage settings

Nominal voltage V	Required setting V	Optional low setting V	Optional high setting V
12	12,6	11,4	14,4
24	25,2	22,8	28,8
36	37,8	34,2	43,2
48	50,4	45,6	57,6
Other	2,1*	1,9*	2,4*
* Volts per cell			

H.7 Derived results

a) in 9.1: for wind turbines with passive power control such as furling or blade fluttering, wind speed shall be sea level normalised using Equation (14) (wind speed normalisation), Equation (13) (power normalisation), or an alternative method. Documentation shall be provided to justify the use of an alternative method; However, if the wind turbine is already adjusted to adapt to the site specific air density, this should be reported and no additional normalisation is allowed;

b) in 9.1.6: for small wind turbines, the turbulence correction is not recommended, however if it is carried out it shall be reported whether the method is applied for 1 min averages instead of 10 min averages of the measured power and wind speed, and either are permitted. If the turbulence correction is applied the power curves both with and without turbulence correction shall be reported and clearly identified;

c) in 9.3: in cases where the small wind turbine does not shut down in high winds, AEP measured and AEP extrapolated shall be calculated as though cut-out wind speed were the highest, filled wind speed bin or 25 m/s, whichever is greater.

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H.8 Reporting

In Clause 10: in addition to the information listed in Clause 7, the description of the wind turbine and the test set-up shall include:

a) wiring sizes, conductor material, types, lengths and connectors used to connect the wind turbine to the load;

b) voltage setting(s) for any over or under-voltage protection devices that are part of the small wind turbine generator system;

c) nominal battery bank voltage (e.g. 12 V, 24 V, 48 V);

d) battery bank size (i.e. amp-hour capacity), battery type and age;

e) description including make, model, and specifications of the voltage regulation device used to maintain the battery bank voltage within specified limits;

f) reference power;

g) the calculated annual energy production based on AEP-measured and a Rayleigh wind speed distribution with an average wind speed of 5 m/s and the sea level density normalised power curve shall be reported as the Reference Annual Energy;

h) the 1 min turbulence intensity for each data set (sequential, unbroken, time series) as a scatter plot across the observed wind speed range.

H.9 Annex A – Assessment of influence cause by wind turbines and obstacles at the test site

a) The requirements in Table A.1 may be relaxed to accommodate small wind turbines but additional uncertainty should be included for the wind speed uncertainty. However, do not disregard other sections of Annex A (i.e. the method for excluded sectors due to obstacles).

H.10 Annex B – Assessment of terrain at test site

a) In recognition of the typical environments where small wind turbines are installed the maximum slope requirements in Table B.1 may be increased to 10 % for all distances and all directions. However, additional uncertainty in wind speed should be added.

H.11 Annex C – Site calibration procedure

a) in C.3.2: additional measurements to characterize wind shear are not recommended. This includes vertical wind speed and wind veer measurements;

b) In Clause C.5: disregard analysis for wind shear and atmospheric stability;

c) also in Clause C.5: wind shear measurements are not required at both meteorological masts;

d) also in Clause C.5: for each 1-minute data point, the wind speed ratio shall be calculated, which is the hub height wind speed at the wind turbine meteorological mast location divided by the hub height wind speed at the reference meteorological mast;

e) in C.5.1 and C.5.2: these subclauses will be disregarded;

f) in C.5.3: this subclause will be used for site calibration analysis;

g) for site calibration for small wind turbines, it is acceptable to use the wind turbine support tower rather than a meteorological mast at the wind turbine location, provided that flow distortion requirements are satisfied.

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Annex I
(normative)

Classification of cup and sonic anemometry

I.1 General

Cup and sonic anemometers are wind measurement instruments that may be used for power performance measurements. In order to transfer traceability they shall be calibrated in a wind tunnel according to Annex F. Wind tunnel calibrations are performed under controlled environmental conditions with a smooth and low turbulent flow. However, during measurements and operation in the field, these instruments are subject to turbulent flow and environmental conditions that can deviate significantly from wind tunnel calibration conditions. The field conditions may significantly influence the instrument characteristics and cause the instrument output to deviate from wind tunnel calibrations. If the ranges of the influential parameters during field operation are determined, then the systematic deviations may be analysed and the deviations in instrument output may be put into a classification scheme.

Known influence parameters on cup anemometer measurements are turbulence, air temperature, air density, and average upflow angle. Known influence parameters on sonic anemometer measurements are wind direction, upflow angle, and air temperature. These influence parameters shall be considered in the classification. Other environmental parameters may influence the instruments. If such influence parameters are known to give systematic deviations, the influence shall be analysed and included in the classification scheme. Furthermore, the combined effect of all influential parameters shall be assessed. The systematic deviations due to influential parameters shall be analysed according to the procedures described in Annex J resulting in a classification specification of the type of anemometer. At least five samples of the anemometer type shall be assessed. Modification of an anemometer type that may influence the output requires a new assessment. Change in geometry of the anemometer type, measurement principle, software algorithm for calculation of the output, software settings, or supporting structure geometry, requires a new assessment.

The classification method only considers normal operation of the sensors. The method does not consider, for example wear, malfunctioning or icing (see Annex O).

I.2 Classification classes

The classification of an anemometer type is divided into five classes dependent on the purpose. Class A, B, C and D are based on predefined terrain and climate ranges, see Table I.1. Class A and C shall be used for terrain that meets the requirements in Annex B and in type A terrain in C.3.1. Class B and D shall be used for terrain that does not meet the requirements in Annex B. Class B and D could be used in terrain type B in C.3.1. If information about the influence parameter ranges during the measurements are available then class S may be used.

Class S is a special class, where the influence parameter ranges may be defined by the user, see Table I.1. This may be for a special climate, for example cold climate conditions, see Annex O. The class S may also be used for uncertainty estimate for a measurement campaign where the influence parameter ranges are determined during the measurements. Class S may be used for measurements in type A, B and C terrain, see C.3.1.

The classification number k shall be used in determination of the wind speed operational characteristics uncertainty, as listed in Annex D (Table D.1).

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Annex B provides an assessment of the terrain to evaluate if the flow distortion due to the terrain will be significant. For classification of cup and sonic anemometers, this terrain assessment supports the definition of the classification classes A, B, C and D.

Class A: Associated with terrain that meets the requirements of Annex B and with general influence parameter ranges for this type of terrain.

Class B: Associated with terrain that does not meet the requirements of Annex B and with general influence parameter ranges this type of terrain.

Class C: Same as class A but with temperatures down to –20 °C.

Class D: Same as class B but with temperatures down to –20 °C.

For terrain or climate that deviates from classes A to D a class S climate may be specified.

Class S: Associated with conditions that deviates from class A, B, C or D. In this class, the user defines the influence parameter ranges. This may be due to special or user defined terrain or climate conditions.

I.3 Influence parameter ranges

The minimum required influence parameter ranges of cup and sonic anemometer classification are listed in Table I.1.

I.4 Classification of cup and sonic anemometers

The classification of an anemometer is specified by the amount of systematic deviations from calibrated values (calibration according to Annex F) where the systematic deviations are determined for values varying within the influence parameter ranges. For a sonic anemometer and for directional sensitive cup anemometers, a reference direction that is used for calibrations according to Annex F shall be defined for the instrument type. The systematic deviations shall be derived for all values that are relevant for the class determination between min and max values for each parameter. The class number k_n of an anemometer sample number n shall be determined as the maximum systematic deviation from the wind tunnel calibration value, weighted with a wind speed function ε_i:

$$k_n = 100 \cdot \max\left|\varepsilon_i / w_i\right| \tag{I.1}$$

where

k_n is the class number of anemometer sample number n (n=1…5 or more);

w_i is a weighting function in m/s that defines the deviation envelope, see Equation (I.2);

ε_i is the deviation in m/s for influence parameter combination i.

The weighting function w_i averages the influence of absolute and relative deviations[33]:

$$w_i = 5 \text{ m/s} + 0{,}5 \cdot U_i \tag{I.2}$$

where

U_i is the wind speed in m/s for influence parameter combination i.

33 A class number of 1 corresponds to 1 % at 10 m/s but more than 1 % below 10 m/s and less than 1 % above 10 m/s.

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Table I.1 – Influence parameter ranges (10 min averages) of Classes A, B, C, D and S

	Class A **Terrain meets requirements in Annex B**	**Class B** **Terrain does not meet requirements in Annex B**	**Class C** **Terrain meets requirements in Annex B**	**Class D** **Terrain does not meet requirements in Annex B**	**Class S**[34] **Special class with user defined ranges**
	Range	Range	Range	Range	Range
Wind speed V (m/s)	4 to 16	4 to 16	4 to 16	4 to 16	4 to 16
Turbulence intensity	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	0,03 to 0,12 + 0,48/V	0,03 to 0,12 + 0,96/V	User defined
Turbulence [35] structure $\sigma_u/\sigma_v/\sigma_w$	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	1/0,8/0,5*	User defined or 1/0,8/0,5*
Air temperature (°C)	0 to 40	−10 to 40	–20 to 40	−20 to 40	User defined
Air density (kg/m^3)	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	0,9 to 1,35	User defined
Average upflow angle (°)	−3 to 3	−15 to 15	−3 to 3	−15 to 15	User defined
Wind direction (°)[36]	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups and sonics: 0° to 360°	Cups: 0° to 360° Sonics: user defined
* A non-isotropic Kaimal turbulence spectrum with turbulence length scale 350 m.					

For the five anemometer samples being tested for classification, the class is determined by the average of the k values plus half the range divided by $\sqrt{3}$ assuming a rectangular distribution (see Equation (I.3)).

$$k = \frac{1}{5}\sum_{n=1}^{5} k_n + \frac{k_{\max} - k_{\min}}{2} \cdot \frac{1}{\sqrt{3}} \tag{I.3}$$

A classification, referring to a certain class, is expressed by kA, kB or kS, for example 1,7A or 2,5S. The operational characteristics standard uncertainty (see Table D.1) of a cup or sonic anemometer may be derived from the classification assuming a rectangular uncertainty distribution, in which case the standard uncertainty to be used in the power performance uncertainty assessment is:

$$u_{v2\,j} = (0{,}05\ \mathrm{m/s} + 0{,}005 \times U_j) \times k / \sqrt{3} \tag{I.4}$$

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34 The influence parameter ranges determined during a power performance measurement includes some parameters that are measured as part of the performance measurement: wind speed, turbulence, air temperature, air density. The upflow angle may be determined during a site calibration by mounting a bi-vane or three-dimensional sonic anemometer at hub height on the meteorology mast temporarily mounted at the wind turbines foundation. Upflow angle on the turbine may be determined with a spinner anemometer.

35 For generation of artificial wind, see for example Clause J.4.

36 If a cup anemometer is directional sensitive (should be investigated on at least one sample), then directivity shall be included in the classification. For sonic anemometers directivity shall always be included in the classification, but for class S the wind direction range may be defined by the user.

An example of a classification is described in Annex J.

I.5 Reporting format

Classification reporting of the wind speed sensor shall specify all relevant details of the sensor, including all settings. Documentation of the class of a sonic anemometer shall specify the programmed configuration for which the classification is valid.

Relevant documentation shall be provided with detailed information on the procedures followed, the measurements performed as background for the classification, and documentation of the facilities and instruments used.

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Annex J
(normative)

Assessment of cup and sonic anemometry

J.1 General

Assessment of anemometry for classification shall be derived from traceable wind tunnel tests, other laboratory tests and associated modelling of anemometer characteristics. A thorough assessment method should also include verification field tests.

An assessment of a type of cup or sonic anemometer shall include verified procedures to determine the influence of the following basic characteristics (also note Table I.1):

- tilt angular response characteristics;
- yaw angular response characteristics;
- temperature induced effects on the anemometer performance.

Additionally, for cup anemometers the following characteristics shall be assessed:

- dynamic effects due to rotor torque characteristics.

Clause J.2 describes procedures for measuring anemometer characteristics. Clause J.3 describes a method for classification of cup anemometers with an example and Clause J.4 describes a method for classification of sonic anemometers. An actual assessment shall be based on the methodologies in Clauses J.3 and J.4, but could also be based on other assessment methods, as long as they include verified procedures to incorporate influence of the parameters in Table I.1. Clause J.5 presents a method for field comparison of anemometers.

J.2 Measurements of anemometer characteristics

J.2.1 Measurements in a wind tunnel for tilt angular response characteristics of cup anemometers

The tilt angular response is the measured wind speed at inclined flow angles relative to the measured wind speed at non-inclined flow. The tilt angular response of a cup anemometer shall be measured in a wind tunnel that fulfils the requirements described in Annex F. Additionally it shall be documented that the wind tunnel is sufficient in height for obtaining accurate tilt response characteristics.

The behaviour of an anemometer is strongly influenced by the free space around and especially underneath and above the anemometer. It is important that the tilting mechanism is designed in such a way that the centre of the sensing part of the anemometer is fixed but free to rotate, and the bottom plate of the wind tunnel shall be closed in order to prevent adverse flow effects. Therefore no translatory motion may be performed by the rotor, instead only an inclination of the rotor plane is realized.

The tilt angle response may be measured with two alternative methods, one using a sweep and the other using fixed positions.

The determination of the anemometer's response to quasi statically inclined flow should be performed with the help of an automatic tilt angle device installed in the wind tunnel. During the measurements, the anemometer is slowly tilted back and forth with a very slow sweep rate (less than 0,05°/s) so the influence on the results due to the angular speed can be neglected. Sweeps may only be used if the wind speed in the wind tunnel is kept within 0,5 % of the nominal wind speed for all tilt angles.

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At non-inclined flow, the tilt angle shall be fixed and measurements shall be performed for 300 s to ensure that sufficient data is collected for the zero bin (±0,5°). This zero bin data is used for normalisation of the tilt angular response.

Recording of tilt angle, wind tunnel wind speed and anemometer output shall be made simultaneously and averaged. It can be meaningful to incorporate a finer resolution of the bin-averaging algorithm to account for higher gradients in the tilt angle response around zero degrees.

The tilt angular response should alternatively be determined by stepwise fixed position measurements, where the response at each angle is determined by Annex F wind tunnel calibration at selected nominal wind speeds in the wind speed range.

Measurement matrix recommendations:

a) definition of flow angle: positive for upwards flow on cup rotor;

b) tilt angle range and steps: at least –30° to +30° (for example ±0°, ±1°, ±2°, ±3°, ±4°, ±6°, ±8°…±30°);

c) wind speed range and steps: 4 m/s to 16 m/s (for example 4 m/s, 8 m/s, 12 m/s and 16 m/s);

d) bin averaging range for the sweep method: bin width max 2°.

An example of tilt angular response (including the "ideal" cosine shape) is shown in Figure J.1.

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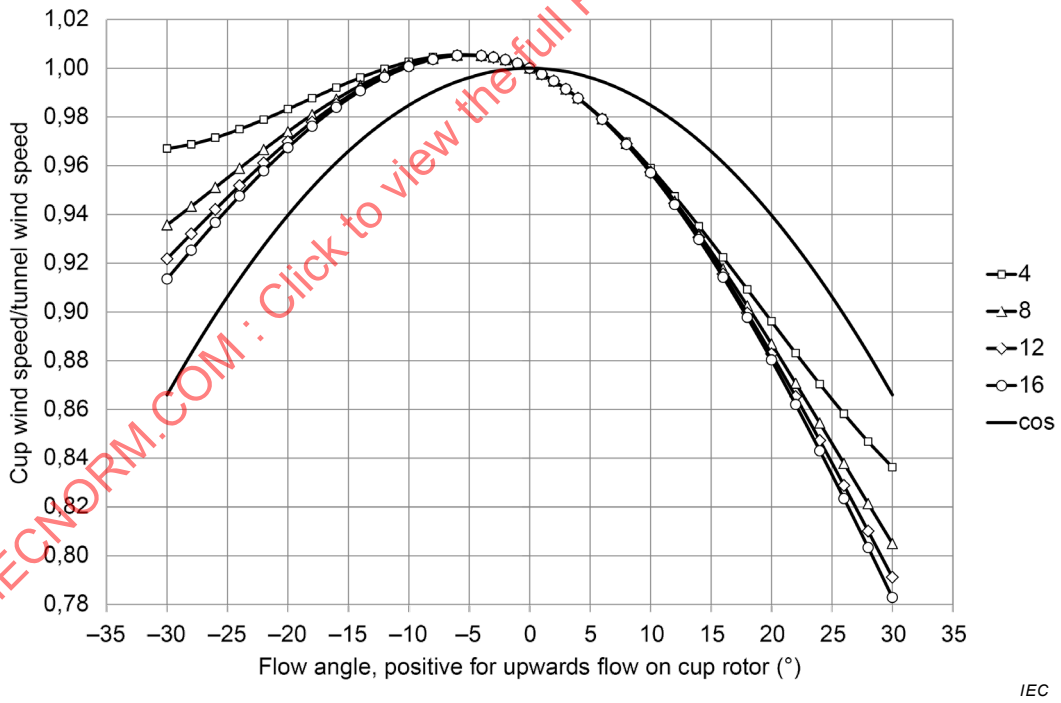

Figure J.1 – Tilt angular response $V_\alpha / V_{\alpha=0}$ of a cup anemometer as function of flow angle α compared to cosine response

J.2.2 Wind tunnel measurements of directional characteristics of cup anemometers

The design of certain cup anemometers (e.g. asymmetric housing shape, asymmetric cable entries, etc.) may have an adverse effect of the anemometer wind speed signal with respect to the horizontal flow direction and the reference direction used for calibration (yaw sensitivity). This effect is not desired since it usually cannot be corrected for. It may contribute

substantially to the total uncertainty in the wind speed measurement. Yaw sensitivity measurements shall be conducted at wind speeds of 4 m/s, 8 m/s, 12 m/s, and 16 m/s.

J.2.3 Wind tunnel measurements of cup anemometer rotor torque characteristics

The dynamic response of a cup anemometer to wind is governed by Equation (J.1), where I is the mass moment of inertia, ω is the angular velocity, t is time, Q_A is the aerodynamic rotor torque and Q_F is the torque due to friction (mainly in bearings).

$$I\frac{\mathrm{d}w}{\mathrm{d}t} = Q_A - Q_F \tag{J.1}$$

The net torque, $Q_A - Q_F$, on the cup anemometer rotor, and thus the rotor torque characteristics, can be measured in a wind tunnel.

The aerodynamic torque can be measured by forcing the rotor to turn at off-equilibrium specific angular speeds while measuring the torque with a torque sensor.

The aerodynamic rotor torque on the cup anemometer is equal to the reaction torque on the shaft, measured with the torque sensor, minus friction torque. Measurements close to the equilibrium angular speed should be very accurate and detailed. An example of a torque measurement, where the wind tunnel speed was kept constant at 8 m/s and the rotational speed of the rotor was varied, is shown in Figure J.2.

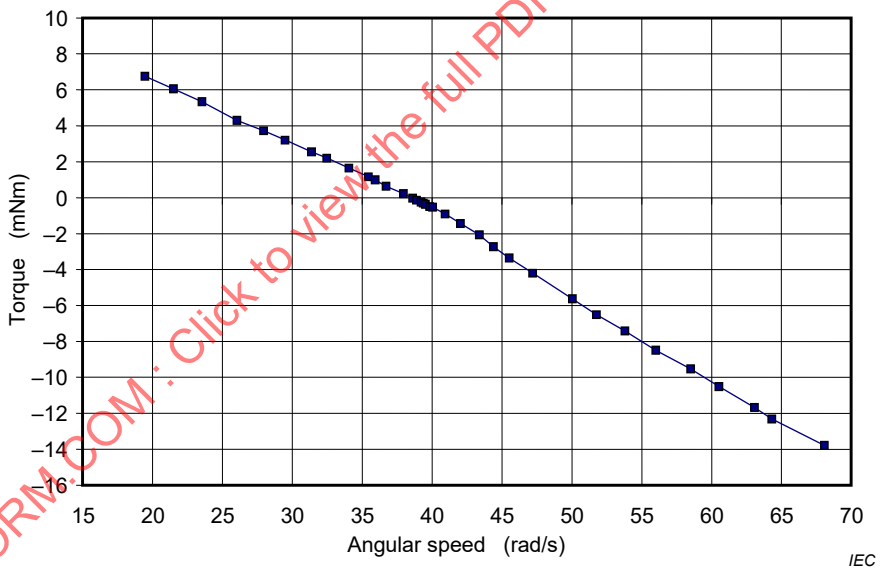

Figure J.2 – Wind tunnel torque measurements $Q_A - Q_F$ as function of angular speed ω of a cup anemometer rotor at 8 m/s

J.2.4 Wind tunnel measurements of step responses of cup anemometers

The rotor torque characteristics may alternatively be measured with a step response method in a wind tunnel. This method is less precise than the method in J.2.3 because linear torque characteristics on either side of the equilibrium speed ratio (torque coefficient equal to zero, see J.3.2) shall be assumed.

A step response is a method where a cup anemometer, in a wind tunnel of constant flow speed, is forced to an off-equilibrium rotational speed, above or below the equilibrium wind speed, where the recovery to equilibrium angular speed is monitored. The recovery region close to equilibrium is the important part of the recovery. It is recommended to use the data from the recovery region between 50 % and 98 % of the equilibrium rotor speed during the

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acceleration tests, and between 150 % and 102 % during the deceleration tests when fitting the torque coefficient lines.

The method to force the anemometer to operate off-equilibrium can be made by attaching a thin shaft to the top of the cup anemometer rotor, and extending it through a hole in the tunnel wall to a motor. The rotational speed is controlled by the motor, which is mechanically disengaged from the rotor when the measurement of the acceleration or deceleration is to start.

Alternatively, the off-equilibrium state can be achieved by applying one or more jets of compressed air to the one or the other side of the cup anemometer rotor. However, care shall be taken not to disturb the upstream wind in the tunnel.

The off-equilibrium starting states should be well outside the rotational range for the analysis (50 % to 150 % of equilibrium rotor speed) to ensure the excitation device is not influencing the data used for fitting.

In case the torque characteristics can be expressed by a linear relationship on either side of torque equilibrium (torque equal to zero), then the step response can be expressed with the equation:

$$u(t) = u_t - \Delta u \cdot \exp\left(\frac{t - t_0}{\tau}\right) \tag{J.2}$$

where

$u(t)$ is the measured wind speed by the cup anemometer at time t using the ordinary calibration function;

u_t is the tunnel wind speed;

Δu is the difference between wind tunnel wind speed and the indicated wind speed of the cup anemometer, at the beginning of the step response measurement, at time t_0;

t is the time;

τ is the time constant to be determined for the step response (τ_{low} for step response from below and τ_{high} for step response from above).

In fitting the data to the two unknown constants τ and t_0, it is useful to reformulate Equation (J.2) and to use linear regression to determine the time constant τ:

$$\ln\left(\frac{u_t - u(t)}{\Delta u}\right) = \frac{t - t_0}{\tau} \tag{J.3}$$

An example of using the step response method results to determine the linear torque from the time constants is further described in J.3.2.

J.2.5 Measurement of temperature induced effects on anemometer performance

Temperature induced effects influencing the anemometer performance shall be assessed.

J.2.5.1 Measurement of friction torque in a cup anemometer

The temperature-dependant effects due to bearing friction shall be assessed by a flywheel test in a climate chamber [11].

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Friction torque measurements shall be made by replacing the cup anemometer rotor with a flywheel, and by measuring the deceleration from a rotational speed corresponding to 20 m/s. There are two torques acting on the rotor, friction torque in the bearings[37] and air friction torque on the flywheel (which shall be subtracted from the measured torque). The tests shall be performed at temperatures from –20 °C to +40 °C at least with a 5 °C graduation. For each temperature the friction may be expressed with a second order polynomial with three constants F_0, F_1 and F_2.

$$Q_F = F_0 + F_1\omega + F_2\,\omega^2 \tag{J.4}$$

Figure J.3 shows an example of friction torque in bearings as function of temperature for fixed rotational speeds.

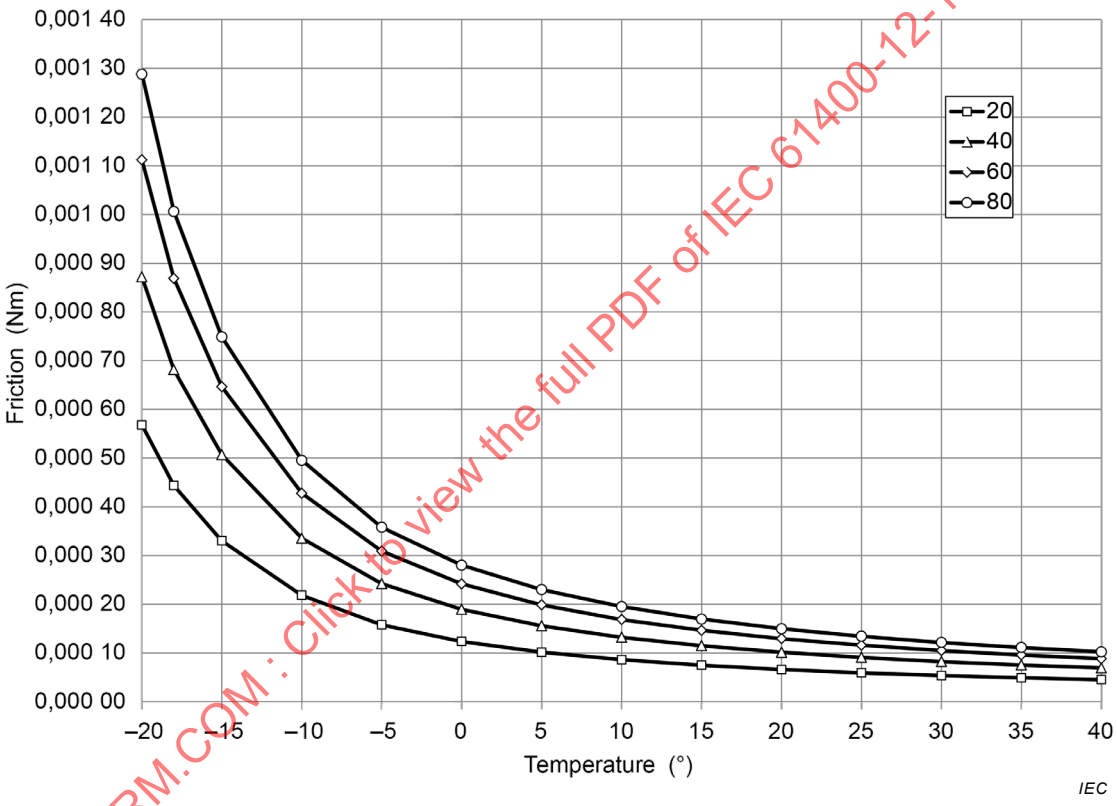

Figure J.3 – Example of bearing friction torque Q_F as function of temperature for a range of angular speeds ω

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J.2.5.2 Wind tunnel tests at different temperature and wind speeds

Influence of temperature effects on a whole anemometer (cup anemometers as well as sonic anemometers) may be verified with climate wind tunnel tests. The tests may be performed at temperatures according to Table I.1 from –20 °C to +40 °C at a 5 °C graduation. The tests may be conducted at 4 m/s, 8 m/s, 12 m/s and 16 m/s. The wind speed deviations from the standard calibration of the anemometer may then be determined. Caution shall be exercised to ensure that the findings of the wind tunnel tests are not biased by undesired effects (e.g.

---

37 There may be friction torque due to other causes than bearing friction, for example friction due to signal generation. Such torque shall be included in the friction torque measurements.

the accretion of rime upon the anemometer rotor). The results should be compared to simulated values calculated with the cup anemometer model in J.3.2.

J.2.6 Wind tunnel measurements of directional characteristics of sonic anemometers

The directional influence on the output of sonic anemometers shall be measured in a wind tunnel that fulfils the requirements described in Annex F.

The determination of the anemometer's response to quasi statically inclined/and or yawed air flow shall be performed with the help of an automatic tilt and yaw angle device installed in the wind tunnel. During the measurements, the anemometer is positioned in a fixed tilt angle. The yaw direction may be specified for fixed yaw positions with measurements for 30 s averages, or it may be yawed continuously with a sweep rate of about 1°/s[38]. The yawing shall be performed for the pre-defined measurement sector of the sonic. The tilt angle of the sonic shall be fixed for the following tilt angles: 0°, ±2°, ±5°, ±10°, ±15°, ±20°, ±30°. Tilt angles should be added or omitted if there is clear evidence that they are needed or unneeded. The measurements shall be performed for the wind speeds: 4 m/s, 8 m/s, 12 m/s, and 16 m/s. For each direction, the deviation of the indicated wind speed of the sonic anemometer from the ordinary calibration at the reference direction shall be derived.

J.3 A cup anemometer classification method based on wind tunnel and laboratory tests and cup anemometer modelling

J.3.1 Method

The classification method shall use an appropriate cup anemometer model to determine deviations due to influence parameters according to Table I.1. The cup anemometer model shall be verified to be able to include all the influential parameters properly. The method shall be based on the wind tunnel and laboratory measurements described in Clause J.2. Furthermore, the method shall use an artificial wind generator in order to generate three-dimensional time domain input wind data for the cup anemometer model. The deviations ε_i shall be determined from the differences between the 10 min horizontal wind speed input averages from the artificial wind generator and the 10 min cup anemometer model response averages.

J.3.2 Example of a cup anemometer model

J.3.2.1 General

The example cup anemometer model is a physical model that simulates cup anemometer response in time domain, see references [7] and [8]. Some physical properties of the cup anemometer shall be measured and used throughout the assessment. These are: rotor inertia I, frontal area of one cup A and radius R from shaft centre to the centre of the cups.

The response of the cup anemometer to the three-dimensional wind shall be derived from a torque equilibrium differential equation, where the torque on the rotor consists of aerodynamic torque minus friction torque (right hand side of equation), see Equation (J.1).

From the differential equation the angular speed of the cup anemometer ω is found, and using the wind tunnel calibration values, the response from the resulting aerodynamic torque and friction torques due to wind variations is determined. The aerodynamic torque Q_A is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind

38 The use of fixed yaw directions improves measurement accuracy while the use of a slow sweep rate method is an advantage to reveal the detailed changes that may occur.

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generator. From the wind vector the upflow angle and the scalar of the wind vector is determined:

$$\alpha = \arctan\left(\frac{w}{\sqrt{u^2 + v^2}}\right) \tag{J.5}$$

$$\left|\vec{U}\right| = \sqrt{u^2 + v^2 + w^2} \tag{J.6}$$

An equivalent horizontal wind speed is found by multiplying the scalar of the wind vector with the angular response measured in wind tunnel for the instantaneous upflow angle:

$$U_{\text{eq}} = F_\alpha\left(\alpha, \left|\vec{U}\right|\right) \cdot \left|\vec{U}\right| \tag{J.7}$$

Here $F_\alpha\left(\alpha, \left|\vec{U}\right|\right)$ is the tilt angular response of the cup anemometer as shown in Figure J.1.

The aerodynamic torque can be expressed by a generalized torque curve which has been verified to be valid for all wind speeds and all rotational speeds [11]:

$$Q_A = \frac{1}{2}\rho A R U_{\text{eq}}^2 C_{\text{QA}}(\lambda) \tag{J.8}$$

where

ρ is the air density;

A is the cup area of one cup;

R is the radius to a cup;

U_{eq} is the equivalent horizontal wind speed;

C_{QA} is the generalized aerodynamic rotor torque coefficient.

The generalized aerodynamic rotor torque coefficient is derived from the wind tunnel torque measurements in J.2.3 or J.2.4 where U_{eq} in this case is substituted by the tunnel wind speed:

$$C_{\text{QA}} = C_{\text{QA}}(\lambda) = \frac{Q_{\text{Q}}}{\frac{1}{2}\rho A R U_{\text{eq}}^2} \tag{J.9}$$

The generalized aerodynamic rotor torque coefficient is a function of the speed ratio:

$$\lambda = \frac{\omega R}{U_{\text{eq}} - U_{\text{t}}} \tag{J.10}$$

where

U_{t} is a threshold wind speed (derived as the remaining of the calibration offset when the friction influence has been subtracted; if friction is zero, the threshold wind speed is equal to the calibration offset).

In case the rotor torque coefficient can be characterized by two linear curves on either side of the torque equilibrium then two corresponding time constants can be determined by wind tunnel step response measurements, see J.2.4 and [9]. The linear torque characteristics can

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then be determined from the τ values, for low and high speed ratios respectively, from the equation:

$$K = -\frac{2I(u_0 + \Delta u - U_t)}{\rho A R^2 (u_0 + \Delta u)^2 \tau} \quad \text{(J.11)}$$

The generalized aerodynamic rotor torque coefficient can then be expressed by:

$$\text{for } \lambda \leq \lambda_0 : C_{QA} = K_{low}(\lambda - \lambda_0) \text{ and for } \lambda > \lambda_0 : C_{QA} = K_{high}(\lambda - \lambda_0) \quad \text{(J.12)}$$

where

λ_0 is the speed ratio for C_{QA} = 0.

An example of the rotor torque coefficient is shown in Figure J.4.

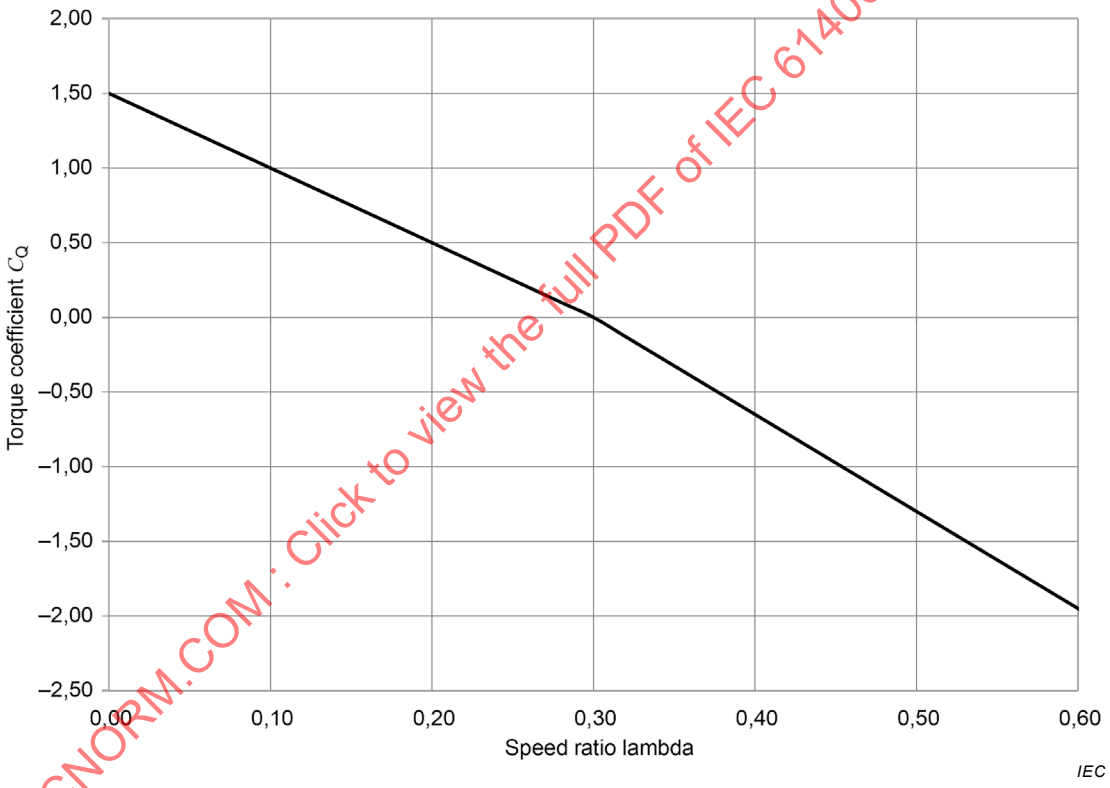

Figure J.4 – Example of rotor torque coefficient C_{QA} as function of speed ratio λ derived from step responses with K_{low} equal to –5,5 and K_{high} equal to –6,5

The friction torque is a function of the temperature and the rotational speed as found from the friction measurements in J.2.5.1:

$$Q_F = Q_F(T, \omega) \quad \text{(J.13)}$$

J.3.2.2 Influence parameter range variations and example class determination

The influence parameter ranges shall be varied by using a turbulence model that generates artificial three-dimensional 10 min time series wind speeds with a sample speed of at least 10 Hz. Exposing the cup anemometer model for such artificial winds, the responses of the cup

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anemometer are derived and the deviations from the horizontal wind speed of the artificial winds are found. The deviations for all combinations of the influence parameter ranges may be derived by a Monte Carlo process. The deviations determine the class as expressed in Equation (I.1). An example of classification of a cup anemometer is shown in Figure J.5 and with the characteristics shown in Figure J.3 and Figure J.4 and with the data presented in Table J.1 and Table J.2. Other data related to the classification are shown in Table J.3.

Deviations for Classes A, B, C and D of all influence parameters are shown in Figure J.5 and Figure J.6. The resulting classes are 1,69A, 6,56B, 8,01C and 9,94D. The cup anemometer with class 1,69A thus meets the requirements of 1,70A for use in terrain that meets the requirements in Annex B and in type A terrain in C.3.1 for temperatures above 0 °C, but not for temperatures below 0 °C with class 8,01C. The cup anemometer do not meet the recommended requirements of a class 2.5B or 2.5D for terrain that do not meet the requirements in Annex B.

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Table J.1 – Tilt angle response of example cup anemometer

Wsp V (m/s)	**4**	**8**	**12**	**16**
Angle α (°)	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$	$V_\alpha/V_{\alpha=0}$
–30	0,967 005	0,935 689	0,921 815	0,913 545
–28	0,968 769	0,943 307	0,932 028	0,925 304
–26	0,971 484	0,951 098	0,942 067	0,936 683
–24	0,974 941	0,958 908	0,951 805	0,947 569
–22	0,978 933	0,966 583	0,961 111	0,957 850
–20	0,983 253	0,973 974	0,969 863	0,967 413
–18	0,987 695	0,980 930	0,977 934	0,976 148
–16	0,992 055	0,987 304	0,985 199	0,983 945
–14	0,996 131	0,992 948	0,991 538	0,990 698
–12	0,999 722	0,997 717	0,996 829	0,996 301
–10	1,002 628	1,001 468	1,000 954	1,000 648
–8	1,004 651	1,004 057	1,003 793	1,003 637
–6	1,005 594	1,005 344	1,005 233	1,005 166
–4	1,005 262	1,005 188	1,005 155	1,005 136
–3	1,004 558	1,004 526	1,004 513	1,004 505
–2	1,003 462	1,003 452	1,003 448	1,003 446
–1	1,001 951	1,001 950	1,001 949	1,001 949
0	1,000 000	1,000 000	1,000 000	1,000 000
1	0,997 595	0,997 594	0,997 593	0,997 593
2	0,994 750	0,994 740	0,994 736	0,994 734
3	0,991 490	0,991 458	0,991 445	0,991 437
4	0,987 838	0,987 764	0,987 731	0,987 712
6	0,979 458	0,979 208	0,979 097	0,979 030
8	0,969 803	0,969 209	0,968 945	0,968 789
10	0,959 068	0,957 908	0,957 394	0,957 088
12	0,947 450	0,945 445	0,944 557	0,944 029
14	0,935 147	0,931 964	0,930 554	0,929 714
16	0,922 359	0,917 608	0,915 503	0,914 249
18	0,909 287	0,902 522	0,899 526	0,897 740
20	0,896 133	0,886 854	0,882 743	0,880 293
22	0,883 101	0,870 751	0,865 279	0,862 018
24	0,870 397	0,854 364	0,847 261	0,843 025
26	0,858 228	0,837 842	0,828 811	0,823 427
28	0,846 801	0,821 339	0,810 060	0,803 336
30	0,836 325	0,805 009	0,791 135	0,782 865

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Table J.2 – Friction coefficients of example cup anemometer

Temp	F0	F1	F2
(°C)	(Nm)	(Nms)	(Nms^2)
–20	2,000E-04	2,000E-05	–8,000E-08
–18	1,563E-04	1,563E-05	–5,714E-08
–15	1,163E-04	1,163E-05	–4,000E-08
–10	7,692E-05	7,692E-06	–3,077E-08
–5	5,556E-05	5,556E-06	–2,222E-08
0	4,348E-05	4,348E-06	–1,739E-08
5	3,571E-05	3,571E-06	–1,429E-08
10	3,030E-05	3,030E-06	–1,212E-08
15	2,632E-05	2,632E-06	–1,053E-08
20	2,326E-05	2,326E-06	–9,302E-09
25	2,083E-05	2,083E-06	–8,333E-09
30	1,887E-05	1,887E-06	–7,547E-09
35	1,724E-05	1,724E-06	–6,897E-09
40	1,587E-05	1,587E-06	–6,349E-09

Table J.3 – Miscellaneous data related to classification of example cup anemometer

Cup diameter	75 mm
Cup area A	0,004 417 87 m^2
Radius to cup centre R	65 mm
Rotor inertia I	0,000 2 kgm^2
Equilibrium speed ratio λ_0	0,3
Calibration temperature	20 °C
Calibration barometric pressure	1 013 hPa
Calibration air density ρ	1,203 821 kg/m^3
Calibration turbulence intensity	0,003
Calibration turbulence structure	Isotropic $\sigma_u/\sigma_v/\sigma_w$ = 1/1/1
Calibration coefficients A and B	0,679 55 and 0,258 70
Calibration friction coefficients F_0, F_1 and F_2 at 20 °C	see Table J.3 for 20 °C
Torque coefficient slopes K_{low} and K_{high}	–5,0 and –6,5

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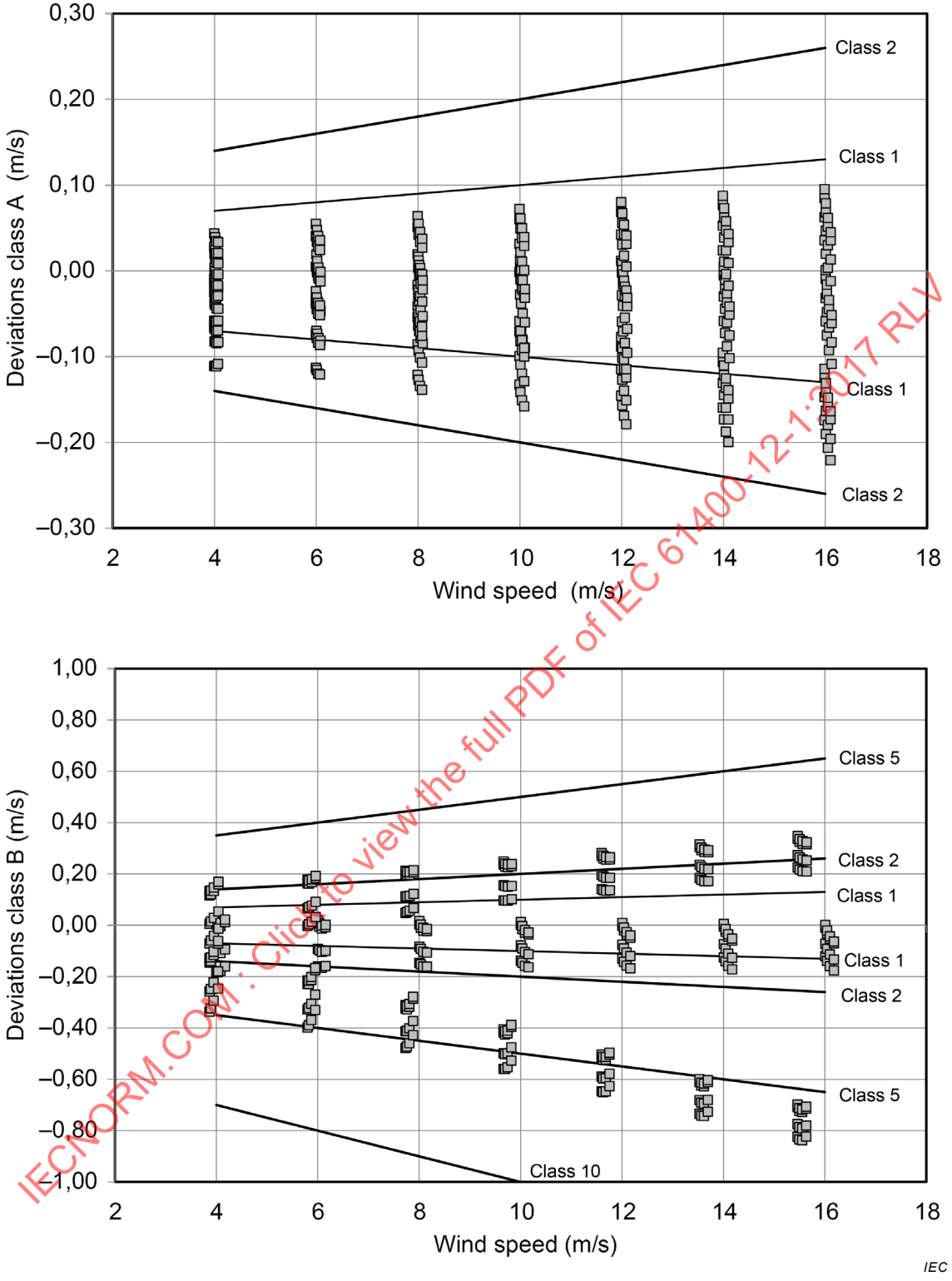

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Figure J.5 – Classification deviations of example cup anemometer showing a class 1,69A (upper) and a class 6,56B (lower)

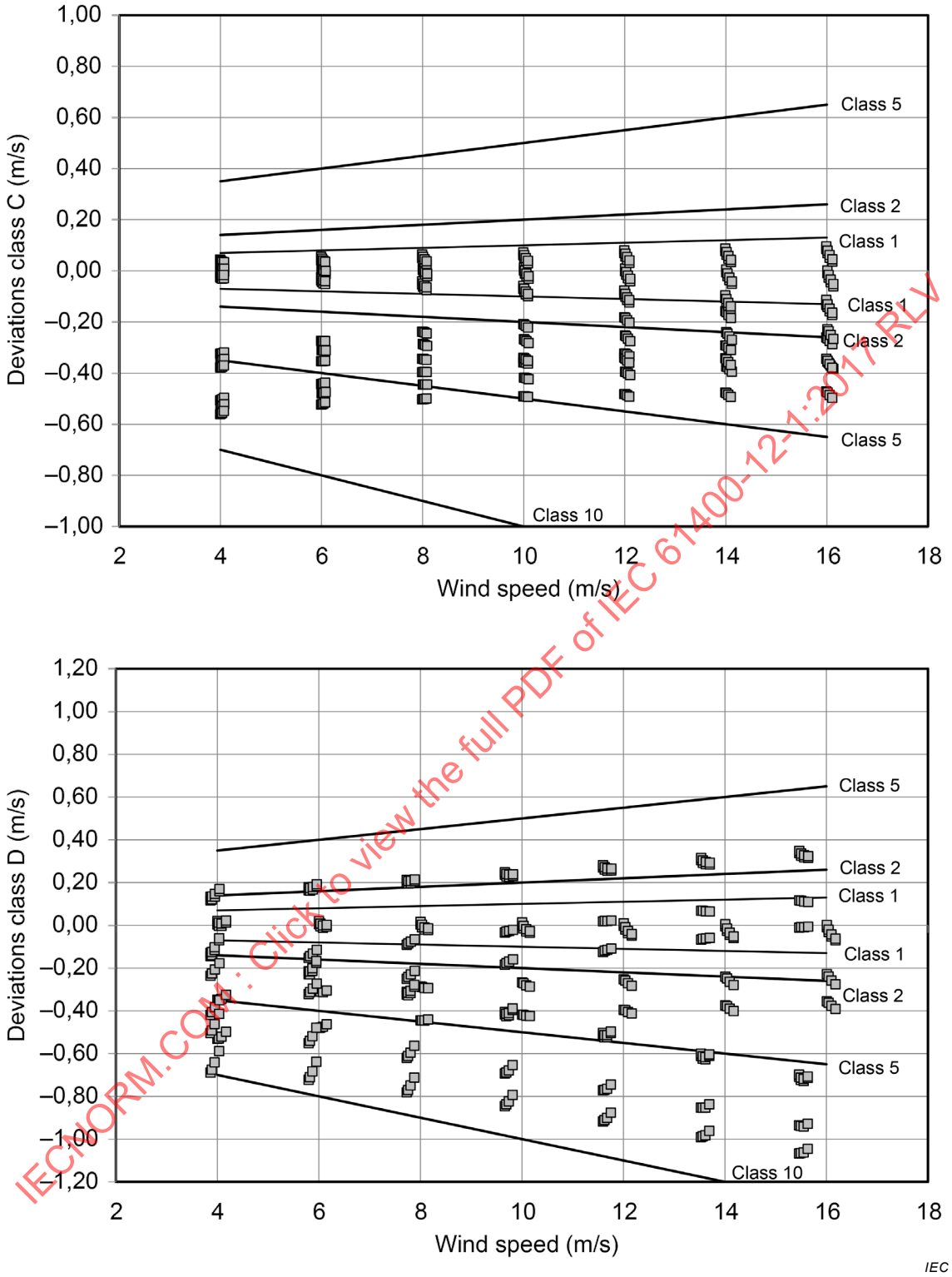

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Figure J.6 – Classification deviations of example cup anemometer showing a class 8,01C (upper) and a class 9,94D (lower)

J.4 A sonic anemometer classification method based on wind tunnel tests and sonic anemometer modelling

The classification method uses a sonic anemometer model to determine deviations due to influence parameters. The method is based on wind tunnel and laboratory measurements as described in J.2.6 and J.2.5.2. Furthermore, the sonic anemometer classification method uses

an artificial wind generator similar to the one for the cup anemometer model, see J.3.2, in order to generate three-dimensional time domain input wind data for the sonic anemometer model.

The response of the sonic anemometer is a function of the instantaneous wind vector $\vec{U} = \{u, v, w\}$ as determined by the artificial wind generator. From the wind vector the upflow angle and the scalar of the wind vector is determined by Equations (J.5) and (J.6). The response is then determined by interpolation in the measured data from the wind tunnel measurements:

$$U_{\text{sonic}} = F_{\alpha,\gamma}\left(\alpha, \gamma, \left|\vec{U}\right|\right) \cdot \left|\vec{U}\right| \tag{J.14}$$

where

$F_{\alpha,\gamma}(\alpha, \gamma, \left|\vec{U}\right|)$ is the tilt and yaw response function for the sonic anemometer.

Deviations are determined from differences between sonic anemometer model responses and artificial wind data averages, see J.3.2.2. The relevant influence parameters are tilt and yaw angular responses and temperature induced effects.

J.5 Free field comparison measurements

In a free field comparison measurement, two anemometers can be compared. The comparison measurement can be used to verify that the methods being used in classification of the instruments are consistent, see J.3 and J.4. The comparison of anemometers requires that both anemometers are calibrated in the same wind tunnel. The setup in the field should be made according the mounting procedures for two top-mounted anemometers as described in Annex G, using the maximum distance between them. A 3D ultrasonic anemometer (U, V, and W calibrated) shall be mounted on a boom below the two sensors to measure the environmental influence parameter ranges (flow angle, turbulence, turbulence spectrum), for a class S measurement campaign classification analysis. Additionally, air temperature shall be measured on the same boom for determination of the temperature range, and air pressure shall be measured for determination of the air density range. Time traces of the 3D sonic shall be recorded, while 10 min average measurements in a relatively small sector perpendicular to the boom are acceptable for the two anemometers under comparison. An acceptable database (at least 180 h) shall be collected for a wind speed range of 4 m/s to 16 m/s and a range of turbulence intensities (for instance from 0,04 to 0,14). Comparison of two anemometers should then be made by deriving a class S classification of the two anemometers from laboratory tests, and comparing these with the field measurements.

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Annex K
(normative)

In-situ comparison of anemometers

K.1 General

It shall be proven that an anemometer used for power performance measurements does not change its calibration during the measurement period. The anemometer can be calibrated in a wind tunnel after the measurement period to show the differences to the calibration before the measurement period. Another method is the in-situ comparison made by comparing the primary anemometer to a control anemometer installed in close proximity during the measurement period. It should be noted that this method does not identify a gradual degradation of the calibration of the anemometer if the control anemometer degrades at a similar rate. The in-situ comparison should be repeated on a regular basis to identify problems at an early stage.

K.2 Prerequisite

During the measurement period the two anemometers are installed on the meteorological mast according to Annex G. The primary anemometer is used for the power performance measurements. The other is the control anemometer, and is used for the in-situ comparison. The anemometers can be installed in three variants:

a) variant 1: top mounted according to Clause G.2;

b) variant 2: alternative top mounted according to Clause G.3;

c) variant 3: both anemometers side-mounted according to Clause G.4.

K.3 Analysis method

Two databases will be compared using the 10 min average values recorded during the power performance measurement period. The first database includes data that starts directly after the installation of the anemometers. The second database includes data for the last part of the power performance measurement period. Each database shall meet the following requirements:

a) cover a range from 4 m/s to 12 m/s;

b) wind directions shall be in the valid measurement sector;

c) each wind speed bin shall have a minimum of 3 points of data. There are two possible choices of binning the data as follows:

   1) Binning option 1: Wind speed bins of 1 m/s width, centred on 1,0 m/s values, based on the control anemometer wind speed from one wind direction bin not larger than ± 15°.

   2) Binning option 2: Wind speed bins of 4 m/s width centred on 2 m/s, 6 m/s, 10 m/s and 14 m/s[39] based on the control anemometer wind speed and wind direction bins of 10°.

d) include a wind direction sector with the meteorological mast free of wakes of any wind turbines and with the anemometers free of wakes of the meteorological mast as follows:

   1) In the case of side-by-side anemometer mounting (variant 2) and using only wind speed binning for one wind direction sector (binning option 1), the wind direction sector should include the wind direction that is 90° to the boom direction and in acceptable wind directions;

[39] Note that this wind speed range of 0 m/s to 16 m/s is for this interim analysis step only and that the final analysis is to be based on the 4 m/s to 12 m/s range.

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2) In the case of a top-mounted anemometer (variant 1), the wind direction bin(s) shall be out of the wake of the meteorological mast. Therefore the horizontal connection lines (see Figure K.1 and Figure K.2) between the centre of the control anemometer and any part of the meteorological mast shall have a minimum angular distance of 45º to the border of the bin(s).

e) maximum duration shall be 8 weeks.

The wind direction bin(s) used for the analysis shall be clearly stated in the report.

If 1 m/s wind speed bins and one wind direction bin of 30° (binning option 1) are applied, a linear regression is performed with the primary anemometer as the dependent variable and the control anemometer as the independent variable. This regression will be used to calculate the estimated primary anemometer wind speed, termed $V_{\text{primary_est}}$.

$$V_{\text{primary_est}} = m \cdot V_{\text{control}} + b \tag{K.1}$$

where

m is the slope of the regression relating V_{control} to $V_{\text{primary_est}}$;

b is the offset of the regression relating V_{control} to $V_{\text{primary_est}}$;

V_{control} is the wind speed of the control anemometer.

The intention is to show a change over time in the behaviour of an anemometer, not an absolute calibration.

If 4 m/s width wind speed bins and 10° wind direction bins (binning option 2) are applied, a piecewise linear interpolation between wind speed bins in each wind direction bin from the first database can be used to estimate the primary anemometer wind speed based on:

$$V_{\text{primary_est}} = \frac{V_{\text{primary},i} - V_{\text{primary},i-1}}{V_{\text{control},i} - V_{\text{control},i-1}} \left(V_{\text{control}} - V_{\text{control},i-1}\right) + V_{\text{primary},i-1} \tag{K.2}$$

In this case, only data of the control anemometer within the wind speed bins covered by the first database in each wind direction bin shall be used for the evaluation of the in-situ comparison in the second database. Equation (K.2) may be used for extrapolation up to the borders of the covered wind speed bins. If there is only one wind speed bin covered in a wind direction bin, the ratio of the bin averages of the wind speeds measured by the primary anemometer and the control anemometer shall be used as correction factor for the measurement of the control anemometer.

K.4 Evaluation criteria

Apply the regression or the piecewise linear interpolations from the first database to the control anemometer measurements of the second database resulting in an estimated primary anemometer wind speed for each 10 min period.

Calculate the average of differences (systematic deviation) in the measured and estimated primary anemometer wind speed for 1 m/s wide wind speed bins centred around 1 m/s values. The systematic deviation is:

$$\gamma = \frac{\sum \left(V_{\text{primary_est}} - V_{\text{primary}}\right)}{n} \tag{K.3}$$

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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:

$$\sigma = \frac{\text{stdev}(\gamma)}{\sqrt{n}} = \frac{\sqrt{\frac{\sum \left(V_{\text{primary_est}} - V_{\text{primary}}\right)^2}{n}}}{\sqrt{n}} \tag{K.4}$$

If the root-sum-square of the average of differences (systemic deviation) and the standard uncertainty of wind speed differences (statistical deviation) does not exceed 0,1 m/s in any bin between 4 m/s and 12 m/s, the in-situ test has passed.

$$\delta = \sqrt{\gamma^2 + \sigma^2} < 0{,}1 \text{ m/s} \tag{K.5}$$

If the value δ is above 0,1 m/s in at least one bin and does not exceed 0,2 m/s in all bins between 4 m/s and 12 m/s, the uncertainty of the anemometer calibration $u_{V1,I}$ shall be increased at least to the maximum value of δ in the wind speed range 4 m/s to 12 m/s. If the value δ is larger than 0,2 m/s in any bin between 4 m/s and 12 m/s, the in-situ test should be shifted to an earlier period until δ does not exceed 0,2 m/s anymore. The power curve data after this period shall be rejected, and the uncertainty of the anemometer calibration $u_{V1,I}$ of the remaining power curve data shall be treated as in the case of no data rejection.

NOTE The in-situ test can be repeated often during the measurement campaign to aid in the identification of intermittent anemometer degradation.

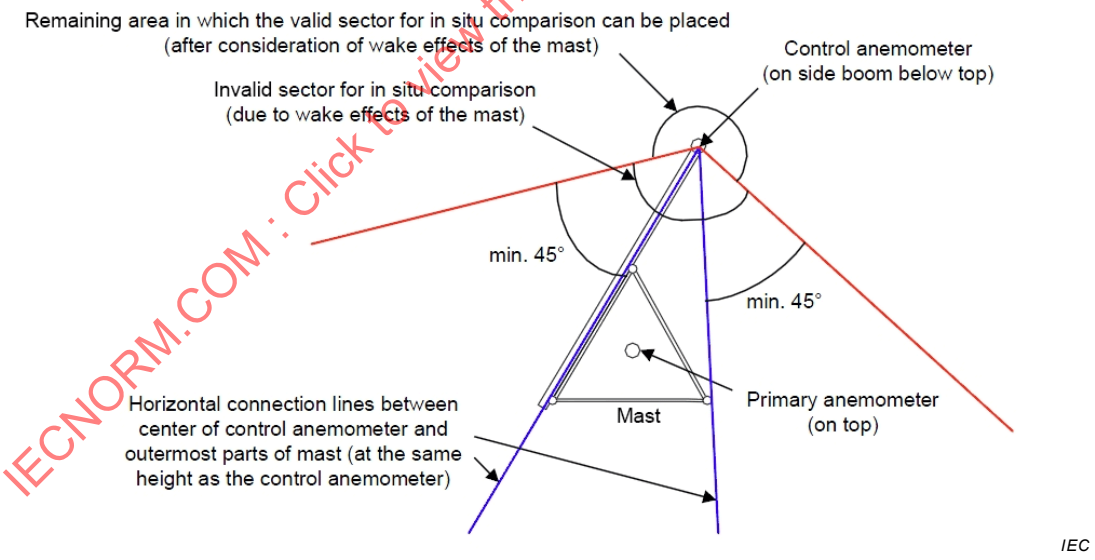

Figure K.1 – Example with triangular lattice meteorological mast

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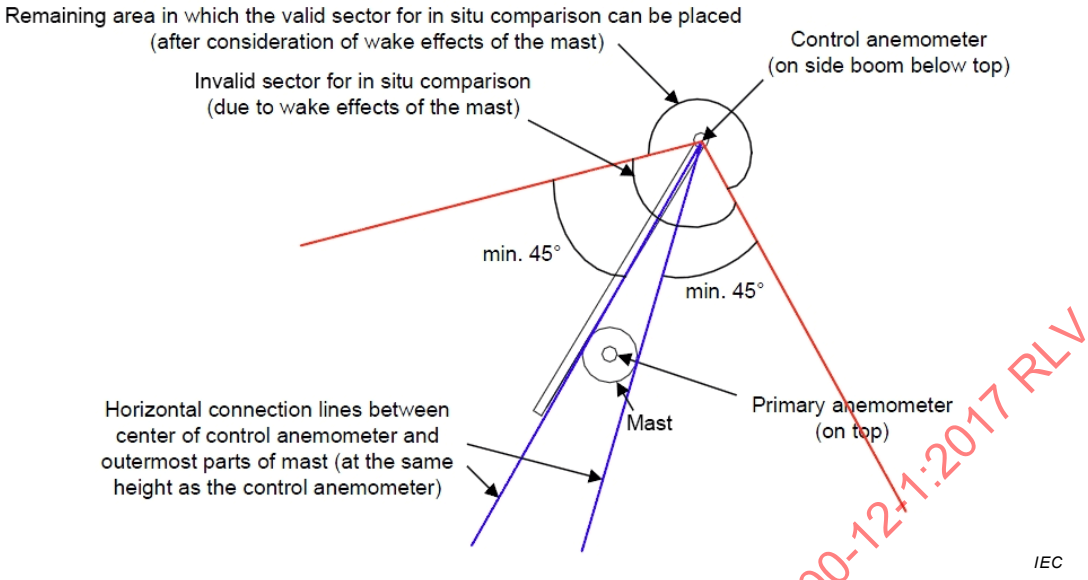

Figure K.2 – Example with tubular meteorological mast

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Annex L
(normative)

The application of remote sensing technology

L.1 General

Annex L describes the requirements for the operation of remote wind speed sensing devices such as light detection and ranging (LIDARS) and sound detection and ranging (SODARS) when deployed in relation to wind turbine power curve testing. A procedure is laid out that ensures the traceability of the measurements to international standards and presents associated uncertainty components for use in the power curve evaluation.

In the present version, the procedures pertain according to the following restrictions:

a) A meteorological mast reaching at least the minimum of 40 m or the lower tip height of the wind turbine being tested shall be used during the power curve test to monitor the performance of the remote sensing device (e.g. a lower rotor tip height of 30 m requires that a monitoring height of at least 30 m is used, while a lower rotor tip height of 50 m requires a monitoring meteorological mast at least 40 m high).

b) Only ground based remote sensing devices are used (e.g. nacelle mountings are not included).

c) The use of remote sensing for conducting power performance assessments is limited to flat terrain, that is, situations where site calibration is not required in accordance with Annex B.

When compared to measurements from a meteorological mast-mounted cup anemometer, remote sensing device measurements typically display some degree of scatter. Some of this scatter arises due to the sensitivity of the remote sensing device to various environmental conditions (e.g. temperature and wind shear). It is the task of the classification test (Clause L.2) to identify and quantify these sensitivities for a number of discrete heights covering the measuring range of interest. As for cup anemometers it is assumed that these sensitivities will be type specific and the classification test needs to be performed for each type of remote sensing device for a minimum of two instruments of each type and at a minimum of two locations.

The remaining scatter in the cup anemometer comparison is considered to be random noise. This arises from a variety of sources. For example, the turbulent de-correlation in the wind due to the distance between the meteorological masts leads to scatter. Also, the distance between the individual probe volumes of the remote sensor itself could contribute to such scatter. The random noise is assumed to be unit and site specific, i.e. it can vary between different evaluations of the same remote sensing device.

Before being used in a power curve test, a particular unit of a remote sensing device shall first undergo a verification test (Clause L.3). As an alternative, the verification test can also be performed during the power curve test. This test is a comparison of the remote sensing device measurements to those from calibrated cup anemometers mounted on a meteorological mast spanning a significant portion of the height range of interest. The purpose of this test is to convey traceability to international standards to this particular device, in the form of an uncertainty. Usually the power curve test will take place at a different location and at a different time and therefore with a different distribution of environmental conditions than for the verification test. Depending on the sensitivities identified during the classification test, the different environmental conditions will alter the performance of the remote sensing device, increasing the uncertainty in relation to that determined in the verification test. Expressions for the uncertainty of the remote sensing device and how these should be used in the evaluation of the power curve uncertainty are given in Clause L.4.

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Clause L.5 describes how the cup anemometer measurements from the short meteorological mast can be used to monitor the performance of the remote sensing device. By ensuring at least one common measuring height, it is possible to assess whether the uncertainty obtained in the classification and the verification test is consistent with the performance of the remote sensing device during the power curve test. If inconsistencies are identified from this monitoring, the corresponding uncertainties used in the power curve test are increased. This provides a useful 'safety net' for the methodology and a feedback mechanism that should promote realistic uncertainty assessments.

Specific details of how to use the remote sensing device in the power curve test are given in Clause L.6. Of particular relevance are the position and dimensions of the remote sensing device's probe volumes in relation to the wind turbine being tested.

Reporting requirements for the complete methodology are given in Clause L.7.

L.2 Classification of remote sensing devices

L.2.1 General

The accuracy of the RSD may be influenced by meteorological variables. As the meteorological conditions during the power curve test may be different from those prevailing during the RSD performance verification test, such influences are linked to additional uncertainty. It is therefore necessary to investigate the sensitivity of the performance of the remote sensing device to meteorological variables. The results of such tests shall identify the variables that influence the performance of the remote sensing device and determine the classification of the instrument.

The simplest of these evaluations entails considering the difference between the remote sensing device measurement and a reference measurement as function of one meteorological variable at a time. An accuracy class of the remote sensing device shall be evaluated for certain ranges of various environmental variables similar to the classification of cup anemometers according to Annex I based on the empirical analysis of the sensitivities observed during classification tests. Care should be taken to allow for the possible interdependency of environmental variables (e.g. wind shear and turbulence intensity) so that sensitivities are not inadvertently double counted. The uncertainties arising due to remote sensing device classification can then be evaluated.

A case-specific accuracy class may also be evaluated based on the sensitivities of the remote sensing system and the variation of the environmental variables observed during the performance verification and power curve tests. It should be clearly stated whether a classification result has been derived generically on multiple units or whether it is based on a case-specific evaluation.

L.2.2 Data acquisition

The classification test is based on concurrent measurements obtained by the remote sensing device and a high reference meteorological mast with which it is compared. The measurements will be co-located, such that they characterise flow within the same volume of air. The degrees of concurrency and co-location that shall apply to the measurements are those that enable the determination of the most precise and well understood relationship between them. In particular:

a) The same averaging intervals shall be used for the remote sensing device and reference sensor being compared: 10 min averages shall be recorded. In addition to 10 min averages, the standard deviations and extreme values of the measured variables within the 10 min periods shall be recorded.

b) The number of samples acquired by each instrument during each averaging interval to obtain an average shall be recorded.

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c) It shall be noted whether the individual samples acquired within the averaging interval by the remote sensing device are cumulative values, representing, for example, a spectrum integrated from the beginning of the averaging interval to the moment at which the sample is acquired. This will have a bearing on statistics that require successive samples to be independent, such as standard deviation used in, for example, turbulence assessments.

d) The device is sited and analysis of the measurements conducted in a manner that minimises extraneous influences on the relationship between the remote sensing device and reference sensor measurements. These influences may include, but are not limited to: flow perturbations; fixed echoes; real variations in the flow between the remote sensing device measurement volume and the reference instrument measurement location. The distance between the meteorological mast and the remote sensing device shall be a compromise allowing good correlation between meteorological mast and remote sensing device measurements while at the same time preventing or limiting the influence of the meteorological mast on the remote sensing device.

e) The meteorological mast-mounted reference sensors shall comply to the requirements of this standard. This applies especially to the calibration, classification and mounting.

f) The reference meteorological mast should preferably have a constant cross section and solidity across its height. In this way the influence of the meteorological mast on boom-mounted anemometers remains constant with height and allows a more accurate comparison of the measured wind shear between the meteorological mast and the remote sensing device.

The remote sensing device and reference sensors will be synchronised to within 1 % of the averaging interval, and this degree of synchronisation will be verified and tested for drift at least once a week. If comparison of time stamps indicates drift has occurred, the remote sensing device system clock will be reset to synchronise with the reference sensor system clock and remote sensing data time stamps adjusted to compensate for the drift over the period during which it is evident by linear interpolation. Data will be acquired until the following data coverage requirements are fulfilled:

a) Reference sensor wind speed measurements will be binned into 0,5 m/s bins centred on integer multiples of 0,5 m/s.

b) The data will be filtered according to the recommendations of the device manufacturer and the requirements of L.2.3. The following requirements shall be fulfilled after filtering.

c) The data acquisition requirements of a classification test shall not be considered fulfilled unless at least 3 pairs of valid concurrent, co-located and filtered measurements have been recorded in each wind speed bin centred between 4 m/s and 16 m/s inclusive.

d) The amount of acquired data shall cover a minimum of 180 h.

e) The duration of the data acquisition campaign will last at least 3 months and cover a significant span of environmental conditions (e.g. winter to summer). The database shall cover at least 25 % of the bins as described in Table L.3 with a minimum number of data points as defined in Equation (L.2) for all variables which are known to influence the accuracy of the RSD.

A remote sensing device classification and verification shall be considered valid for the purposes of a power curve test of a wind turbine if the reference cup anemometers used during the classification and verification tests were mounted at a minimum of 3 heights, including the lower tip height of the wind turbine ± 25 % and the hub height of the wind turbine ± 25 %. These height requirements for the classification and verification apply if the device is used for wind measurements over the entire height range of the wind turbine rotor or only for wind measurements up to hub height.

L.2.3 Data preparation

The following data filters shall be applied:

a) The reference meteorological mast shall be free of wakes from wind turbines and obstacles as defined in Annex A.

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b) Probe volumes within which the remote sensing device acquires a radial velocity measurement shall be free of wakes and flow perturbation from wind turbines and obstacles as defined in Annex A. The influence of the wake of the reference meteorological mast on the measurements of the remote sensing device shall be inspected by plotting the ratio of the remote sensing device and reference sensor measurements as a function of wind direction. Criteria regarding the permissible values of this ratio may be developed with reference to the corresponding considerations for cup anemometry discussed in Clause G.4. Remote sensing device measurements shall be excluded if they are influenced by either the meteorological mast or its guy wires.

c) Reference cup anemometers shall be free from the influence of the wakes of the meteorological mast, its guy wires or lightning receptor as defined in this standard.

d) The reference cup anemometers shall not be influenced by icing. This may be achieved by any means deemed to be suitable subject to the requirement that the method and results are adequately documented.

e) The measurements that are recorded for each averaging interval by both the remote sensing device and reference sensors will represent a single contiguous period of operation whose duration equals the averaging interval. However, as discussed below in L.2.4, there is a possibility that the data availability requirements may be relaxed. The influence that relaxing these requirements could have on the measurement accuracy should be checked by means of a sensitivity analysis. If the remote sensing device does not record the proportion of the period in the 10 min averaging interval during which it has been available, a general quality factor shall be recorded to indicate the reliability of the measurement in a similar manner as device availability. Data may then be filtered or a sensitivity analysis may be performed with reference to the quality factor. Guidance shall be provided by the manufacturer regarding the appropriate treatment of the quality factor;

f) In general no filtering on precipitation should be undertaken. Precipitation should be treated as an environmental variable in the classification test. If a remote sensing device manufacturer's guidelines make provision for filtering with reference to precipitation, these guidelines should be followed. If filtering is undertaken with reference to precipitation, the filtered data should be considered a special dataset and classification, verification and application of the remote sensing device be conducted in a manner consistent with this.

Measurements of boom-mounted reference sensors may be corrected for meteorological mast effects (blockage effects and flow acceleration effects). It should be noted that such correction of meteorological mast effects incurs additional uncertainty in comparison with top mounted reference sensors. The correction may be achieved by any means deemed suitable for reducing the total uncertainty, subject to the requirement that the method and results are adequately documented. Uncertainty associated with the use of boom-mounted anemometers is discussed in Annex D and Clause G.4.

All filtering criteria that are used, and their respective effects on the dataset, shall be recorded and reported.

L.2.4 Principle and requirements of a sensitivity test

The deviation observed between the measurements of the remote sensing device and the reference sensors shall be analysed in terms of their sensitivity to different environmental variables. Depending on the use of the remote sensing device in the power curve test campaign, the accuracy class shall be evaluated in terms of the absolute measurement of the horizontal wind speed component.

An accuracy class of the remote sensing device for alternative applications that entail the acquisition of other wind flow parameters (e.g. turbulence intensity or wind direction) may be derived in terms of the sensitivity of measurements of those parameters to different environmental variables, using suitable reference instrumentation. This is beyond the scope of

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a simple[40] power curve test, and only the evaluation of accuracy class in terms of horizontal wind speed is treated here.

The initial sensitivity to be tested shall relate to the relaxation of the criterion described in item e) in L.2.3. The sensitivity of the deviation between the reference sensors and the remote sensing device on the availability of the remote sensing device within the averaging interval or the corresponding quality factor of the measurements (as defined by the manufacturer) shall be examined. Remote sensing data shall be deemed acceptable if characterised by a level of availability or by a quality factor that has been demonstrated to have no significant influence on the deviation between the reference sensors and the remote sensing device measurements.

The percentage deviation between 10 min averages of the output parameter under consideration acquired by the remote sensing device (RSD) and reference sensors at one height level is considered as a dependent variable which is analysed as a function of one environmental variable by means of a classification test:

$$\text{Dependent variable:} \quad \frac{(v_{\text{RSD}} - v_{\text{reference}})}{v_{\text{reference}}} \times 100\,\% \tag{L.1}$$

All available environmental variables are considered to be potentially within the scope of the sensitivity analysis. A non-exhaustive list of variables to consider can be: wind shear exponent, turbulence intensity, rain, wind direction, air temperature, air density, temperature difference at two different heights, upflow angle, wind veer, and cloud cover. Some relevant parameters may be instrument-specific, for example data availability or quality factor, and may be specified by the manufacturer.

Sensitivity to an environmental parameter can be an artefact of an easily remedied error in the configuration of the remote sensing device. For example, a marked sensitivity to wind shear can arise when there is a systematic error in the heights associated with the remote sensing device wind speed measurements. If a strong sensitivity is observed with a remote sensing device, or a significant variation in sensitivity between tests is observed, the device should be checked for such errors. If errors are detected and corrected, the sensitivity tests should be repeated.

Where the reference cup anemometer exhibits a known sensitivity to an environmental variable, an attempt should be made to remove the influence of this sensitivity from the sensitivity test. This may be done by any means deemed to be suitable with the requirement that the method and results are adequately documented. As an example, Figure J.1 shows the effect of upflow angle on wind speeds measured by a commonly used class 1,7A cup anemometer as determined from industry standard wind tunnel tests.

Figure L.1 a) shows the response of a remote sensing device to upflow angle determined with respect to data from a cup anemometer of the type represented by Figure J.1. In Figure L.1 b) a linear model has been fitted to the data in Figure J.1 in the region between ± 3º and used to adjust the data points to remove the effect of the cup anemometer response. It can be seen from the figure that the sensitivity recorded for the remote sensing device in Figure L.1 a) in this case is at least partially attributable to the reference cup anemometer.

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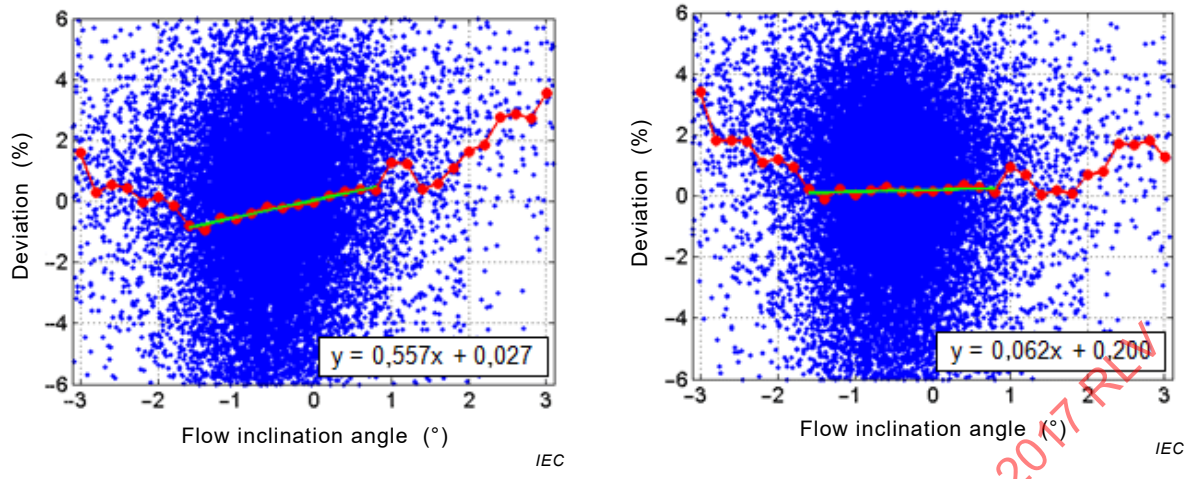
40 For example, a test that does not incorporate wind veer correction or turbulence normalisation.



a) before adjustment for cup anemometer response **b) after adjustment for cup anemometer response**

Figure L.1 – Deviation vs upflow angle determined for a remote sensing device with respect to the cup anemometer in Figure J.1

Environmental variables shall be analysed to identify any interdependency. Where this exists, further analysis shall be undertaken to identify which of the environmental variables influences measurement deviation. This may be done by any means deemed to be suitable with the requirement that the method and results are adequately documented. Documentation should include sufficient detail for the replication of results from the data acquired during the classification test. Suggested methodologies for achieving this are detailed in L.2.6. Only environmental variables found to have a direct influence on measurement deviation are to be included in the sensitivity analysis. These variables are then considered to be independent.

If any environmental variables that are known to directly influence measurement deviation are omitted from the sensitivity test, this is likely to result in additional uncertainty at the application stage, as defined in Clause L.5. If subsequent monitoring of the remote sensing device with a short anemometer meteorological mast during the power curve test shows the results of the sensitivity test have been unduly conservative, revision of the environmental variables included in the sensitivity test may be required.

A one-dimensional, two-parametric ordinary least squares (OLS) linear regression analysis shall be performed for each pair of dependent and independent variables. The following parameters are calculated from the regression analysis:

a) slope: m;
b) offset: c;
c) coefficient of determination, which in the case of OLS linear regression is the correlation coefficient: r^2;
d) standard deviation of the independent variable: std;
e) mean value of the independent variable: avg.

The estimation of the slope m and the offset c shall be performed on bin-averaged data for the measured environmental variable, where the size of the bin to be used is given in Table L.1.

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Table L.1 – Bin width example for a list of environmental variables

Independent variable	Bin width	Unit
Wind shear exponent	0,05	Dimensionless
Turbulence intensity	0,01	Dimensionless
Rain	0,1	mm
Remote sensing device availability	1	%
Wind direction	5	°
Air temperature	2	°C
Air density	0,05	kgm^{-3}
Temperature gradient	0,002	K/m
Upflow	0,2	°
Wind veer gradient	0,04	°/m

For variables to be included in the sensitivity analysis that are not listed in Table L.1, suitable bin widths should be chosen with respect to range and distribution of the data.

For a specific environmental variable, bins should only be included in the sensitivity test where they meet the criteria listed in Equations (L.2) and (L.3):

$$n_i > \frac{N}{2n_b} \tag{L.2}$$

where

n_b is the number of bins according to the ranges of variables given in Table L.3;

N is the total number of data points;

n_i is the number of data points in bin i.

Equations (L.3) is to be applied only when sensitivities on the wind speed measurement are analysed:

$$\frac{\sigma(d_i)}{\sqrt{n_i}} \frac{v_{\text{ref},i}}{100} < 0{,}03\,\text{m/s} \tag{L.3}$$

where

d_i is the data in bin i;

$\sigma(d_i)$ is the standard deviation of the percentage wind speed deviations of the ten minute data in bin i;

$V_{\text{ref},i}$ is the mean value of the reference wind speed in bin i.

The correlation coefficient (r^2), standard deviation of the independent variables (std) *and* mean value of the independent variables (avg) shall be estimated using the 10 min data in the bins included in the sensitivity test.

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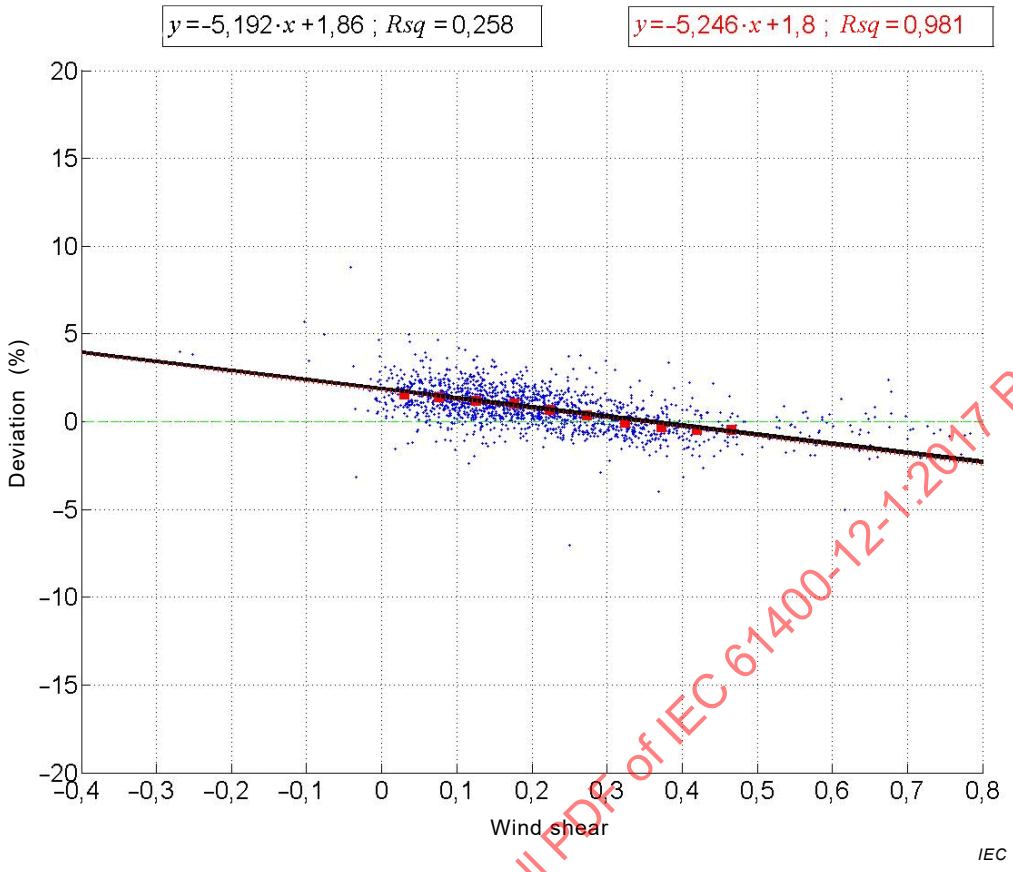

Linear regressions are plotted for 10 min data (black) and for bin-averaged data (red).

Figure L.2 – Example of sensitivity analysis against wind shear

Sensitivity is defined as the slope multiplied by the standard deviation of the independent variable: $m \cdot std$. The sensitivity indicates the extent, expressed as a percentage, that the deviation between the remote sensing device and the reference sensor measurements is changed by a change in the independent variable of one standard deviation.

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Table L.2 – Parameters derived from a sensitivity analysis of a remote sensing device

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[%]	[-]	[%]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Turbulence intensity	0,07	0,03	8,855	0,26	0,08	0,074
104		0,07	0,03	13,902	0,39	0,093	0,119
72		0,08	0,03	15,812	0,4	0,133	0,146
135	Rain (yes=1, no=0)	0,02	0,13	0,205	0,03	0,001	0,001
104		0,04	0,19	1,168	0,22	0,028	0,037
72		0,03	0,18	0,499	0,09	0,007	0,008
135	Wind direction	247,28	31,62	–0,007	–0,22	0,059	–0,053
104		252,83	34,19	0,012	0,43	0,108	0,141
72		225,14	11,39	0,003	0,03	0,001	0,001
135	Air temperature at 131 m	14,66	2,7	0,044	0,12	0,016	0,015
104		14,56	2,66	–0,042	–0,11	0,008	–0,010
72		15,16	3,43	–0,091	–0,31	0,083	–0,089
135	Air density	1,23	0,01	–16,43	–0,24	0,065	–0,061
104		1,23	0,01	1,804	0,03	0	0,000
72		1,22	0,02	5,208	0,08	0,005	0,006
135	Temperature difference between 133 m and 10 m	–0,69	1,36	–0,112	–0,15	0,027	–0,025
104		–0,69	1,36	–0,444	–0,6	0,217	–0,279
72		–0,64	1,53	–0,281	–0,43	0,158	–0,171
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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An example of a sensitivity analysis of a remote sensing device conducted with respect to a variety of environmental parameters is shown above in Figure L.2 and Table L.2. The sensitivity of the device has been analysed at three different heights. Only remote sensing data with availability within the averaging interval of 80 % or more have been considered for the test. As can be seen from Table L.2, and following significance criteria that are defined in L.2.5, the wind shear, turbulence intensity, wind direction, air temperature difference (as simple indicator for stratification), upflow angle and wind veer appear to have a significant influence on the deviation between the remote sensing and reference cup anemometer measurements of wind speed. The other independent variables appear not to be significant. However some variables that appear to influence the performance of the remote sensing device might not have an influence. If their variation is correlated with the variation of some other variables that also have an influence, this correlation may be the reason for their apparent influence. Interdependency between variables shall be analysed to identify which variables exert a genuine meaningful influence as discussed in L.2.6 before estimating the

final accuracy class of the remote sensing device. For example, multivariate regression techniques may be employed to achieve this.

The classification is analogous to the existing classification of cup and sonic anemometers according to this standard as laid out in Annex I and Annex J. The remote sensing device class can be evaluated for either pre-defined conditions or for the specific conditions prevailing during the application of the remote sensing device.

Conditions analogous to the A-classification of cup and sonic anemometry according to this standard as laid out in Annex I and Annex J are presented in Table L.3.

Table L.3 – Ranges of environmental parameters for sensitivity analysis

Independent variable		Max	Min	Range	Source
Wind shear exponent	[-]	0,80	–0,40	1,20	N/A
Turbulence intensity	[-]	0,24	0,03	0,21	This standard
Rain (yes=1, no=0)	[-]	1	0	1	Definition of sensor
Availability	[%]	100	80	20	Definition of filter
Wind direction	[°]	360	0	180	Deviation of 2 directions has a maximum of 180°
Air temperature	[°C]	40	0	40	This standard
Air density	[kg/m^3]	1,35	0,90	0,45	This standard
Temperature gradient From 133 m to 10 m height	[K/m]	0,06	–0,02	0,08	N/A
Upflow angle	[°]	3	–3	6	This standard
Wind veer from 133 m to 35 m height	[°/m]	0,2	–0,2	0,4	N/A

The availability range of the remote sensing device shall be consistent with the range to be applied during deployment in the field. Unless otherwise determined by the configuration of the reference sensors, the limits of the air temperature difference observed between the two height levels indicated shall be 10 times the standard lapse rate between the considered height levels (the standard lapse rate is 0,65 K/100 m) and the wind veer range shall be 4 times the standard deviation of the difference between the 10 minute average wind directions at the heights indicated.

L.2.5 Assessment of environmental variable significance

The significance of a variable is assessed by measuring its degree of influence on the remote sensing device measurement. The sensitivity tests may indicate that no significant relationship exists between the dependent variable and some of the independent variables. Therefore only relevant independent variables shall be considered. Relevance is determined where:

a) a sensitivity of at least 0,5 is demonstrated or a product of correlation coefficient r and sensitivity of at least 0,1 is found;

b) the sensitivity analysis of an independent variable shall be relevant for all measurement heights if one of the above conditions is fulfilled for a single height.

For a sensitivity of 0,5 or more a significant influence of the independent variable on the accuracy of the remote sensing device is directly measured during the classification test. The correlation coefficient may modify this criterion as it indicates the significance of the relationship between the dependent and independent variables. The correlation coefficient and the sensitivity both indicate the relevance of an independent variable. Thus the product of both measures defines the second, alternative condition in the first item above.

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Environmental variables for which the measured range does not cover at least 25 % of the bins as described in Table L.3 with a minimum number of data points as defined by Equation (L.2) should be excluded from the sensitivity analysis. Sensitivity results derived for these variables would be unrepresentative of any relationship with measurement deviation. Although a variable may be eliminated from the sensitivity analysis due to insufficient variation for the reliable establishment of a relationship with measurement deviation, it may be the case that a wider range of variation is observed during application of the device in the course of the power performance test. If the variable in question is found to have an influence on measurement deviation through the monitoring process during application, the device may be rejected. Alternatively, the additional uncertainty will be applied to the results to adequately reflect this, following Clause L.4. Environmental variables that are determined to influence measurement deviation only through their correlation with other environmental variables, as discussed in L.2.6, should be excluded from the sensitivity analysis.

The selection of relevant independent variables for a remote sensing device is illustrated in Table L.4.

Table L.4 – Example selection of environmental variables found to have a significant influence

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[%]	[-]	[%]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Turbulence intensity	0,07	0,03	8,855	0,26	0,08	0,074
104		0,07	0,03	13,902	0,39	0,093	0,119
72		0,08	0,03	15,812	0,4	0,133	0,146
135	Wind direction	247,28	31,62	–0,007	–0,22	0,059	–0,053
104		252,83	34,19	0,012	0,43	0,108	0,141
72		225,14	11,39	0,003	0,03	0,001	0,001
135	Temperature difference between 133 m and 10 m	–0,69	1,36	–0,112	–0,15	0,027	–0,025
104		–0,69	1,36	–0,444	–0,6	0,217	–0,279
72		–0,64	1,53	–0,281	–0,43	0,158	–0,171
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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L.2.6 Assessment of interdependency between environmental variables

The sensitivity analysis in L.2.4 makes the assumption that the environmental variables under consideration are independent, i.e. uncorrelated. In practice this may not be the case. This can lead to entries being registered in the accuracy class for specific variables due to their correlation with other variables rather than through any direct relationship with measurement deviation. An illustration of the effect of correlation between environmental variables can be seen in Figure L.3 and Figure L.4 for wind shear and turbulence intensity. Figure L.3 shows

the relationship between wind shear and turbulence intensity during a classification test. It can be seen that wind shear and turbulence intensity at this test site are not entirely uncorrelated during the measurement period in question. This manifests itself in Figure L.4 as a clustering of the data points within the scatter plot of measurement deviation against turbulence intensity according to the magnitude of the wind shear. This clustering may skew the line fit from which the sensitivity of the device with respect to turbulence intensity is determined. Through this mechanism a relationship in the sensitivity test can be transferred from an environmental variable that is directly correlated to measurement deviation to one that is not if the environmental variables are not mutually independent.

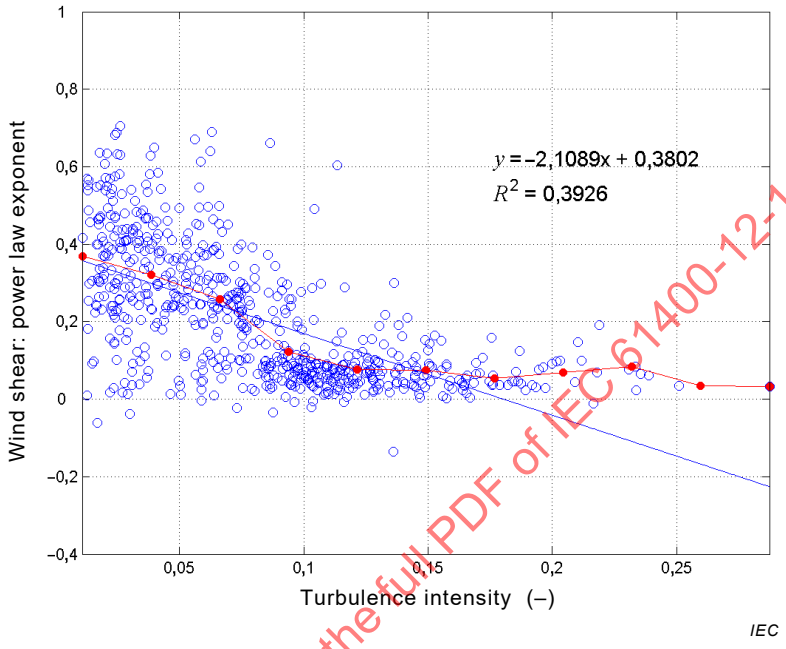
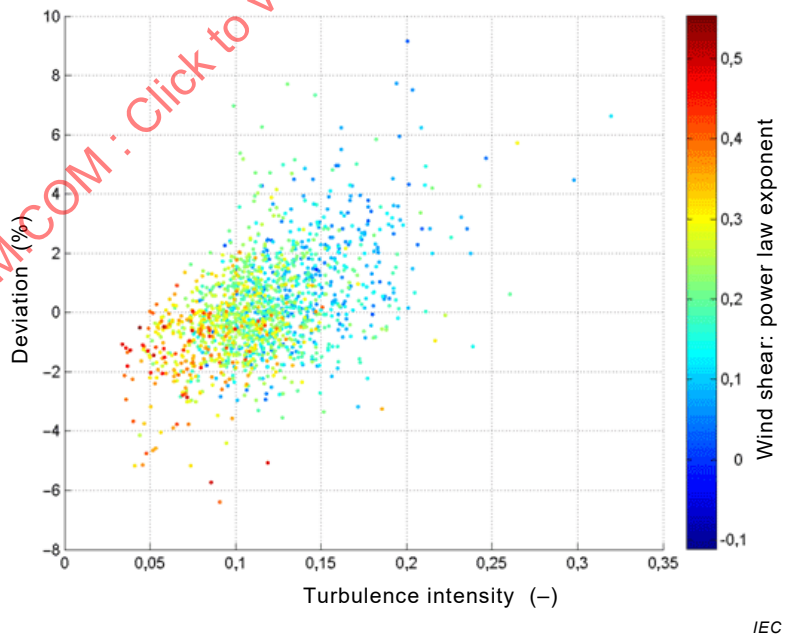


Figure L.3 – Example of wind shear versus turbulence intensity



The colour indicates the wind shear.

Figure L.4 – Example of percentage deviation of remote sensing device and reference sensor measurements versus turbulence intensity

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In order to mitigate over estimation of uncertainty, it is necessary to eliminate from the sensitivity analysis any correlated environmental variables that can be demonstrated not to directly influence measurement deviation. An example is shown in Figure L.4, where it is clear the inclusion of both turbulence intensity and wind shear in the calculation of the uncertainty estimate would result in “double counting” of uncertainty contributions due to the relationship evident between them. The elimination of correlated environmental variables may be done by any means deemed suitable with the requirement that the method and results are adequately documented, as discussed in L.2.4. Documentation should include sufficient detail for the replication of results from the data acquired during the classification test.

Dependencies between environmental variables have been analysed for the data used in Table L.4. Variables that do not have a direct influence on the measurement deviation that are correlated with one or more variables that do have a direct influence on measurement deviation have been eliminated from the sensitivity test. After removing the effect of the wind shear from the dataset, the remaining influence of the turbulence intensity was not relevant. The remaining variables are shown in Table L.5. Only wind shear, upflow angle and wind veer appear to have a significant influence on the deviation between the remote sensing and reference cup anemometer wind speed measurements.

Table L.5 – Sensitivity analysis parameters remaining after analysis of interdependency of variables

Height above ground level	Independent variable	*avg* Independent variable	*std* Independent variable	*m*	Sensitivity *m* × *std*	r^2	Sensitivity × *r*
[m]	[-]	[unit variable]	[unit variable]	[%/unit variable]	[-]	[-]	[-]
135	Wind shear exponent	0,21	0,19	–2,324	–0,45	0,235	–0,218
104		0,21	0,2	–1,918	–0,38	0,085	–0,111
72		0,17	0,17	0,607	0,1	0,009	0,009
135	Upflow angle	0,35	1,37	–0,085	–0,12	0,015	–0,015
72		–0,35	0,73	0,665	0,49	0,17	0,202
135	Wind veer between 133 m and 35 m	15,36	10,01	–0,036	–0,36	0,145	–0,137
104		15,26	10,05	–0,07	–0,71	0,298	–0,388
72		15	9,26	–0,036	–0,33	0,092	–0,100

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L.2.7 Calculation of accuracy class

The general principle of the calculation of accuracy classes is as follows:

a) define ranges of all remaining variables having significant influence as described in the example of Table L.5;

b) calculate the maximum deviation of each independent variable on the accuracy of the remote sensing device by multiplication of the regression slope m and the range of the independent variable, as taken from Table L.3. An illustrative example is given in Table L.6;

c) calculate the accumulated maximum influence of all independent variables on the accuracy of the remote sensing device by considering the different variables as fully independent from each other, such that the maximum measurement errors caused by each individual variable are added in quadrature.

In relation to item c), it is acknowledged that the environmental variables under consideration are not fully independent from each other. However, with respect to uncertainty assessments, the differences between environmental conditions prevailing during the application of the remote sensing device for the purposes of the power curve test and during performance

verification is a key consideration. These differences are highly dependent on the power curve test site and on the RSD performance verification test site. This site dependency decouples the variables from each other with respect to uncertainty calculations. Therefore to estimate the accumulated maximum influence, independence between variables is a necessary assumption, despite the efforts undertaken in L.2.6 for addressing the interdependency of variables.

The preliminary accuracy classes resulting from this scheme are presented in Table L.7. These have been calculated as the sum in quadrature of the maximum deviations of both all and only the individual significant environmental variables according to Table L.6 and Table L.4. The values do not represent the final classification result.

Table L.6 – Example scheme for calculating maximum influence of environmental variables

Height above ground level	Independent variable	Range variable	*m*	*m* × range
[m]	[-]	[unit variable]	[%/unit variable]	[-]
135	Wind shear exponent	1,20	–2,324	2,79
104		1,20	–1,918	2,30
72		1,20	0,607	0,73
135	Turbulence intensity	0,21	8,855	1,86
104		0,21	13,902	2,92
72		0,21	15,812	3,32
135	Rain (yes=1, no=0)	1,00	0,205	0,21
104		1,00	1,168	1,17
72		1,00	0,499	0,50
135	Remote sensing device availability	20,00	0,017	0,34
104		20,00	–0,068	1,36
72		20,00	–0,318	6,37
135	Wind direction	180,00	–0,007	1,28
104		180,00	0,012	2,24
72		180,00	0,003	0,51
135	Air temperature at 131 m	40,00	0,044	1,76
104		40,00	–0,042	1,69
72		40,00	–0,091	3,65
135	Air density	0,45	–16,430	7,39
104		0,45	1,804	0,81
72		0,45	5,208	2,34
135	Temperature difference between 133 m and10 m	8,00	–0,112	0,90
104		8,00	–0,444	3,55
72		8,00	–0,281	2,25
135	Upflow angle	6,00	–0,085	0,51
72		6,00	0,665	3,99
135	Wind veer between 133 m and 35 m	40,00	–0,036	1,45
104		40,00	–0,070	2,81
72		40,00	–0,036	1,42

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Table L.7 – Preliminary accuracy classes of a remote sensing device considering both all and only the most significant influential variables

Height	Accuracy classes	
	Considering all variables	Considering only significant influential variables
[m]	[-]	[-]
135	8,6	3,2
104	7,1	3,6
72	9,7	4,3

To calculate the final accuracy class, the preliminary accuracy class shall be divided by $\sqrt{2}$. The maximum influences as calculated in Table L.6 are valid under the assumption that the performance verification test of the remote sensing device has been conducted at the one extreme of the ranges of all environmental variables while the power curve test is conducted at the opposite extreme, which is considered to be an unlikely scenario. A more likely assumption is that the variables x during both measurements lie close to the centre of the maximum range with a maximum deviation of half of the range:

$$x_{\text{application}} \in \left[x_{\text{centre}} - \frac{x_{\text{range}}}{2}; x_{\text{centre}} + \frac{x_{\text{range}}}{2} \right]$$
$$x_{\text{verification_test}} \in \left[x_{\text{centre}} - \frac{x_{\text{range}}}{2}; x_{\text{centre}} + \frac{x_{\text{range}}}{2} \right] \quad \text{(L.4)}$$

If the conditions during performance verification and the power curve test are considered independent of each other, the deviations of the environmental variables have the maximum ranges:

$$\mathrm{d}\left(x_{\text{application}} - x_{\text{verification_test}}\right) = \sqrt{\left(\frac{x_{\text{range}}}{2}\right)^2 + \left(\frac{x_{\text{range}}}{2}\right)^2} = \frac{x_{\text{range}}}{\sqrt{2}} \quad \text{(L.5)}$$

The resulting accuracy classes for the influences of variables given as examples in Table L.6 are shown in Table L.8.

Table L.8 – Example final accuracy classes of a remote sensing device

Height	Final accuracy class
[m]	[-]
135	2,3
104	2,5
72	3,0

L.2.8 Acceptance criteria

The classification test shall be performed for a minimum of two devices of the specific type of remote sensing device at a minimum of two different sites. This will enable type-specific classification, provided the results of these tests converge sufficiently. At least one of the test

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devices shall be tested at two different sites, resulting in a minimum of three tests required to achieve type classification.

If the results are too divergent an individual unit may be withdrawn on the assumption that it is malfunctioning and is therefore not representative of the instrument type. A withdrawal of a unit on these grounds is subject to the requirements stated above regarding the minimum number of individual units tested to derive a type-specific classification. A type-specific classification is not possible if the withdrawal of units on the grounds that they are malfunctioning results in an insufficient number of tested units. If units are withdrawn, consideration should be given to the number of units withdrawn compared to the number accepted as representative. The reason for withdrawal of a unit from the sensitivity test shall be well justified and reported.

Results of these classifications are considered to converge sufficiently if the order of magnitude of the influence of the environmental variables considered is coherent among the different classification tests (e.g. for each significant independent variable, the magnitude of the sensitivity derived from each individual test differs by no more than 50 % from the mean value).

L.2.9 Classification of RSD

The class is determined from a minimum of three classification tests (2 units at the same location and one unit at 2 different locations).

The final sensitivity slope should be used in Equation (L.7) to calculate the uncertainty. The final slopes result from the combination of the slopes from the various classification tests as follow:

a) every significant independent variable resulting from every classification test should be considered (i.e. if a variable is found to be significant and independent in one test out of three, it should be considered in the final class).

b) for every significant independent variable:

   1) interpolate the slope to the height of interest for every classification test,

   2) combine the slopes from the various classification test using Equation (I.3).

L.3 Verification of the performance of remote sensing devices

Measurements acquired by the remote sensing device shall be calibrated against concurrent and co-located measurements of the same wind flow parameters acquired by meteorological mast-mounted reference sensors which would have been deemed compliant for conducting a power curve test. Depending on the use of the remote sensing device in the power curve test campaign, the accuracy shall be evaluated in relation to those same remote sensing device output parameters considered during the classification test and which are relevant to the power curve test.

The calibration shall be conducted not earlier than one year prior to the start of the power curve test (or during the power performance test) for its results still to be considered valid in relation to the power curve test in which the remote sensing device is being deployed.

Regarding data acquisition and data preparation, the calibration test is conducted in the same way as the sensitivity analysis as described in L.2.2 and L.2.3, with the exception that criterion L.2.2 e) is relaxed, such that it is sufficient to acquire 180 h of data. The requirements on the heights of the reference sensors described in L.2.2 in relation to classification tests also apply to verification tests.

A bin average procedure shall be used to compare the measurements acquired using the remote sensing device and the reference sensors. The bin-wise deviation between the remote

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sensing device measurement and the measurement of the reference sensor is considered the key result. The width and centre of the bins shall be as follows[41]:

a) 0,5 m/s wide reference wind speed bins centred on multiple integers of 0,5 m/s shall be applied for the comparison of horizontal wind speeds and the comparison of standard deviation values of the horizontal wind speed;

b) 5° wide wind direction bins shall be applied for comparison of wind directions, centred on multiple integers of 5°.

The raw data, expressed as 10 min averages, shall be presented as a scatter plot of the measurements acquired by the remote sensing device against the measurements acquired by the reference sensor. In addition, the deviations between the remote sensing device measurements and reference measurements shall be plotted against the reference measurements. These shall be shown on the same plot, an example of which is shown in Figure L.5. For the first scatter plot, the correlation coefficient shall be computed. For the second scatter plot, the mean value and standard deviation of the deviations shall be computed. For both scatter plots, mean values and standard deviations per bin of the dependent variable shall be calculated (Table L.9).

The bin averages of the remote sensing measurements shall be plotted as a function of the bin averages of the reference sensor measurements (Figure L.6). A two-parameter ordinary least squares (OLS) linear regression shall be plotted through the data points that lie within the reference wind speed range 4 m/s to 16 m/s inclusive.

The total uncertainty of the remote sensing device remaining from its calibration test shall be assessed as described in L.4.3 (Figure L.6, Table L.9). The bin-averaged deviations of the RSD measurements and reference measurements shall be compared to the standard uncertainty of the calibration test reduced by the bin averaged deviations as given by the following expression where all components have consistent units:

$$\sqrt{u_{\text{ver},i}^2 - \left(\overline{V}_{\text{RSD},i} - \overline{V}_{\text{Ref},i}\right)^2}$$

where

$\overline{V}_{\text{RSD},i}$ bin average of RSD at calibration test in bin i;

$\overline{V}_{\text{Ref},i}$ bin average of reference measurement at calibration test in bin i;

$u_{\text{ver},i}$ standard uncertainty of calibration test in bin i according to L.4.3.

The wind speed measurements of the RSD may be corrected based on the calibration test results in order to remove a bias. Such a correction is recommended if the bin-averaged deviations exceed the above expression (at least in one bin). The wind speed correction may consist of a linear regression of the bin averaged reference sensor measurements versus the RSD measurements.

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41 Comparisons of parameters other than those listed may be desirable in the context of alternative applications of remote sensing. For example, 0,1 m/s wide bins may be used for the comparison of vertical wind speeds and the comparison of standard deviations of the horizontal wind speed, centred on multiple integers of 0,1 m/s, while 1 % (0,01) wide bins may be used for comparison of turbulence intensities, centred on multiple integers of 1 % (0,01).

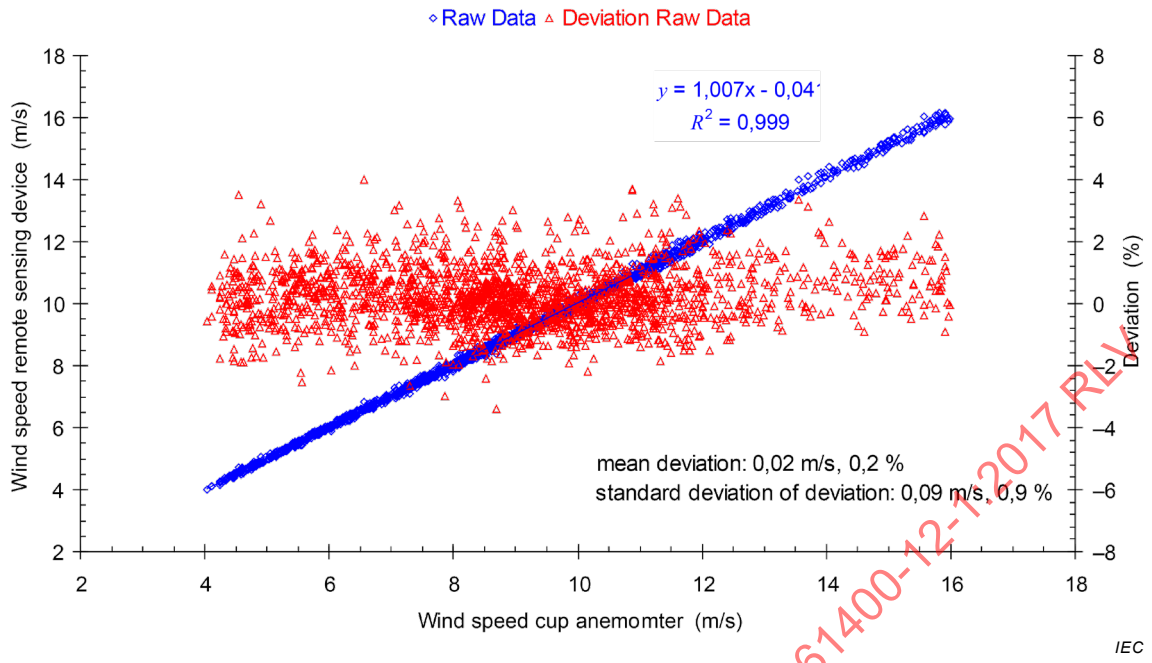

Figure L.5 – Comparison of 10 minute averages of the horizontal wind speed component as measured by a remote sensing device and a cup anemometer

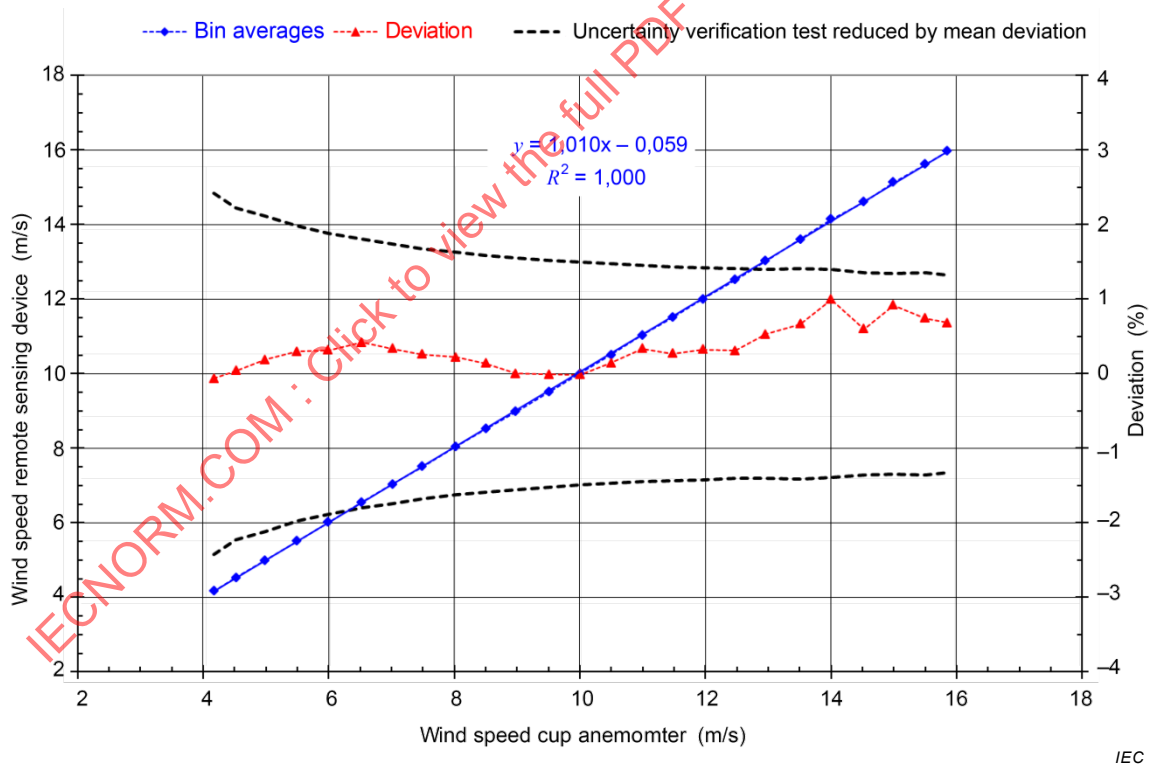

Figure L.6 – Bin-wise comparison of measurement of the horizontal wind speed component of a remote sensing device and a cup anemometer

The considerations discussed in L.2.4 in relation to errors and sensitivities detected during classification tests that are artefacts of incorrect remote sensing device configuration, in particular, the introduction of errors and sensitivities to wind shear as a result of incorrect assignment of measurement heights, should also be considered in the context of calibration tests, see reference [10].

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L.4 Evaluation of uncertainty of measurements of remote sensing devices

L.4.1 General

The following components shall be taken into account for the evaluation of the uncertainty of the measurements with remote sensing devices:

a) uncertainty resulting from the RSD calibration test according to L.4.3;

b) uncertainty resulting from the classification of the remote sensing device according to L.4.4;

c) uncertainty due to non-homogenous flow within the measurement volume of the remote sensing device according to L.4.5;

d) uncertainty due to mounting effects of the remote sensing device according to L.4.6;

e) uncertainty due to variation in flow across the power curve test site according to L.4.7;

f) a possible uncertainty due to unexpected results of the monitoring of the remote sensing device's accuracy on the application site according to Clause L.5.

The different uncertainty components shall be assumed to be independent from each other and shall be added in quadrature.

L.4.2 Reference uncertainty

The following uncertainty components are considered for the evaluation of the standard uncertainty of the reference sensor (in case of a cup anemometer) and shall be considered to be independent from each other and thus shall be added in quadrature:

a) wind tunnel calibration;

b) cup anemometer effects according to the anemometer classification;

c) cup anemometer mounting effects;

d) uncertainty of any applied meteorological mast correction to the reference cup anemometer measurements;

e) uncertainty in the data acquisition system of the reference instrument for the wind speed in bin i.

L.4.3 Uncertainty resulting from the RSD calibration test

The measurements of the remote sensing device are linked to the following systematic uncertainties (category B uncertainties) resulting from the calibration test, which shall be calculated for each bin of the measurement of the remote sensing device:

a) the standard uncertainty of the reference sensor according to L.4.2;

b) the mean deviation of the remote sensing device measurements and the reference sensor measurements. If a correction of the measurement of the remote sensing device is performed, the average deviation between the corrected measurements of the remote sensing device and the reference sensor measurements are evaluated;

c) the standard uncertainty of the measurement of the remote sensing device calculated as the standard deviation of the measurements divided by the square root of the number of data records per bin (category A uncertainty of calibration test);

d) uncertainty of the remote sensing device due to mounting effects during the calibration test;

e) uncertainty of the remote sensing device due to non-homogenous flow within the measurement volume during the calibration test according to L.4.5.

Site effects may be considered as an additional uncertainty if the remote sensing device and the reference sensor meteorological mast are separated from each other by a significant distance that compromises compliance with item L.2.2 d). In particular, an additional

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uncertainty in wind speed of 1 % times the separation distance divided by the measurement height shall be applied. The separation distance is the distance between the centroid of the measurement volume and the reference sensor being used for the test. The measurement height is the height at which the comparison between the reference sensor and the remote sensing device is being performed. This is not referred to the hub height or rotor diameter of the test wind turbine as these may not be known at the time the classification or calibration tests are being conducted. The additional uncertainties associated with similar issues arising during the power curve test due to the distance of the remote sensing device from the test wind turbine are discussed in L.4.7.

Uncertainties of the data acquisition system of the remote sensing device are automatically integrated in the calibration test results and shall not be considered additionally.

The different uncertainty components shall be assumed to be independent from each other and shall be added in quadrature for each wind speed bin. An example calculation is shown in Table L.9. The total category B uncertainty of the measurements of the remote sensing device resulting from the calibration test shall be taken into account as category B uncertainty of the power curve test in any case.

Table L.9 – Example of uncertainty calculations arising from calibration of a remote sensing device (RSD) in terms of systematic uncertainties

V_{cup}	V_{RSD}	Number of data sets	V_{RSD} max	V_{RSD} min	V_{RSD} std	V_{RSD} std/$\sqrt{n}$	Mean deviation	V_{cup} uncertainty	Mounting uncertainty RSD	V_{RSD} uncertainty
[m/s]	[m/s]	[-]	[m/s]	[m/s]	[m/s]	[m/s]	[%]	[%]	[%]	[%]
4,133	4,148	15	4,30	4,00	0,090	0,023	0,4	2,3	0,5	2,4
4,528	4,525	33	4,85	4,28	0,139	0,024	0,0	2,2	0,5	2,3
5,064	5,086	26	5,31	4,74	0,141	0,028	0,4	2,0	0,5	2,2
5,538	5,593	47	5,92	5,28	0,166	0,024	1,0	1,9	0,5	2,2
5,985	6,025	44	6,27	5,72	0,141	0,021	0,7	1,9	0,5	2,0
6,513	6,546	45	6,80	6,26	0,158	0,024	0,5	1,8	0,5	1,9
6,995	7,019	87	7,33	6,73	0,151	0,016	0,3	1,7	0,5	1,8
7,500	7,501	109	7,83	7,14	0,156	0,015	0,0	1,7	0,5	1,7
8,010	8,013	118	8,41	7,69	0,160	0,015	0,0	1,6	0,5	1,6
8,512	8,537	145	8,97	8,22	0,183	0,015	0,3	1,6	0,5	1,6
8,993	9,033	146	9,45	8,71	0,176	0,015	0,4	1,5	0,5	1,6
9,498	9,554	121	9,97	9,16	0,171	0,016	0,6	1,5	0,5	1,6
10,008	10,059	166	10,57	9,63	0,181	0,014	0,5	1,5	0,5	1,6
10,506	10,536	106	10,91	10,25	0,141	0,014	0,3	1,5	0,5	1,5
11,003	11,037	78	11,52	10,68	0,185	0,021	0,3	1,4	0,5	1,5
11,502	11,510	59	11,92	11,13	0,188	0,025	0,1	1,4	0,5	1,4
12,000	12,035	63	12,62	11,68	0,217	0,027	0,3	1,4	0,5	1,5
12,519	12,521	68	12,97	12,15	0,182	0,022	0,0	1,4	0,5	1,4
12,957	12,998	64	13,40	12,64	0,186	0,023	0,3	1,4	0,5	1,4
13,469	13,470	40	13,87	13,17	0,177	0,028	0,0	1,4	0,5	1,4
14,011	14,014	25	14,36	13,67	0,192	0,038	0,0	1,3	0,5	1,4
14,444	14,490	30	14,83	14,21	0,172	0,031	0,3	1,3	0,5	1,4
14,983	14,951	14	15,48	14,62	0,246	0,066	–0,2	1,3	0,5	1,4
15,509	15,585	17	15,92	15,38	0,135	0,033	0,5	1,3	0,5	1,4
15,990	16,038	16	16,24	15,77	0,130	0,032	0,3	1,3	0,5	1,4

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V_{cup}	V_{RSD}	Number of data sets	V_{RSD} max	V_{RSD} min	V_{RSD} std	V_{RSD} std/$\sqrt{n}$	Mean deviation	V_{cup} uncertainty	Mounting uncertainty *RSD*	V_{RSD} uncertainty
16,475	16,479	10	16,69	16,22	0,149	0,047	0,0	1,3	0,5	1,3
17,066	17,140	12	17,50	16,75	0,227	0,065	0,4	1,3	0,5	1,4
17,515	17,682	13	17,91	17,44	0,153	0,042	1,0	1,3	0,5	1,6
18,001	18,020	8	18,32	17,82	0,157	0,056	0,1	1,3	0,5	1,3
18,430	18,549	13	18,82	18,25	0,173	0,048	0,6	1,3	0,5	1,5
18,849	18,980	4	19,16	18,80	0,149	0,075	0,7	1,3	0,5	1,5
19,415	19,430	3	19,67	19,23	0,223	0,129	0,1	1,3	0,5	1,4
The uncertainty due to non-homogenous flow within the measurement volume is assumed to be zero.										

It is pointed out that the statistical standard uncertainty of the measurement of a remote sensing device related to single 10-minute averages of a measured variable as resulting from the calibration test is given by the standard deviation of the deviations of the measurements of the remote sensing device and the reference sensor. This uncertainty is significantly higher than the statistical uncertainty of the bin averages of the calibration test described in above bullet point c). However, the statistical uncertainty of single 10-minute averages is automatically included in the category A uncertainty of the bin averages of the evaluated power curve and shall therefore not be accounted for by additional means.

L.4.4 Uncertainty due to remote sensing device classification

Sensitivity of the device due to varying conditions introduces uncertainty due to the fact that the meteorological conditions during the application of the remote sensor may deviate from the meteorological conditions present during the calibration test. The standard uncertainty arising from the accuracy class as determined following L.2.7 will be the final accuracy class number divided by $\sqrt{3}$.

The accuracy class according to L.2.7 represents the maximum measurement error of the remote sensing device due to the influence of environmental conditions within each 10 min period (after the associated calibration test). This uncertainty includes uncertainties due to a variation of the environmental variables around its mean values as present at the power curve test in each wind speed bin. However, the uncertainty due to this variation of the environmental variables at the power curve test is of statistical nature and is fully reflected in the category A uncertainty of the bin averages of the power curve (category A uncertainty of the power curve) and should therefore not be accounted for as category B uncertainty of the wind speed measurement. The category B uncertainty of the wind speed measurement due to the influence of environmental variables on the performance of the remote sensing device should rather take into account only the deviations of the mean values of the environmental variables during the calibration test and the power curve test and should be calculated for each wind speed bin as:

$$u_{VR,\mathrm{class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \left| \bar{x}_{PC,j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)^2} \tag{L.6}$$

where

$u_{VR,\mathrm{class},i}$ is category B standard uncertainty of wind speed measurement in wind speed bin i due to the influence of the environmental variables on the performance of the remote sensing device;

M is number of environmental variables considered to have a relevant influence on the accuracy of the remote sensing device according to the classification test;

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m_j is slope describing the sensitivity of the wind speed measurement of the remote sensing device on the environmental variable j as gained from the combination of the results from a minimum of 3 classification tests;

$\bar{x}_{PC,j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the power curve test;

$\bar{x}_{\text{ver},j,i}$ is mean value of the environmental variable j in wind speed bin i as present during the calibration test of the remote sensing device.

For relevant environmental variables not measured during the power curve test, the maximum range of that variable as present at the power curve test shall be estimated, and the deviation of the mean values of the environmental variables during the power curve test and during the calibration test in the above equation shall be replaced by the expected maximum absolute deviation of that variable as present during the power curve test from its mean value present during the calibration test divided by $\sqrt{3}$. However, as the classification derivation is based on the assumption of a linear response to perturbations in the independent variables, where the maximum and minimum values of the independent variables during the power curve or calibration test exceed the ranges obtained during the classification sensitivity tests, care should be taken when interpreting the classification uncertainty result. If the calibration test includes the same data as the power curve test, the uncertainty according to L.4.4, becomes equal to zero.

L.4.5 Uncertainty due to non-homogenous flow within the measurement volume

Many remote wind sensing devices assume equivalent wind conditions in regions within the measurement volume that have significant spatial separation. This assumption can be violated in complex terrain. Even in terrain not classified as complex according to this standard, significant errors can occur due to the non-homogeneity of the flow. The uncertainty linked to the assumption of equivalent wind conditions in spatially separated probe volumes shall be assessed. Remote sensing devices should be subject to a rigorous and thorough analysis of the influence of non-uniform flow on measurement bias with reference to their particular configuration.

For example, the combination of a suitable flow model and a model reproducing the remote sensing device horizontal wind speed extraction algorithm might be used to assess the uncertainty due to non-homogeneous flow.

A simplified alternative to estimate this uncertainty applicable to many monostatic systems implemented by observations of the Doppler effect is given by the method used by Bingöl et al., reference [11], with extensions by Albers *et al.*, reference [12].

The user should consult with the remote sensing device manufacturer for the best method for evaluating the uncertainty for their specific device at the test site.

L.4.6 Uncertainty due to mounting effects

The uncertainty of the remote sensing device due to non-ideal levelling of the device shall be estimated. The uncertainty is highly dependent on the type of instrument being used.

L.4.7 Uncertainty due to variation in flow across the site

The same uncertainty as in the application of a mast shall be assumed for this uncertainty, i.e. a standard uncertainty of 2 % in terms of the horizontal wind speed component for a distance range of 2 to 3 rotor diameters and a standard uncertainty of 3 % for a distance range above 3 rotor diameters. When an RSD is used, it is the horizontal distance between the centre of the probe volume of the remote sensing device and the position of the test turbine that shall be considered.

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L.5 Additional checks

L.5.1 Monitoring the performance of the remote sensing device at the application site

A meteorological mast reaching at least the minimum of 40 m or the lower tip height of the tested wind turbine shall be applied at the power curve test for monitoring the performance of the remote sensing device. The set-up of the meteorological mast and the remote sensing device and the data preparation shall comply with the requirements described in L.2.2 and L.2.3 with the exception that the meteorological mast has only a relatively small height and may be equipped with reference sensors only at the top of the meteorological mast. The data analysis described in L.5.1 to L.5.3 shall be undertaken.

L.5.2 Identification of malfunctioning of the remote sensing device

Time series plots of the wind measurements (wind speed and wind direction) performed with the meteorological mast shall be compared to time series plots of the measurements of the respective wind measurements of the remote sensing device. In addition scatter plots of the measurements of the wind speed and wind direction of the remote sensing device versus the respective measurements with the meteorological mast shall be inspected. Periods with obvious outlier data or other anomalies shall be excluded from the power curve test.

L.5.3 Consistency check of the assessment of the remote sensing device systematic uncertainties

Note that this subclause does not apply if the RSD calibration is done simultaneously with the power performance measurement. The comparison and analysis of the measurements of the remote sensing device and the reference sensors at common measurement heights as performed for a calibration test according to Clause L.3 shall be repeated with the meteorological mast at the power curve test site for the full duration of the power curve measurement period. It is expected that the absolute value of the mean deviation of the measurements of the remote sensing device and the reference sensor per wind speed bin at the power curve test does not exceed the square root of the sum of the squares of the following uncertainty components:

a) the category B standard uncertainty of the measurement of the remote sensing device resulting from the calibration test performed prior to the power curve test assessed in full accordance with L.4.3;

b) systematic effects of environmental variables on the performance of the remote sensing device at the power curve test as assessed according to the equation given in L.4.4, taking into account only mean deviations of the influential environmental variables at the power curve test and the calibration measurement prior to the power curve test.

If the absolute value of the mean deviation of the measurements of the remote sensing device and the reference sensor exceeds this expectation in a certain wind speed bin, the difference of the true and expected deviation is considered an additional category B uncertainty component of the measurement of the remote sensing device at the power curve test in that wind speed bin. For the measurement heights of the remote sensing device not captured by the meteorological mast at the power curve test site, this additional uncertainty shall be calculated as follows:

$$u_{\text{added_systematic},j,i} = u_{\text{added_systematic},1,i} \frac{u_{\text{systematic},j,i}}{u_{\text{systematic},1,i}} \quad \text{(L.7)}$$

where

$u_{\text{added_systematic},j,i}$ is added category B standard uncertainty at measurement height j (not covered by the meteorological mast);

$u_{\text{added_systematic},1,i}$ is added category B uncertainty at the height of the top of the meteorological mast;

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$u_{\text{systematic},j,i}$ is cumulated other category B uncertainties of the remote sensing device at height j;

$u_{\text{systematic},1,i}$ is cumulated other category B uncertainties of the remote sensing device at the height of the top of the meteorological mast.

The added category B uncertainty shall be cumulated with the other category B uncertainties of the remote sensing device measurements in quadrature.

L.5.4 In-situ test of the remote sensing device

In order to check the consistency of the accuracy of the measurements of the remote sensing device throughout the power curve measurement campaign, the meteorological mast present at the test site may be used to perform an in-situ test of the remote sensing device similar to the in-situ test defined in Annex K. If in-situ testing is performed, it shall be done for all common measurement heights covered by the meteorological mast and the remote sensing device.

A successful in-situ test can replace a repetition of the calibration test after the power curve test.

L.6 Other requirements specific to power curve testing

Before using the remote sensing device for power curve measurements, a classification test according to Clause L.2 and a calibration test according to Clause L.3 shall be performed. Alternatively, the calibration test can be performed during the power curve test. If the calibration test is not performed at the power curve test site, the remote sensing device shall either be stored or shall be directly transported to the location where the power curve campaign shall take place at the end of the calibration test. A repetition of the calibration test shall be performed after the power curve test. As an alternative, an in-situ test of the remote sensing device against the meteorological mast present at the power curve test site can be performed. Deviations of the calibration test methodology or of such deviations implied by the in-situ test shall be treated like deviations of cup anemometer calibrations as defined in this standard.

If a measurement height required for the power curve test is between two measurement heights available from the calibration test or the classification test, linear interpolation of the results of the calibration test or of the classification test according to the height shall be performed. Linear extrapolation[42] of the results of the calibration test or of the classification test should not be performed. If the measurements required for the calculation of the rotor equivalent wind speed extend beyond the height range covered by the calibration test or the classification test, a higher uncertainty than the uncertainty pertaining to the nearest height covered by the calibration test or the classification test shall be considered.

In some cases it is helpful to carry out a site calibration in terrain which is sufficiently non-complex to satisfy the requirements of Annex B. If the remote sensing device is used in conjunction with a site calibration measurement, the measurement volume shall be centred horizontally within 10 m or 10 % of the hub height H of the reference meteorological mast, whichever is larger. Where a site calibration is not required, the remote sensing device may be situated consistent with the requirements of 6.3.2. In both cases, when acquiring hub height wind speed measurements, the extremes of the measurement volume at hub height H shall not lie closer to the test wind turbine than $2D$, where D is the rotor diameter, and the centroid of the measurement volume shall not lie further than $4D$ from the test wind turbine. This is illustrated in Figure L.7, where an inverted conical scan geometry is used for illustrative purposes only: this guidance is not limited to this particular scan geometry. The extremes of the measurement volume at all heights evaluated for the power curve test shall

42 Other types of extrapolation are permitted as long as they are conservative.

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lie outside a sphere centred at the position and hub height of any wind turbine with a radius of 2 rotor diameters of the respective wind turbine.

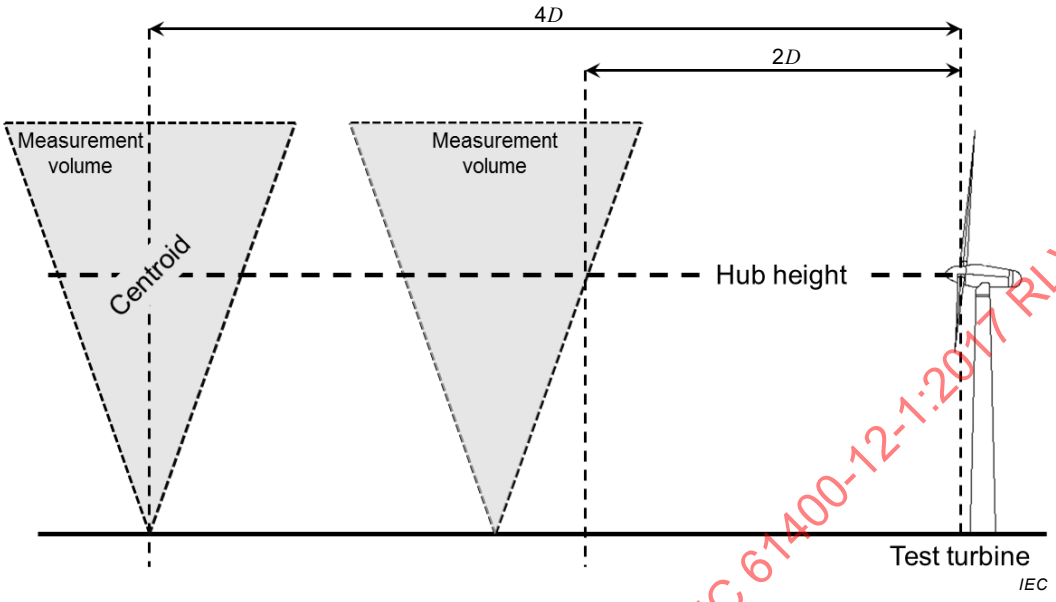

Figure L.7 – Example of permitted range of locations for measurement volume

Probe volumes within which the remote sensing device acquires a radial velocity measurement shall be free of wakes and flow perturbation from wind turbines and obstacles as defined in Annex A. For clarity:

a) the measurement volume is the region within which wind flow characteristics can influence a wind speed measurement and is defined by the scan geometry, device configuration or arrangement of the multiple beams penetrating the volume in order to acquire that measurement;

b) the probe volume is the region from which a single constituent physical measurement of, for example, Doppler shift, radial or line of sight velocity, is acquired, several of which are typically required to derive a wind speed measurement. The probe volume is a characteristic of the basic physical interaction of the remote sensing device with the atmosphere, rather than the wind speed measurement derived from these interactions, which is determined by the flow within the measurement volume.

Device-specific measures should be undertaken according to the advice and guidance of the manufacturers of the remote sensing device employed. The aim is to comply with the general requirements in measurement height.

The same remote sensing device configuration, operating parameters, software/firmware and performance related hardware components shall be used during the power curve test as were used during device classification and during the calibration test. No major changes shall be implemented that might affect performance between calibration, classification and power curve test.

If the meteorological mast available for the power curve test does not reach hub height, the atmospheric pressure measured by the meteorological mast instruments shall be adjusted to hub height following this standard. Furthermore, the air temperature will be adjusted to hub height assuming that the atmosphere varies according to ISO 2533:1975. An alternative method is to mount a temperature sensor on the wind turbine nacelle. The sensor shall be mounted at least one meter (1 m) above the nacelle and upwind of any existing ventilation systems. The effects of the nacelle on the sensor shall be mitigated in accordance with the international standard IEC 61400-12-2.

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The following measurements are required for the power curve test, the calibration test and for the classification test if the remote sensing device requires respective data filtering for the provision of accurate measurements:

a) measurement of precipitation;

b) measurement of cloud height;

c) measurement of ambient acoustic noise level.

The need for such measurements shall be reasonably assessed during the classification test.

L.7 Reporting

L.7.1 Common reporting on classification test, calibration test, and monitoring of the remote sensing device during application

The reports on the classification test, on the calibration test and on the monitoring of the remote sensing device during the application shall include the following common contents:

a) all details of the set-up of the reference measurement and all details of the test site as required for a power curve test;

b) all details of the set-up of the remote sensing device, including exact position of the remote sensing device, relative position to reference meteorological mast, orientation, version and set-up of operating software, pitch and roll angle and its monitoring;

c) serial number and type of the remote sensing device;

d) measurement period;

e) description of data analysis including filtering;

f) presentation of raw data as described in Clause L.3;

g) bin-wise analysis of measurement of remote sensing device versus reference measurement including graphical and tabular documentation as described in Clause L.3 and L.4.3;

h) analysis of uncertainty of reference measurements, where applicable in accordance to L.4.2;

i) environmental conditions during the test remaining after all data filtering: At least all variables having a significant influence on the accuracy of the remote sensing device as resulting from the classification test shall be documented. Each of these variables shall be plotted as a function of the wind speed at the evaluation height and shall be bin-averaged against this wind speed using bins with a width of 0,5 m/s centred on multiple integers of 0,5 m/s. In addition, the distribution of these variables shall be shown. For the performance monitoring at the power curve test, this documentation is limited to the available measurements of environmental conditions;

j) all calibration certificates of all reference sensors and of the data acquisition system.

L.7.2 Additional reporting on classification test

The report about the classification test shall contain in addition to the items given in L.7.1:

a) scatter plots of 10 min data and bin averages related to the sensitivity analysis for all considered variables as detailed in L.2.4;

b) description and reasoning of the selection of considered environmental variables;

c) complete documentation of the process of the identification and elimination of insignificant environmental variables;

d) complete documentation of the process of the investigation of inter-correlations of the considered environmental variables;

e) sensitivity parameters, sensitivities, correlation coefficients, mean values and standard deviations of all variables considered according to Clause L.2;

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f) ranges of environmental variables considered for the classification;

g) choice of the classification method;

h) classification results for the parameter ranges defined in Table L.3.

L.7.3 Additional reporting on calibration test

The report about the calibration test shall contain in addition to the items given in L.7.1:

a) standard uncertainty of the remote sensing device resulting from the calibration test according to L.4.3;

b) if the calibration test is repeated after the power curve test: comparison of results of calibration tests and consequences of the comparison;

c) additional reporting on monitoring of remote sensing device during application;

d) any anomalies of the measurements according to L.5.2;

e) amount and periods of data filtered out based on data check according to L.5.2;

f) uncertainty analysis according to L.4.3 and L.4.4;

g) bin-wise representation of evaluation criteria according to L.5.3 and added uncertainty;

h) training and test period, results and consequences of in-situ test, so far performed.

L.7.4 Additional reporting on application

The report about the application shall contain in addition to the items given in L.7.1:

a) full uncertainty assessment of measurements of the remote sensing device according to Clause L.4;

b) realisation of air density measurements and description of associated data corrections to hub height.

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Annex M
(informative)

Normalisation of power curve data according to the turbulence intensity

M.1 General

Wind turbine power curves are influenced by turbulence intensity. A significant part of the turbulence intensity effect is caused by the averaging of the measured power output and the measured wind speed over 10 min periods. This can be understood from the non-linear relationship between the power output and the wind speed: In the wind speed range where the power output increases proportionally with the wind speed (ankle of the power curve), the 10 min averaging leads to an increase of the power output with increasing turbulence intensity. This is typically the case at low wind speeds and at wind speeds around the maximum power coefficient. In the wind speed range where the power output increases less than proportional with the wind speed (knee of the power curve), the 10 min averaging leads to a decrease of the power output with increasing turbulence intensity. This is typically the case at the knee of the power curve at wind speeds just below rated wind speed.

Annex M describes a procedure for normalising power curve data to a reference turbulence intensity (see references [13] and [14]). The reference turbulence intensity can be defined as a function of the wind speed. The given procedure considers only the effect of 10 min averaging of the measurement data. Other turbulence effects on the wind turbine power output are not covered by the method. It is recommended to apply the turbulence normalisation procedure to make power curves measured at different turbulence intensities more comparable to each other.

The turbulence normalisation procedure outlined here makes simplifying assumptions such as the wind turbine follows, at each instant, a certain power curve, which is independent of the turbulence intensity, and the assumption that the wind speed fluctuations relevant for the entire rotor area within a 10 min period are adequately characterised by the turbulence intensity at hub height. Despite the simplicity of these assumptions, the method enables the adjustment of the effect of 10 min averaging for a large variety of wind turbine types, rotor sizes and turbulence ranges.

A procedure for the estimation of uncertainties linked to the effects of turbulence on power curves both for the case of turbulence normalisation and for the case that no turbulence normalisation is performed is given in Clause M.5. The suggested uncertainty calculation is also intended to cover contributions to power curve test uncertainties due to turbulence effects not related to the 10 min averaging.

M.2 Turbulence normalisation procedure

It is assumed for the turbulence normalisation that at each instant the wind turbine follows a certain power curve, here defined as zero turbulence power curve. The determination of the zero turbulence power curve is described in Clause M.3. Figure M.1 illustrates the turbulence normalisation process.

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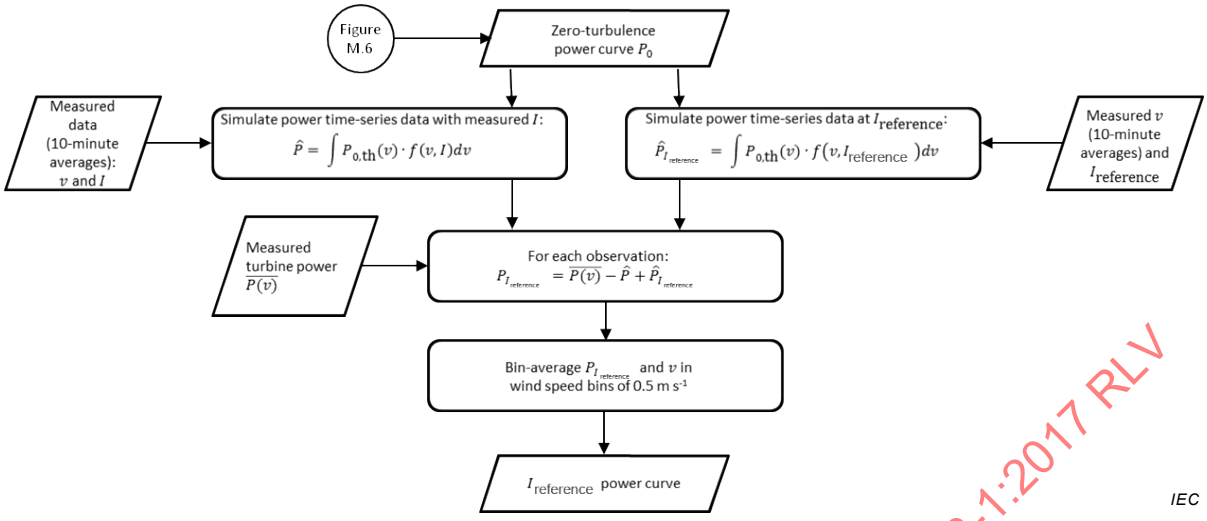

Figure M.1 – Process for obtaining a power curve for a specific turbulence intensity ($I_{\mathrm{reference}}$)

Based on the zero turbulence power curve and wind speed distribution within a 10 min period, the 10 min average of the wind turbine power output can be simulated by the following equation:

$$\overline{P_{\mathrm{sim}}(v)} = \int_{v=0}^{\infty} P_{I=0}(v) \cdot f(v) dv \qquad \text{(M.1)}$$

where

$f(v)$ is the wind speed distribution within 10-minute period;

$P_{I=0}(v)$ is the zero turbulence power curve;

$P_{\mathrm{sim}}(v)$ is a simulated 10 min average of measured power output.

Equation (M.1) shall be applied to power curve data (every 10 min period) to calculate two simulated power outputs for the following conditions:

1) The wind speed distribution as measured in the 10 min period at hub height. A Gaussian distribution $f(v)$ may be assumed, which is fully determined by the average wind speed and the standard deviation of the wind speed as recorded within the 10 min period. In case of a wind turbine with active power control, Equation (M.1) shall be evaluated for the air density normalised hub height wind speed. The standard deviation to be applied is calculated as the product of the measured turbulence intensity (standard deviation of wind speed divided by the average wind speed at hub height) and the air density normalised average wind speed (at hub height);
2) A Gaussian wind speed distribution with the 10 min average of the wind speed measured at hub height and a standard deviation equal to the product of the 10 min average of the wind speed measured at hub height and the reference turbulence intensity. In case of a wind turbine with active power control, Equation (M.1) shall be evaluated for the air density normalised wind speed (at hub height).

The measured power output is then normalised to the reference turbulence intensity by the following equation:

$$\overline{P_{I_{\mathrm{ref}}}(v)} = \overline{P(v)} - \overline{P_{\mathrm{sim},I}(v)} + \overline{P_{\mathrm{sim},I_{\mathrm{ref}}}(v)} \qquad \text{(M.2)}$$

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where

$\overline{P(v)}$ is the 10 min average of measured power output;

$\overline{P_{\text{sim},I}(v)}$ is the simulated 10 min average of measured power output according to the above condition 1: Equation (M.1) applied for the measured wind speed distribution (measured average wind speed and measured turbulence intensity);

$\overline{P_{\text{sim},I_{\text{ref}}}(v)}$ is the simulated 10 min average of measured power output according to the above condition 2: Equation (M.1) applied for the measured average wind speed and for the reference turbulence intensity I_{ref} by assuming a Gaussian wind speed distribution.

In case of a stall-regulated wind turbine, Equation (M.2) shall be applied with the air density normalised measured power output.

The power coefficient data (as applied only for graphical demonstration of the measurements) shall be calculated on the basis of the power output normalised to the reference turbulence intensity. In case of a stall-regulated wind turbine, the power coefficient data shall be calculated on the basis of the power output normalised to the reference turbulence intensity and on the basis of the reference air density (not on basis of the measured air density).

M.3 Determination of the zero turbulence power curve

An initial zero turbulence power curve is calculated on the bin-averaged power curve normalised according to the air density, but not normalised according to the turbulence intensity and not corrected according to the wind shear. The initial zero turbulence power curve is determined as a first approach as follows (see also Figure M.2 and Figure M.3):

a) assumption of zero power output below cut-in wind speed. As a first approach, the cut-in wind speed is set to the average wind speed of the wind speed bin, where the measured power output reaches at least 0,1 % of the rated power;

b) assumption of constant power coefficient c_{P} equal to the maximum power coefficient $c_{\text{P,max}}$ between cut-in wind speed and rated wind speed. This assumption is equal to an increase of the power output with the third power of the wind speed. The initial zero turbulence power curve shall be calculated with this assumption and on the basis of the reference air density between the cut-in wind speed and the rated wind speed in increments not larger than 0,1 m/s. As a first approach, the maximum power coefficient $c_{\text{P,max}}$ shall be set to the maximum power coefficient of the measured bin-averaged power curve;

c) calculation of rated wind speed v_{rated} from rated power P_{rated}, rotor swept area A, maximum power coefficient $c_{\text{P,max}}$ and reference air density ρ by: $v_{\text{rated}} = \left(\frac{2 \cdot P_{\text{rated}}}{\rho \cdot c_{\text{P,max}} \cdot A} \right)^{\frac{1}{3}}$. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins;

d) power output equal to rated power for wind speeds above rated wind speed v_{rated}. As a first approach, the rated power is set to the highest bin-averaged power output of all wind speed bins of the measured power curve. This rated power output shall be assumed for wind speeds far above cut-out wind speeds (e.g. 100 m/s) for the definition of the initial zero turbulence power curve.

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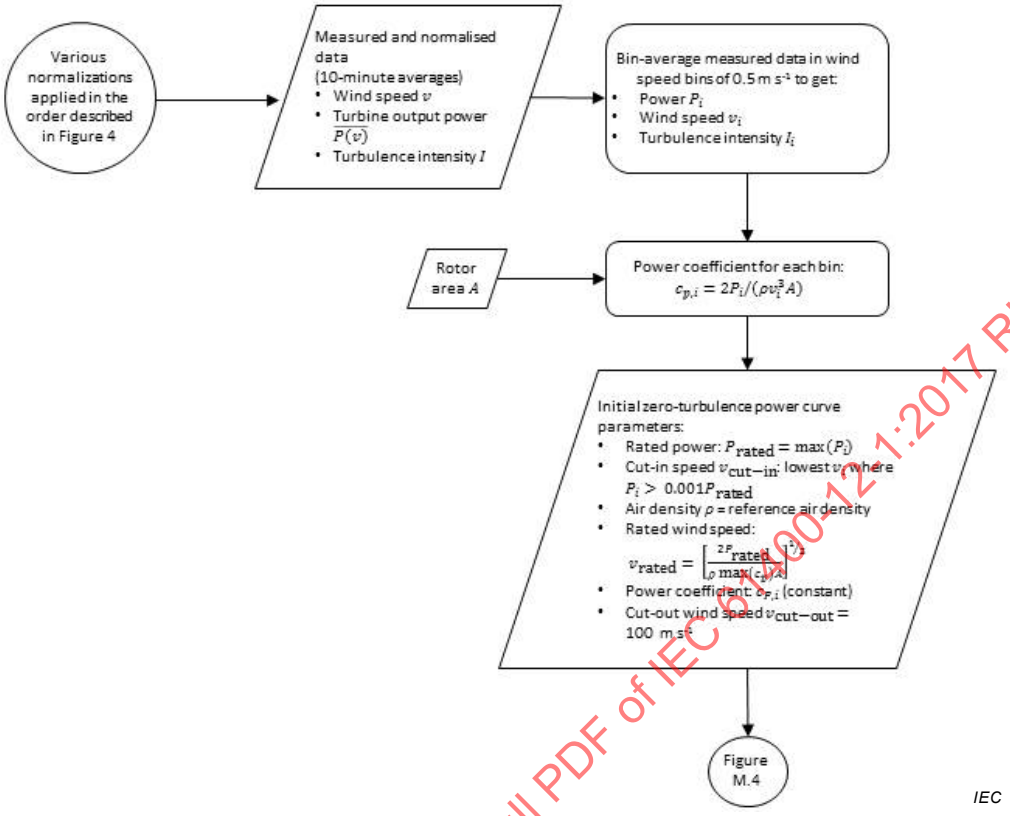

Figure M.2 – Process for obtaining the initial zero turbulence power curve parameters from the measured data

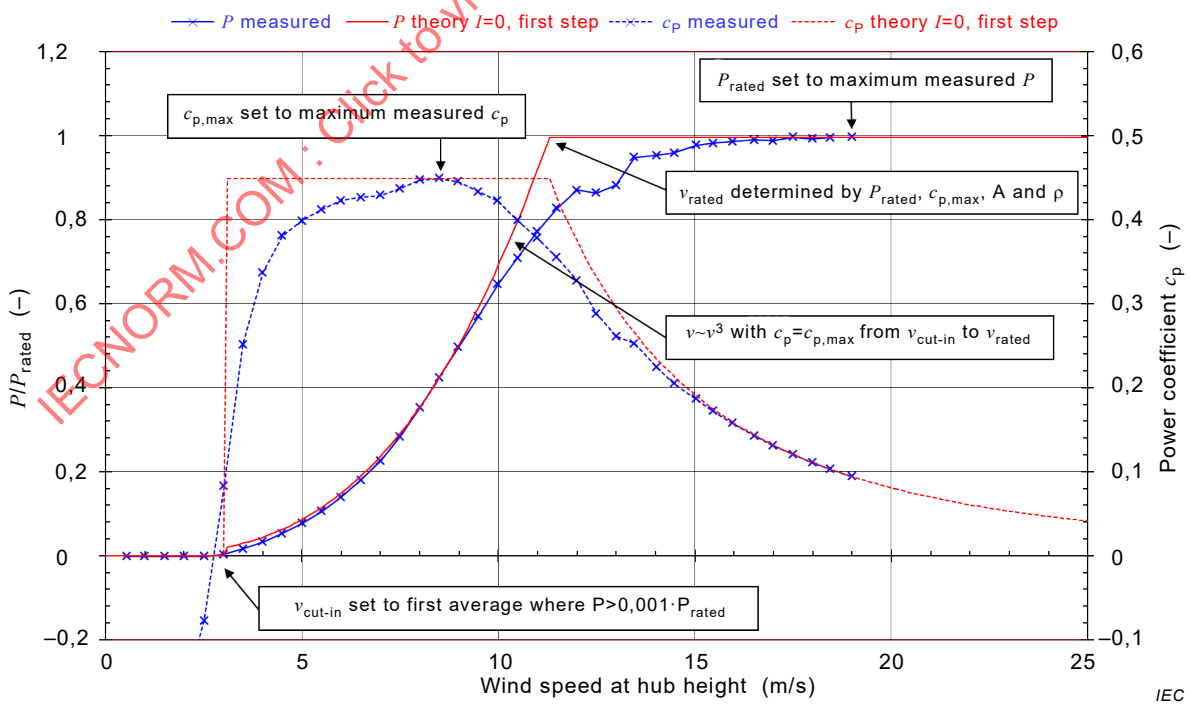

Figure M.3 – First approach for initial zero turbulence power curve

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In the next step, the rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall be adjusted because these three parameters are dependent on the turbulence intensity and because values for these parameters have been applied in the previous step instead the values corresponding to the turbulence intensity of zero. A bin-average of the measured turbulence intensity as a function of the wind speed measured at hub height shall be performed. In case of a wind turbine with active power control, the turbulence intensity shall be bin averaged according to the air density normalised wind speed at hub height.

The initial zero turbulence power curve shall be integrated over a Gaussian wind speed distribution according to Equation (M.1) with the average wind speed equal to the bin average of the measured power curve and with the standard deviation calculated as product of the bin-averaged wind speed and the bin averaged turbulence intensity. The air density normalised wind speed at hub height shall be applied in case of a wind turbine with active power control. By this procedure, the power curve is simulated for each wind speed bin for the measured turbulence intensity, while the simulated power curve refers to exactly the same wind speed bins than the measured power curve. The rated power, the cut-in wind speed and the maximum power coefficient of the initial zero turbulence power curve shall then be adjusted as follows (see Figure M.4):

a) the rated power shall be adjusted such that the maximum power of the simulated power curve fits the maximum bin averaged power of the measured power curve;

b) the cut-in wind speed shall be adjusted such that the cut-in wind speed of the simulated power curve fits the cut-in wind speed of the bin averaged measured power curve. Cut-in wind speed is for both power curves defined as lowest wind speed bin where the power output reaches at least 0,1 % of the rated power;

c) the maximum power coefficient shall be adjusted such that the maximum power coefficient of the simulated power curve fits the maximum power coefficient of the measured power curve.

Steps a) to c) above shall be all three repeated at every iteration, in the given order, until the three parameters converge at least as follows:

a) the maximum power of the simulated power curve deviates from the maximum bin averaged power of the measured power curve by no more than 0,1 %;

b) the cut-in wind speed of the simulated power curve deviates from the cut-in wind speed of the bin averaged measured power curve by no more than 0,5 m/s;

c) the maximum power coefficient of the simulated power curve deviates from the maximum power coefficient of the measured power curve by no more than 0,01.

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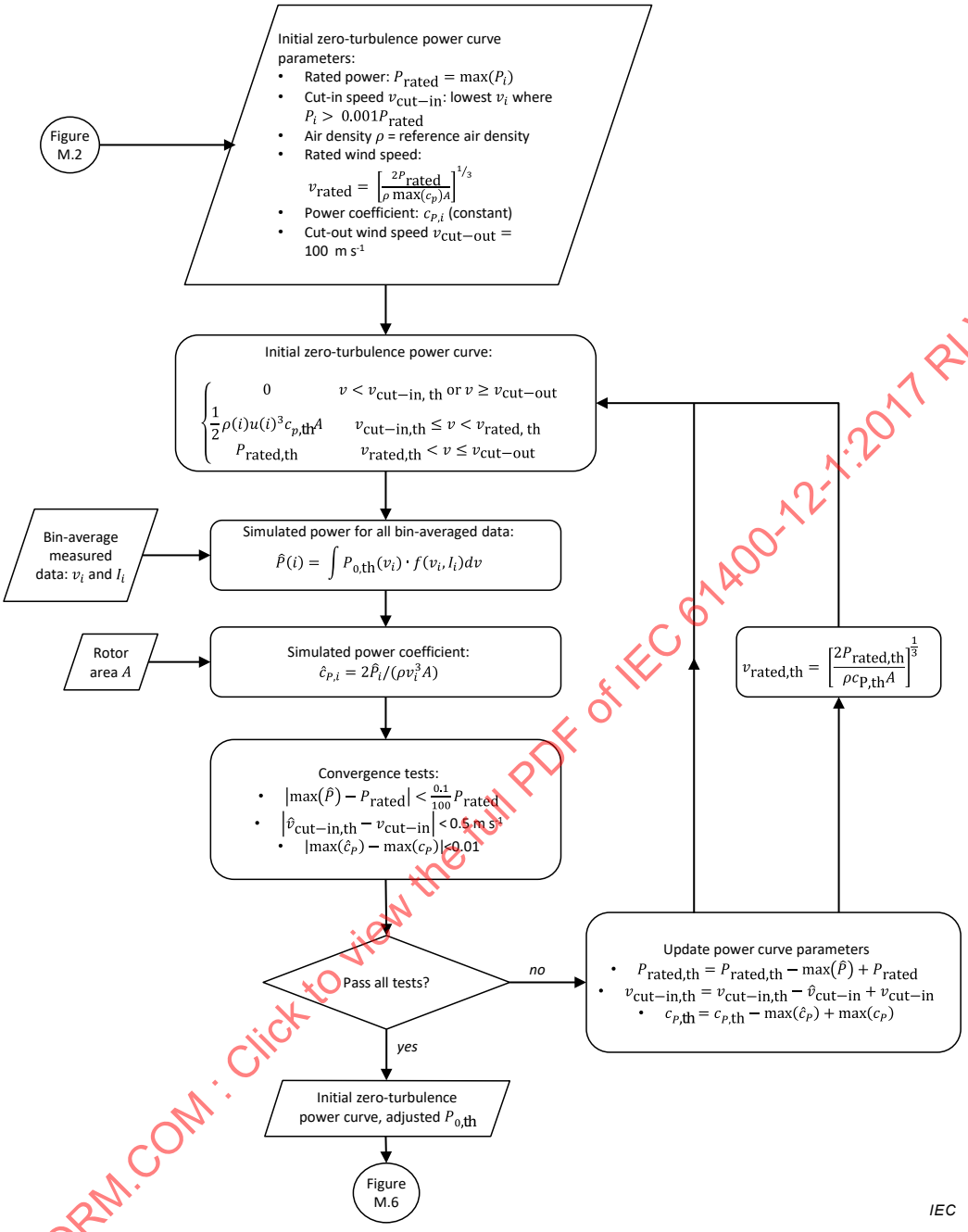

Figure M.4 – Process for obtaining the theoretical zero-turbulence power curve from the measured data

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Sufficient convergence is normally reached after the first or second iteration. Figure M.5 illustrates how the adjustments normally change the initial zero turbulence power curve from the first step.

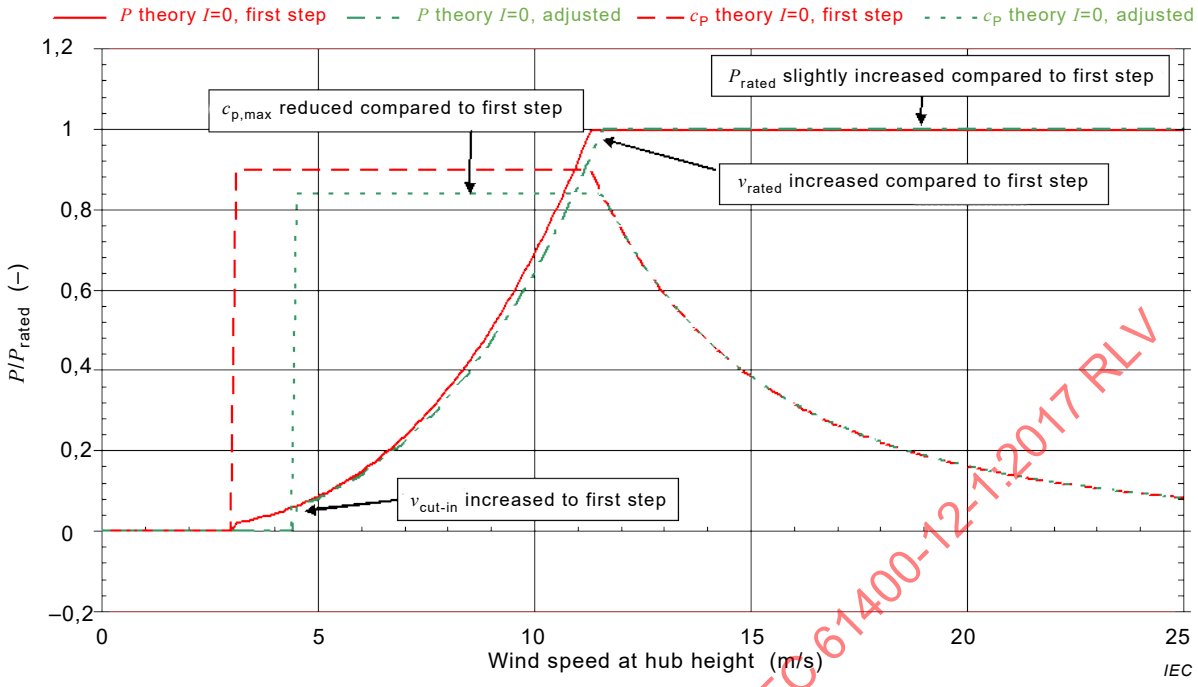

Figure M.5 – Adjusted initial zero turbulence power curve (green) compared to first approach (red)

The zero turbulence power curve shall then be determined by applying the data normalisation process described in Clause M.2 with the zero turbulence power curve set to the initial zero turbulence power curve in Equation (M.1) and by assuming a turbulence intensity of zero (constant wind speed during 10 min period). The final zero turbulence power curve is gained by bin-averaging the so normalised power curve raw data as illustrated in Figure M.6. This bin-averaged power curve shall be extended with the power output of the highest bin to wind speeds far above cut-out wind speeds (e.g. 100 m/s) when applying Equations (M.1) and (M.2) for turbulence normalisations.

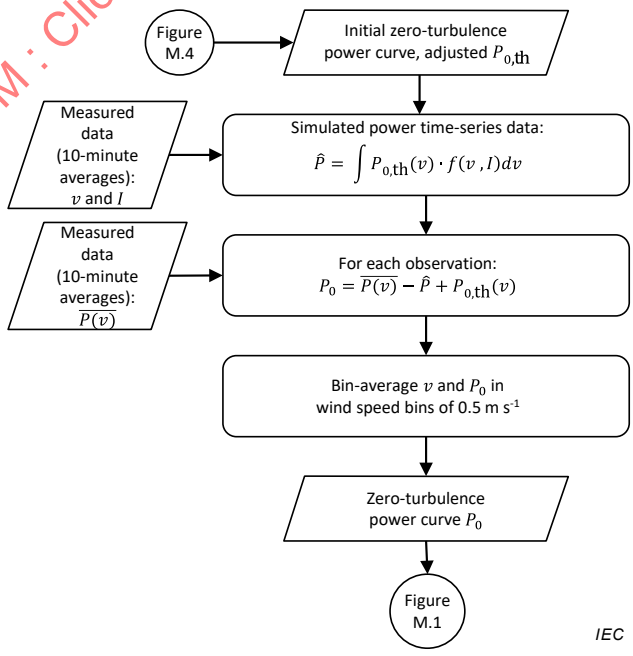

Figure M.6 – Process for obtaining the final zero-turbulence power curve from the measured data

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Figure M.7 illustrates how the final zero turbulence power curve typically compares to the initial zero turbulence power curve.

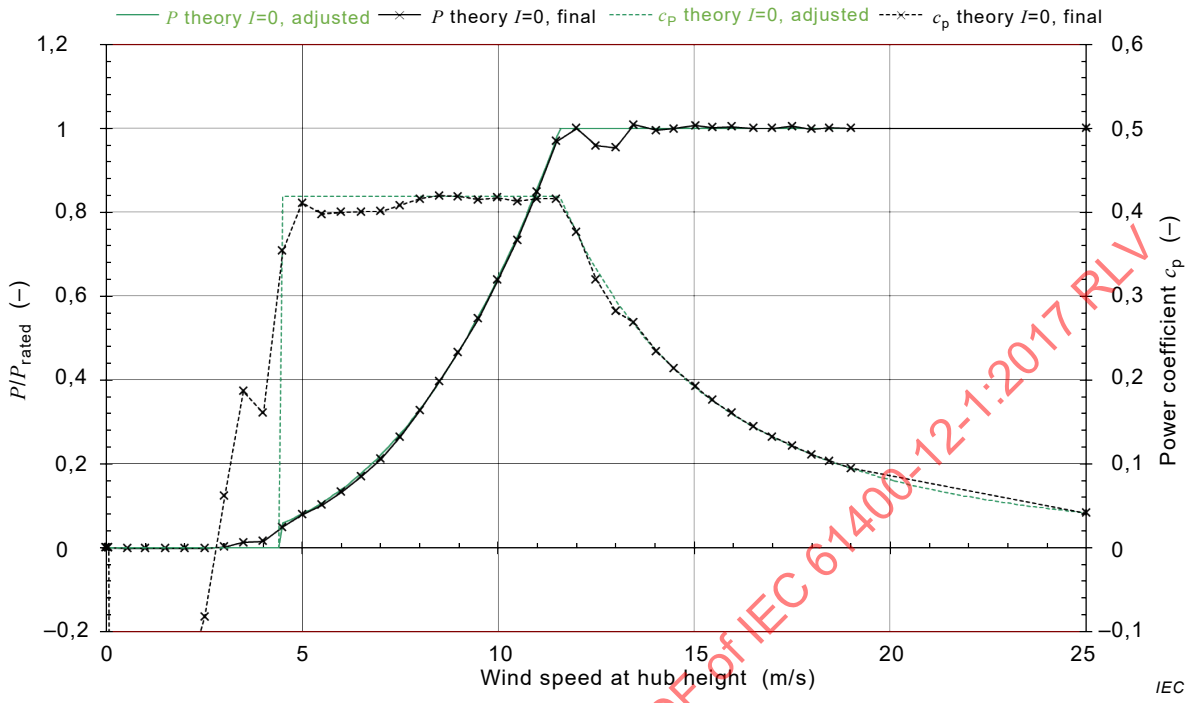

Figure M.7 – Adjusted initial zero turbulence power curve (green) compared to final zero turbulence power curve (black)

M.4 Order of wind shear correction (normalisation) and turbulence normalisation

The order of the application of the wind shear or wind veer correction (or normalisation) and the turbulence normalisation normally has no major influence on the final power curve. It is more convenient to apply the turbulence normalisation only on the basis of the hub height wind speed, as it is described in Clause M.2 and M.3, although it could also be applied on the basis of the wind shear- or wind veer-corrected (or-normalised) wind speed when wind speed measurements over the entire rotor height allow applying the wind shear correction. At the end, the final power shall be calculated by bin-averaging the turbulence-normalised power output against the wind shear- or wind veer-corrected (or-normalised) wind speed. In case of a wind turbine with active power control, the wind shear corrected (wind shear normalised) wind speed shall be normalised according to the air density prior to the bin-averaging. In case of a stall-regulated wind turbine, the turbulence-normalised power output according to Clause M.2 is already corrected for the air density.

M.5 Uncertainty of turbulence normalisation or of power curves due to turbulence effects

The turbulence normalisation given in Clause M.2 and M.3 is designed to handle effects of the 10 min data averaging on the evaluated power curve. There are further effects of the turbulence intensity on wind turbine power curves, which could, for instance, be due to direct impact of the turbulence intensity on the aerodynamics or due to the 3-dimensional character of turbulence. In the end, the turbulence intensity normalisation is a strongly simplified approach for characterising short term wind speed fluctuations. Thus, there is a remaining uncertainty of the evaluated power curve due to possible turbulence effects, even if the turbulence normalisation procedure is applied. The turbulence normalisation often removes about half of the observed effect of the turbulence intensity on measured wind turbine power

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curves. Thus, the following steps should be performed in order to calculate the uncertainty of the turbulence normalisation:

a) the final bin-averaged power curve shall be evaluated on the basis of the turbulence normalised power output and on the basis of the non-turbulence normalised power output;

b) the deviation of these two power curves shall be assumed to be the maximum uncertainty of the turbulence-normalised power curve per wind speed bin resulting from the turbulence normalisation. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the power curves divided by $\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties of the power performance measurement for the determination of the total standard uncertainty according to Annex D.

The uncertainty of turbulence effects on the measurement shall also be taken into account if no turbulence normalisation is performed, the uncertainty is higher, as the power curve is valid only for the turbulence conditions present during the power performance test and not for a reference turbulence intensity deviating from the test conditions. Thus, if no turbulence normalisation is applied, the following estimation of uncertainty due to turbulence effects is recommended:

1) two turbulence normalised power curves shall be evaluated according to Clause M.2 and M.3 just for the determination of the uncertainty. First, the power curve shall be normalised to an extremely low turbulence intensity, second, the power curve shall be normalised to an extremely high turbulence intensity. If the user does not have pre-defined extreme turbulence intensity limits, the turbulence intensities 0,05 and 0,15 shall be considered as the extreme turbulence intensities for the two power curve normalisations;

2) the deviation of the two normalised power curves shall be assumed to be half of the maximum uncertainty due to turbulence effects. The standard uncertainty resulting from the turbulence normalisation per wind speed bin shall be calculated as the deviation of the two normalised power curves multiplied by the factor $.2/\sqrt{3}$. The standard uncertainty shall be combined with the other uncertainties for the determination of the total uncertainty of the power curve according to Annex D;

3) if the measured power curve shall be compared with a power curve that refers to a certain (possibly wind speed dependent) turbulence intensity (e.g. a warranted power curve) and no power curve normalisation is performed, the two extreme turbulence intensities applied in step 1) shall be replaced by the bin-averaged measured turbulence intensity and by the reference turbulence intensity of the to be compared power curve for the uncertainty calculation.

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Annex N
(informative)

Wind tunnel calibration procedure for wind direction sensors

N.1 General

This procedure describes the calibration method of wind direction sensing devices including wind vanes and sonic anemometers operating as wind direction sensing devices.

N.2 General requirements

The general requirements for the calibration of wind direction sensors are summarized as follows:

a) the calibration of the wind direction sensor shall be carried out in an operating wind tunnel that is suitable for the calibration of wind direction sensors;

b) the calibration facility shall be accredited in accordance with ISO/IEC 17025, the standard for testing and calibration laboratories;

c) all transducers and measuring equipment relevant for the calibration of wind direction sensors shall have traceable calibrations. Calibration certificates and reports shall contain all relevant traceability information. All reference standards used during the calibration of the wind direction sensor shall be stated within the test report of the calibration campaign;

d) prior to every calibration campaign (when a batch of wind direction sensors is being calibrated) the integrity of the experimental set-up shall be verified by means of a comparative calibration of the calibration facility's "quality control wind direction sensor";

e) flow quality measurements shall be carried out according to Clause N.3;

f) the repeatability of the calibration shall be verified according to Clause N.3;

g) wind direction sensor calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO/IEC Guide 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement* (GUM 1995).

N.3 Requirements of the wind tunnel

The wind tunnel shall meet the requirements of Clause F.2.

The presence of the wind direction sensor shall not substantially affect the direction of the flow (field) in the wind tunnel. The presence of the wind direction sensor during its calibration may cause a flow diversion that is not encountered by the wind direction sensor when operated in the open field. To keep these effects at an acceptable level, the blockage ratio – defined as the ratio of the wind direction sensor frontal area with the fin oriented in line with the flow plus its mounting system to the total test section area – shall not exceed 0, for an open test section and 0,05 for a closed test section.

Special focus shall additionally be applied to verify that the horizontal direction of the wind tunnel flow is aligned parallel in relation to the test section centreline. The uniformity of the flow field (as required in Annex F) and the direction of flow shall be assessed prior to the calibration of the wind direction sensor. The flow direction shall be surveyed relative to the test section centreline at the representative location of the wind direction sensor by utilizing direction-sensitive flow measuring devices (i.e. two-hole conical yaw meter). The measured horizontal direction of flow shall be parallel to the test section centreline within 0,2°, the deviation shall be considered in the data evaluation.

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The facility shall undergo a detailed examination of the repeatability of wind direction sensor calibrations. The facility shall designate at least one reference wind direction sensor for use in these tests. The reference wind direction sensor(s) shall be used only for checking performance of this and other wind direction sensor calibration facilities. The repeatability examination shall include at least 10 calibrations of the quality control wind direction sensor. The repeatability test shall not be conducted in succession. It is more representative if the calibrations are conducted over a longer time span. This will provoke a greater range of atmospheric conditions during the tests. The maximum difference between calibrations of the same reference sensor should be less than 0,5° at 8 m/s wind speed throughout the measuring range of the wind direction sensor excluding the north band (wind vanes) where usually undefined conditions exist. This process shall be repeated after any modification or recalibration of the facility. The facility shall prove, through proficiency testing, that its results are comparable with other anemometer calibration facilities, according to ISO 17043.

The facility's average reference wind direction sensor calibration (as determined from repeatability tests described above) should agree with the average result of other calibration facilities within a deviation of the indicated equivalent flow direction of less than 1° throughout the measuring range, excluding the north band, at a wind speed of 8 m/s.

N.4 Instrumentation and calibration set-up requirements

Dedicated external signal conditioning equipment such as instrument amplifiers etc. shall be calibrated in isolation from the wind direction sensor, so that the wind direction sensor's calibration can be derived and reported in isolation from the signal conditioning equipment. The resolution of the data acquisition system used shall be at least 12 bits. Care shall also be exercised in the case of an analogue voltage instrument to ensure that the signal is adequately buffered to prevent its attenuation by low impedance logging equipment. Such effects are easily overlooked since 'believable' signals are still registered. The reference angle measurement system shall be the direct type (direct angle encoding, counting of increments, measuring proportional quantity such as magnetic, inductive or potentiometric methods). The shaft of the reference angle measurement system shall be connected to the shaft of the wind direction sensor rotation mechanism by means of a backlash-free coupling. The coupling shall be resistant to torsion and flexible to bending (flexion-elastic) in order to achieve the maximum possible elimination of assembly-influencing quantities (tolerances of concentricity and angles of both axes of rotation). The axes of rotation shall be oriented concentric and coaxial. The housing of the reference angle measurement system shall be securely fixed in a backlash-free manner. The reference angle measurement sensor shall be positioned in the tunnel as accurate as possible, and it may not disturb the wind direction sensor under test. The maximum deviation allowed is 0,1°. Figure N.1 illustrates an example of a calibration setup in a wind tunnel.

During calibration, the wind direction sensor shall be mounted on top of a tube in order to minimize flow distortion. This tube shall be of the same dimensions as the one on which the wind direction sensor will be mounted in service in the free atmosphere. It is important to ensure that the flow field around the wind direction sensor is not influenced by the presence of any reference wind speed measurement equipment. Conversely the presence of the wind direction sensor shall not affect the direction of the flow in a significant way.

The wind direction sensor shall be mounted at the test section perpendicular to the flow field of the wind tunnel as accurately as possible. The maximum deviation allowed is 0,2°. The fin shall also be aligned relative to the datum line/north mark and held there in position by an adjustable support until the calibration process begins. An accurate alignment of the wind direction sensor and its fin may be achieved by an appropriate device such as a mechanical jig or the employment of an optical instrument (i.e. 2D laser level). The wind direction sensor output signal shall be examined during calibration to ensure that it is not subject to interference or noise. The determination of the wind tunnel flow speed shall be in accordance with Annex F.

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Great care shall be taken when aligning the wind direction sensor relative to the datum line (centreline) of the wind tunnel. The mechanical reference indicator (usually the north mark) of the wind direction sensor has to be properly aligned in relation to the datum line of the wind tunnel. It is not acceptable to perform the angular alignment of the wind direction sensor just by utilizing its electrical output signal. This would provoke an angular deviation between the external reference mark and the indicated value from the internal angular transducer of the wind direction sensor. This deviation would later be difficult to identify since the alignment of the vane at the meteorological mast is usually realized by means of the north mark. The proper angular alignment for the calibration shall be assured using an adequate method to measure the external reference mark.

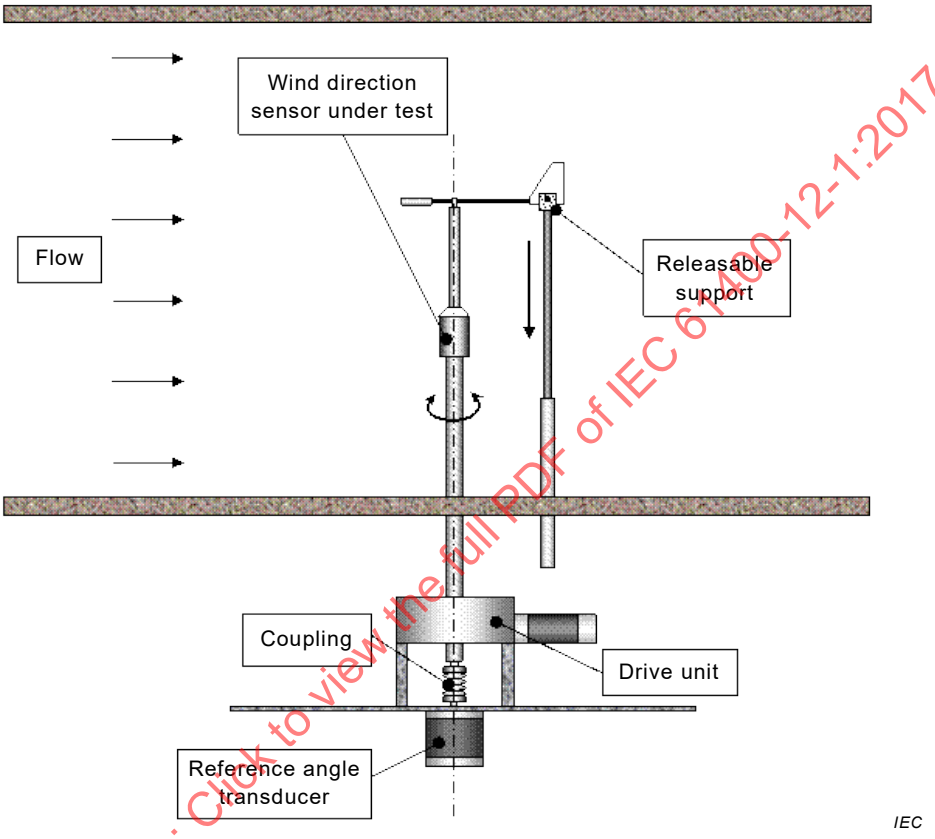

Figure N.1 – Example of calibration setup of a wind direction sensor in a wind tunnel

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N.5 Calibration procedure

Generally the wind direction sensor shall be directionally positioned by means of an adequate rotation mechanism (i.e. rotary table) while the direction and the speed of the flow remains unchanged. The output signal of the wind direction sensor is then assessed in relation to the reference angle measurement system installed at the rotation mechanism.

The procedure for the calibration of wind direction sensors is as follows:

The wind direction sensor is rotated at a constant yaw rate or stepwise. The indicated yaw angle (measured value of the wind direction sensor) is simultaneously recorded together with the reference yaw angle (measured value of the rotation mechanism). The selected rate of rotation is a compromise between adequate measurement precision and feasible measurement time. The recommended rate is 0,5 °/s. For a stepwise procedure, it is important to have an adequately fine increment of less than 3° in order not to miss erroneous direction data. The sampling frequency shall be high enough (usually 1 Hz or faster) to have a sampling bias within acceptable limits. The temperature of the wind direction sensor shall not vary significantly during its calibration to minimize an additional uncertainty due to

temperature-induced effects upon the indicated direction. A run in time of > 1 min shall be included to minimize temperature deviation between the wind direction sensor and the flow in the wind tunnel prior to the calibration run.

The calibration process shall consist of at least two complete yaw sweeps (including the north jump) for each of the above procedure. Each sweep shall be of opposite directions to account for possible hysteresis effects. There shall be an angular overlap of the data points of at least 10° at the beginning and the end of each sweep. A possible sequence may cover a clockwise sweep from –10° to 370° and a counter clockwise run from 370° to –10° for the subsequent sweep.

The calibration shall be performed at a constant wind speed of (8 ± 10 %) m/s. The average wind speed should not vary throughout the duration of the wind direction sensor calibration.

N.6 Data analysis

Only the horizontal wind vector shall be considered during the wind direction sensor data assessment. The evaluation of the wind direction signal shall, for both wind vanes and sonic anemometers, be performed using the method of vector averaging as described in ISO 16622 [4] and 7.3.

All relevant data shall be evaluated as bin-averaged data. Data of the reference yaw sensor is hereby used as a basis to define the bin interval for the remaining data base. The bin-width shall have at least a resolution of 10°, centred at 5°, 15°.etc. of the yawing device. The bin-width shall be reduced to adequately assess the behaviour of certain sensor types (i.e. sonic anemometer) or to better represent sensor characteristics (i.e. excessive non-linearity).

N.7 Uncertainty analysis

It is important to identify the uncertainty of the horizontal flow direction measurement in conjunction with the wind direction sensor.

It is required that an uncertainty analysis shall be carried out in accordance with the ISO guide 98-3 to the expression of uncertainty comprising both category A and category B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall account for:

a) measurement uncertainty of the reference angle measuring system (reference angle transducer, coupling, mounting, electrical transducers, digital conversion, etc.);

b) uncertainty of the flow direction sensed by the wind direction sensor, including an assessment of possible flow diversion due to the presence of the wind direction sensor;

c) mounting uncertainty of the wind direction sensor (alignment of north mark and fin relative to the wind tunnel centreline);

d) category A uncertainty due to short-term scatter (signal of wind direction sensor may vary over time due to unsteady flow conditions);

e) category A uncertainty due to long-term scatter (scatter/drift of calibration results of the reference wind direction sensor over time for a number of calibrations);

f) uncertainty when measuring the electrical signal of the wind direction sensor (electrical transducer, digital conversion, etc.).

N.8 Reporting format

The relevant documentation shall provide information on the procedure followed and the facility used for calibrating the wind direction sensor (test report on the calibration campaign) and on the individual wind direction sensor calibration (wind direction sensor calibration

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report). The test report on the calibration facility setup shall contain the following information as a minimum:

a) description of the wind tunnel (including test section, settling chamber, flow straighteners, fan arrangement);
b) sketch of the wind tunnel showing the exact positions of the wind direction sensor and pitot tube(s) in the test section;
c) flow quality measurements;
d) turbulence measurements;
e) instrumentation certificates;
f) measurement procedure;
g) data evaluation procedure;
h) repeatability documentation of wind direction sensor calibration;
i) uncertainty analysis;
j) deviations from these requirements.

The calibration report of a wind direction sensor shall as a minimum contain the following information:

a) make, type and serial number of the tested wind direction sensor and fin serial number if the item can be separated;
b) tube diameter of the mounting system;
c) make, type and serial number of external converters, if taken (i.e. frequency-to-voltage converters);
d) name and address of the customer;
e) signatures from the persons who carried out the calibration, checked the results and approved their issue;
f) name of the wind tunnel;
g) environmental conditions during calibration (air temperature, barometric air pressure and humidity);
h) regression parameters (offset and slope), in tabular and graphical presentation of all calibration points;
i) information of measured north dead-band width;
j) The table shall contain the following information:
    1) bin number;
    2) average reference (flow) direction per bin;
    3) average indicated direction signal of the wind direction sensor per bin;
    4) uncertainty per bin;
    5) wind tunnel flow speed per bin.
k) The graphical presentation shall include:
    1) indicated wind direction sensor signal as a function of reference yaw angle per bin;
    2) scatter plot of wind direction sensor signal vs. reference yaw angle if sweep is used;
    3) scatter plot of residuals of sensor signal vs. reference yaw angle;
    4) residuals per bin (deviation between indicated wind direction sensor signal and result of wind direction sensor calibration function);
    5) uncertainty associated with each measuring point.
l) reference to the corresponding calibration campaign report and date of the calibration;
m) photo showing the wind direction sensor and the mounting in the wind tunnel;

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n) rate of angular velocity, data bin-width and number of acquired data points per bin.

N.9 Example of uncertainty calculation

N.9.1 General

The determination of the measurement uncertainty is based on the assumption that the following three main sources contribute to the total uncertainty:

a) determination of flow direction in the wind tunnel (type B);

b) uncertainty due to the wind direction sensor to be calibrated (wind vane, sonic anemometer) (category B);

c) repeatability (category A).

In the following only category B uncertainties are considered. To determine the total uncertainty, the category A component shall be included as well.

N.9.2 Measurement uncertainties generated by determination of the flow direction in the wind tunnel

N.9.2.1 General

To evaluate the measurement uncertainty in the determination of the flow direction, the following individual uncertainties have to be considered:

N.9.2.2 Uncertainty contribution by uncertainties in the determination of the geometrical centreline α_{CL} (wind tunnel centreline)

Assuming that the centreline is defined with simple geometrical methods and the lines are accurate to 2 mm for a test section of 1,00 m by 2,00 m, the uncertainty of the geometrical centreline is 0,1°. Accepting a rectangular distribution, the contribution to the total standard uncertainty is 0,06°.

N.9.2.3 Contribution by uncertainties in the determination of flow direction α_{dir}

Calibration of flow direction occurs by means of a wedge type probe. A well designed wind tunnel shows practically no deviation of the flow direction from the geometrical centreline of the wind tunnel. The contribution to uncertainty is deemed to be 0,1°. Accepting a rectangular distribution the contribution to the total standard uncertainty is 0,06°.

N.9.2.4 Contribution by uncertainties in the calibration of the reference yawing sensor α_{sensor}

The reference angle is defined by using an electronic yawing sensor. Contribution to uncertainty resulting from the calibration of this sensor is assumed to be 0,35°. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,2°.

N.9.2.5 Contribution by aligning the centreline with the north marking of the wind direction sensor α_{set}

Using a laser, the sensor (north marking, fin, wind tunnel centreline) can be aligned. Assuming that the laser beam has a maximum deviation of 1 mm from the centreline, the uncertainty contribution is less than 0,1°. A contribution to total uncertainty of 0,1° is assumed. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,06°.

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N.9.2.6 Contribution due to influence of the angle between the axes of rotation $\alpha_{\text{incl.1}}$

When mounting the reference unit on the turning drive, errors can occur in the angle between the rotary axes of the turning drive and the reference unit (inclination of the calibrated object relative to the calibration device inclination). The rotary axes do not align, but a coupling between the shafts of the reference and of the calibrated object compensates within certain limits for the effect of the position of the angle measurement planes. The angle error can be calculated using the following equation:

$$\delta\alpha_{\text{incl.1}} = 0{,}125 \cdot (2 \cdot p / r)^2 \cdot \sin\alpha \quad \text{(N.1)}$$

where, according to VDI/VDE 2648, reference [5]:

α is the angle to be measured (calibration value);

p is the axial run-out deviation;

r is the effective radius of angle measurement.

With an assumed deviation of the levels of 1 mm and a radius of 50 mm for the yaw sensor, the extreme case of α = 90° results in an uncertainty of 0,01°.

N.9.2.7 Contribution to uncertainty by potential eccentricity between wind direction sensor and reference unit α_{Exz}

By mounting the wind direction sensor on the turning drive of the reference unit, eccentricities can occur, referring to the parallel misalignment between the respective rotary axes. The rotary axes do not align. The angle error that may occur because of the parallel misalignment can be calculated using the following equation:

$$\delta\alpha_{\text{Exz}} = 2 \cdot (e / r) \cdot \sin(\alpha / 2) \quad \text{(N.2)}$$

where, according to VDI/VDE 2648, reference [5]:

α is the angle to be measured (calibration value);

e is the eccentricity;

R is the effective radius of angle measurement.

Based on an assumed eccentricity of the rotary axes of 0,2 mm and a radius of 50 mm, the uncertainty of the extreme case of α = 180° is 0,2°.

N.9.3 Contribution to measurement uncertainty by the wind direction sensor

N.9.3.1 General

Wind direction sensors may have different output signals. There are also digital sensors indicating directly the azimuth direction angle in degree. Usually the specimen is a wind direction sensor with an analogue output signal (current or voltage) or a potentiometric sensor.

N.9.3.2 Contribution to uncertainty by digital output signal α_{Digital}

Half of the digital resolution is assumed to contribute to the measurement uncertainty.

N.9.3.3 Contribution to measurement uncertainty by analogue output signal α_{Analog}

Sensors with an analogue signal (typically 10 V or 20 mA) are supposed to contribute to uncertainty with the resolution of the analogue-to-digital conversion. Assuming a measurement system with a resolution of 12 bit, the contribution to uncertainty is

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360°/4 096=0,1°. Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,06°.

N.9.3.4 Contribution to uncertainty by the determination of the ohmic resistance of a wind direction sensor α_{Ω}

The resistance of a potentiometric wind-vane can only be determined by means of a known voltage/current measurement. When determining the resistance of a potentiometric wind-vane (typically several kΩ) by means of indirect resistance measurement of voltage and constant current, the following uncertainties can occur:

- percent error of instrument shunt 0,030 %;
- error current through measurement system 0,020 %;
- resolution of analogue-to-digital conversion 0,025 %;
- assumed measurement uncertainty 0,05 % ~ 0,16 °.

Supposing a rectangular distribution, the contribution to total standard uncertainty is 0,1°.

N.9.3.5 Contribution to uncertainty by mounting the wind direction sensor α_{item}

Typical wind direction sensors have a diameter of approximately 50 mm. The north marking often has a breadth of 1 mm and is therefore typically 2°. For the alignment of the north marking with a laser beam an uncertainty of 0,25 mm is assumed, thus resulting in a contribution to uncertainty of 0,25°. Assuming a rectangular distribution, the contribution to total standard uncertainty is 0,15°.

N.9.3.6 Contribution to uncertainty by possible malposition of the wind direction sensor $\alpha_{Incl.2}$

When mounting the wind direction sensor on the turning drive and the reference unit, angle errors in the alignment angle between the rotary axes can occur. The angle error is assumed to be 0,05°.

N.9.4 Result of the uncertainty calculation

To determine the total standard uncertainty, the following individual uncertainties have been considered (see Table N.1 and Table N.2):

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Table N.1 – Uncertainty contributions in wind directions sensor calibration

Factor	Uncertainty category	Uncertainty distribution	Sensitivity coefficient	Measurement uncertainty	Standard deviation	Contribution to uncertainty	Unit
Reproducibility	A	1	1	-		0,1	°
Determination of geometrical centreline	B	2	1	0,1	$u_{CL} = \frac{1}{\sqrt{3}} \cdot CL$	0,06	°
Determination of flow direction	B	2	1	0,1	$u_{DIR} = \frac{1}{\sqrt{3}} \cdot DIR$	0,06	°
Reference yaw sensor	B	1	1	0,35	$u_{REF} = \frac{1}{2} \cdot REF$	0,2	°
Inclination angle	B	2	1	0,01	$u_{Incl.1} = \frac{1}{\sqrt{3}} \cdot INCL.1$	0,01	°
Eccentricity	B	2	1	0,2	$u_{EXZ} = \frac{1}{\sqrt{3}} \cdot EXZ1$	0,12	°
1 = normal distribution; 2 = rectangular distribution							

The calculation of the standard measurement uncertainty in the determination of the flow direction is carried out by means of quadratic accumulation:

$$u_{Flow_dir} = (u_{CL}^2 + u_{DIR}^2 + u_{REF}^2 + u_{Incl.1}^2 + u_{EXZ1}^2)^{0,5} \quad \text{(N.3)}$$

$$u_{Flow_dir} = (0,06^2 + 0,06^2 + 0,2^2 + 0,01^2 + 0,12^2)^{0,5} = 0,25° \quad \text{(N.4)}$$

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Table N.2 – Uncertainty contributions and total standard uncertainty in wind direction sensor calibration

Factor	Uncertainty category	Uncertainty distribution	Sensitivity coefficient	Measurement uncertainty	Standard deviation	Contribution to uncertainty	Unit
Digital output signal	B	2	1	half of digital resolution	$u_{\text{Digital}} = \frac{1}{2} \cdot \text{LSB}$	-	°
Or analogue output signal	B	2	1	0,1	$u_{\text{Analog}} = \frac{1}{\sqrt{3}} \cdot \text{ANALOG}$	0,06	°
Or potentiometric sensor	B	1	1	0,2	$u_{\Omega} = \frac{1}{\sqrt{3}} \cdot \Omega$	0,12	°
Mounting of sensor	B	1	1	0,25	$u_{\text{Mounting}} = \frac{1}{\sqrt{3}} \cdot \text{Mounting}$	0,15	°
Inclination angle	B	2	1	0,01	$u_{\text{INCL.2}} = \frac{1}{\sqrt{3}} \cdot \text{INCL.2}$	0,01	°
Eccentricity	B	2	1	0,2	$u_{\text{EXZ2}} = \frac{1}{\sqrt{3}} \cdot \text{EXZ2}$	0,12	°
1 = normal distribution; 2 = rectangular distribution							

The total standard uncertainty for e.g. a potentiometric wind vane is:

$$u_{\text{Total}} = (u_{\text{Flow_dir}}{}^2 + u_{\Omega}{}^2 + u_{\text{Mounting}}{}^2 + u_{\text{Incl.2}}{}^2 + u_{\text{Exz2}}{}^2)^{0,5} \quad \text{(N.5)}$$

$$u_{\text{Total}} = (0,25^2 + 0,12^2 + 0,15^2 + 0,01^2 + 0,12^2)^{0,5} = 0,34° \quad \text{(N.6)}$$

The contribution to total standard uncertainty by the individual uncertainty sources therefore result in a total standard uncertainty of 0,34 °for k =1 for a potentiometric wind vane. Usually this value is multiplied with the coverage factor k =2.

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Annex O
(informative)

Power performance testing in cold climate

O.1 General

Power performance testing at temperatures below 0 °C may be desirable for different reasons. For example, low temperatures may be frequent or there could be a need to determine the power performance degradation due to iced blades.

Annex O gives guidance on what is important to consider when carrying out power performance tests in cold climates and to provide recommendations.

O.2 Recommendations

O.2.1 General

It is recommended to use wind speed measurement sensors that are not susceptible to ice, such as heated cup anemometers, heated ultra-sonic anemometers, and remote sensing devices or to use suitable icing detectors to reliably monitor the presence of ice and filter the data accordingly.

Equipment for power performance testing in cold climate should include reliable icing detection. There are several possibilities to detect ice, including ice detectors for atmospheric icing, ice detectors for instrumental icing, visual observation or similar. Ice accretion occurs at temperatures below, or around zero. Power performance testing at temperatures far below 0 °C could therefore be performed without any significant difficulties, provided that suitable instruments and methods are used.

Ice accretion on supports and mounting structures can have a significant effect on the flow conditions for the anemometer. It is essential that such situations are avoided. A thorough assessment or monitoring of the conditions is required. It is recommended to use sufficiently heated structures in the vicinity of the instruments to prevent ice accretion.

O.2.2 Sonic anemometers

Sonic anemometers are allowed for power performance testing provided that suitable calibration procedures and classification procedures according to Annex F and in Annex I and Clause J.4 are adhered to.

Sonic anemometers that have sufficient heating capabilities may be used because they have no moving parts and are therefore suitable to be used in cold conditions.

O.2.3 Cup anemometers

The lower temperature limit for class A anemometers may be extended from 0 °C to –30 °C in the case of proper shaft (bearing) heating. This does not remove the need for ice detection.

Extension of the temperature range below the lower limit for the class can be carried out provided that sufficient evidence can be provided that the frictional effects can be assessed and accounted for.

The classification of the anemometer with an extended temperature range can be accomplished by extending the temperature range in Annex J provided that measurements of bearing friction cover the whole temperature range.

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O.3 Uncertainties

Extended temperature range: Given by the class S.

O.4 Reporting

In addition to the normal reporting requirements, the precautions that have been adopted to ensure that the instruments that are used to measure the wind speed are not affected by ice and that low temperature effects on the measurement of the wind speed are accounted for.

The filtering for ice conditions should be individually documented. The results of the power performance test with and without the temperature extension taken into account shall be reported.

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Annex P
(informative)

Wind shear normalisation procedure

P.1 General

For deriving a climate specific power curve, the influence of the wind shear and wind veer on the power curve shall be accounted for by normalising the hub height wind speed to a pre-defined reference wind shear and wind veer. The reference wind shear and wind veer profile can have any shape and may be defined as function of the wind speed at hub height. The reference wind shear and wind veer could for instance reflect the conditions expected at the power curve test site if the purpose of the power curve test is to verify a warranted power curve that is specified for the same reference conditions. If not defined otherwise, a power law wind shear profile with shear exponent of 0,2 and a wind veer of 0° throughout the entire height range of the turbine rotor shall be applied.

The normalisation of the wind speed at hub height to the reference wind shear and wind veer shall be performed by means of the rotor equivalent wind speed concept. The kinetic energy in the wind across the rotor height range is:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho(V\cos(\varphi - \varphi_{\text{hub}}))^3 \,\mathrm{d}A \tag{P.1}$$

and the rotor equivalent wind speed that corresponds to the kinetic energy is:

$$V_{\text{eq}} = \left(\frac{1}{A}\int_i (V_i \cos(\varphi_i - \varphi_{\text{hub}}))^3 \,\mathrm{d}A_i\right)^{1/3} \tag{P.2}$$

The ratio of the rotor equivalent wind and the hub height wind speed characterises the shape of the wind shear profile and wind veer profile that is relevant for the description of the available kinetic energy at a certain wind speed at hub height. This ratio is called wind shear correction factor:

$$f_r = \frac{V_{\text{eq}}}{V_h} \tag{P.3}$$

The same rotor equivalent wind speed can be reached by different combinations of hub height wind speeds and wind shear/veer conditions, e.g. by the wind shear/veer and hub height wind speed present within a 10-minute period at the power curve test as well as by the reference wind shear / veer and a corresponding hub height wind speed (here called normalised wind speed):

$$V_{\text{eq}} = f_{r,\text{measured}} \cdot V_{h,\text{measured}} = f_{r,\text{reference}} \cdot V_{h,\text{normalised}} \tag{P.4}$$

Consequently, the wind shear/veer normalised hub height wind speed shall be calculated for each 10-minute period as:

$$V_{h,\text{normalised}} = \frac{V_{\text{eq}}}{f_{r,\text{reference}}} \tag{P.5}$$

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or as

$$V_{h,\text{normalised}} = \frac{f_{r,\text{measured}}}{f_{r,\text{reference}}} \cdot V_{h,\text{measured}} \quad \text{(P.6)}$$

For a reference wind shear correction factor of 1 ($f_{r,\text{reference}}$ = 1), i.e. in case of zero shear and veer, the normalised hub height wind speed equals the rotor equivalent wind speed. The uncertainty of the measurement of the wind shear and wind veer normalised wind speed shall be assessed according to Clause E.8, E.11.2.2 and E.11.2.3. It is pointed out that the rotor equivalent wind speed may overestimate the wind energy effectively usable by large wind turbines in case of the presence of high wind shear. Thus, a method uncertainty of one third of the correction of the hub height wind speed shall be applied as additional uncertainty to the uncertainty of the measurement of the wind shear and wind veer normalised wind speed.

Under certain conditions, the evaluation of the wind shear and wind veer over the height range of the turbine rotor may not be possible, because no measurements of the wind speed or wind direction over the height range of the turbine rotor are available or because a site calibration of the wind speed and wind direction at other heights than hub height is not possible. In this case, the lack of the integration of the wind shear/veer in the power curve evaluation shall be accounted for according to E.11.2.2.2 and E.11.2.3.2 for the desired reference wind shear/veer conditions. In addition, a method uncertainty of one third of a virtual wind speed correction from the assumed wind shear/veer conditions at the power curve test to the desired reference wind shear/veer conditions shall be taken into account.

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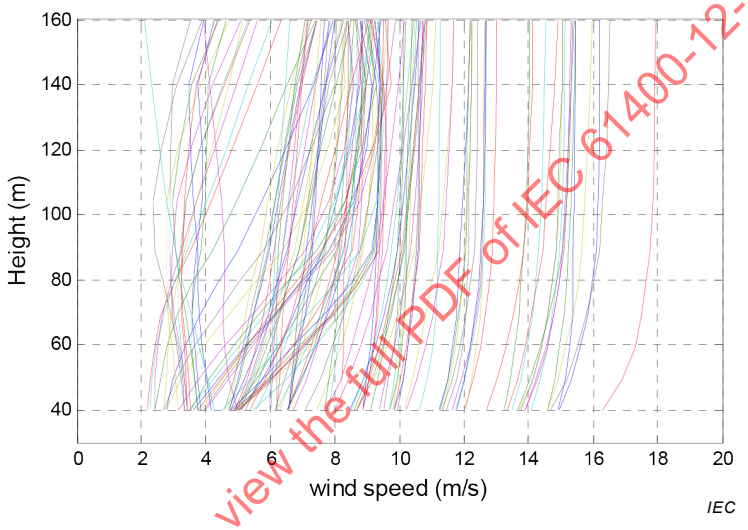
Annex Q
(informative)

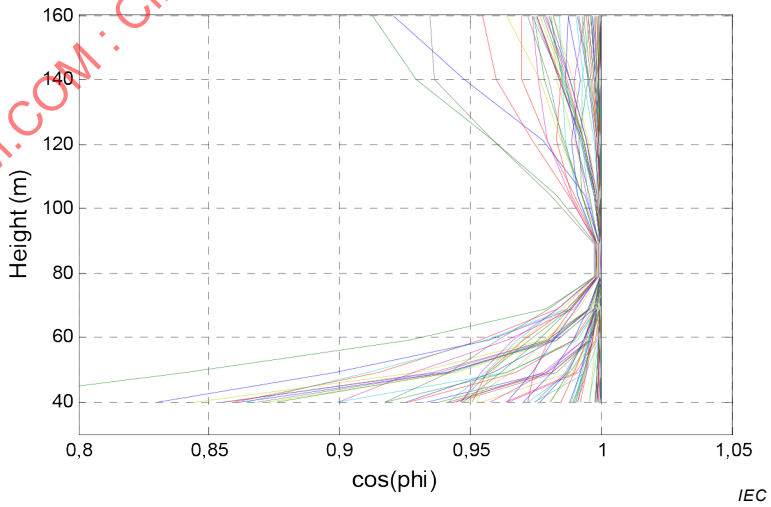
Definition of the rotor equivalent wind speed under consideration of wind veer

Q.1 General

The wind speed at hub height is not always representative of the wind over the whole rotor. Large wind speed and direction variations may be present as a result of either the atmospheric stability and/or terrain influence. Figure Q.1 shows LIDAR wind profiles over flat terrain as well as the cosine of wind direction changes relative to an assumed hub height. It is seen that the wind speed component perpendicular to the wind turbine rotor at a specific height will occasionally be much less than the wind speed at the specific height.



a) Lidar wind profiles



b) Cosine of wind direction variation angle relative to a height

Figure Q.1 – Wind profiles measured with LIDAR over flat terrain

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Therefore, the energy yield through the wind turbine rotor will depend on both the wind shear and wind veer of the specific profile. Using the power curve based on the wind speed at hub height ignores both wind shear and wind veer. The power curve obtained with the rotor equivalent wind speed depends less on the wind shear and wind veer than the power curve obtained with the wind speed at hub height.

Q.2 Definition of rotor equivalent wind speed under consideration of wind veer

The rotor equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the wind shear and wind veer. For the case that at least three measurement heights are available (see 7.2.6) the rotor equivalent wind speed is defined as

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n} \left(v_i \cos(\varphi_i) \right)^3 \frac{A_i}{A} \right)^{1/3} \tag{Q.1}$$

where

n is the number of available measurement heights ($n \geq 3$);

v_i is the wind speed measured at height i;

φ_i is the angle difference between the wind direction at hub height and segment i;

A is the area swept by the rotor (i.e. πR^2 with radius R);

A_i is the area of the i^{th} segment, i.e. the segment the wind speed v_i represents (refer to 9.1.3.2, Equation (6).

Q.3 Measurement of wind veer

The rotor equivalent wind speed as defined in Equation (Q.1) is influenced by the difference of wind direction measurements at various heights relative to hub height. In order to provide accurate measurements of the difference of wind directions, it is important to measure the wind directions at the different height levels with the same type of sensor, i.e. one remote sensing device measuring all heights, or same sensors on the meteorological mast at all heights.

Q.4 Combined wind shear and wind veer normalisation

The procedures described in Annex P may be extended to referencing back the measured power curve to reference wind veer conditions by considering also a reference wind veer profile in addition to a reference wind shear profile. The integration of the reference profiles over the rotor area shall be done according to Equation (Q.1).

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Annex R
(informative)

Uncertainty considerations for tests on multiple turbines

R.1 General

Annex R addresses the uncertainty considerations that arise when compiling test results from multiple turbines. When testing multiple turbines, the quantities of interest are typically the mean AEP of the sample and the uncertainty in that mean. The mean AEP can most simply be determined by taking a simple average of the individual turbine AEPs.

The determination of the uncertainty in the average AEP is not as straightforward. As this is a frequently encountered situations, this standard provides an informative approach as to how this uncertainty may be estimated. The mathematical framework for this approach is exactly the same as explained in IEC 61400-12-2:2013 Annex I and J and will not be repeated here. What is different for this standard is Table R.1 of estimated correlations between tests on different turbines and the results as represented in Figures J.1 and J.2 of IEC 61400-12-2:2013, which will be repeated here. As an introduction, a short discussion of the problem at hand will be repeated.

One approach to combining uncertainties is a simple average of the individual test uncertainties. However, the simple average fails to account for the chief benefit of multiple tests, i.e. a reduction in the combined test uncertainty. A second approach is to calculate the standard uncertainty of the mean of the uncertainties:

$$u_{AEP_{\mathrm{AVG}}} = \frac{1}{L}\sqrt{\sum_{i=1}^{L} u_{AEP,i}^2} \tag{R.1}$$

where

$u_{AEP_{\mathrm{AVG}}}$ [43] is the uncertainty in the average AEP;

$u_{AEP,i}$ is the uncertainty in AEP for turbine i;

L is the number of turbines tested.

Equation (R.1) assumes full independence among the individual turbine test results, meaning there is no correlation in the individual test results from one unit to the next. As a consequence application of Equation (R.1) would lead to an underestimation of the uncertainty in the average AEP. Therefore, in order to accurately assess the uncertainty in the average AEP, it is necessary to identify a practical method for handling correlated uncertainty components. An approach is suggested based on the ISO information publication '*Guide to the expression of uncertainty in measurement*' with minor adjustments in the handling of correlation.

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43 Please note that the equation here is slightly different from the equation in IEC 61400-12-2. As this is the uncertainty of an average and division by $1/L$ is a linear transformation, we get a $1/L^2$ under the square root or a $1/L$ in front of the square root.

Table R.1 – List of correlated uncertainty components

Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
Electric power	Current transformers	$\rho_{up1,m,n}$	Same instrument make Different instrument make	0,9 0,1	C_{Ts} of the same make tend to have similar cat B error values relative to the true value.
	Voltage transformers	$\rho_{up2,m,n}$	Same instrument make Different instrument make	0,9 0,1	V_{Ts} of the same make tend to have similar cat B error. Direct measurement of voltage eliminates this uncertainty.
	Power transducer or power measurement device	$\rho_{up3,m,n}$	Same instrument make Different instrument make	0,9 0,1	Power measurement devices of the same make tend to have similar cat B error.
	Dynamic power measurement	$\rho_{up4,m,n}$	Same instrument make Different instrument make	0,9 0,1	Power measurement devices of the same make tend to have similar cat B error.
	Data acquisition	$\rho_{udp,m,n}$	Same instrument make Different instrument make	0,9 0,1	Data acquisition devices of the same make tend to have similar cat B errors relative to the true value.
Wind speed	Anemometer calibration	$\rho_{uv1,m,n}$	Shared instrument (same met mast) Different masts, same make/model, same calibration lab Different masts, different make/model, same calibration lab Different masts, same make/model, different calibration labs Different masts, different make/model, different calibration labs	1,0 0,9 0,7 0,4 0,1	Calibration reference and method produces similar cat B error.
	PostCal / In-situ cal	$\rho_{uv2,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,7	Anemometers of the same make tend to have similar cat B errors relative to the true value.
	Operational uncertainty	$\rho_{uv3,m,n}$	Shared Instrument (same masts) Same instrument make Different instrument make	1,0 0,9 0,8	Anemometers of the same make tend to have similar cat B errors relative to the true value.
	Mounting effects	$\rho_{uv4,m,n}$	Per specification in this standard	0,9	Similar mounting required for use of a given transfer function drives a correlated uncertainty.
	DAQ	$\rho_{uv5,m,n}$	Shared DAQ Different DAQ of same make, same design Different DAQ of different make, same design Different DAQ of same make, different design Different DAQ of different make, different design	1,0 0,9 0,7 0,5 0,2	DAQ will be correlated the more similar the setup is.

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Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
	Flow distortion due to terrain without site cal	$\rho_{uv6,m,n}$	Both turbines $2D$ to $3D$ (or $3D$ to $4D$) from met mast One turbine $2D$ to $3D$ and one turbine $3D$ to $4D$	0,9 0,6	Increased terrain complexity and variation in terrain amongst test units will tend to have dis-similar cat B errors on the wind speed relative to the true value, distance plays an important role.
	Flow distortion due to terrain amongst test units with site cal, anemometer calibration	$\rho_{uv7,m,n}$	Shared instrument (same met mast) Different masts, same make/model, same calibration lab Different masts, different make/model, same calibration lab Different masts, same make/model, different calibration labs Different masts, different make/model, different calibration labs	1,0 0,9 0,7 0,4 0,1	
	Flow distortion due to terrain amongst test units with site cal, operational uncertainty	$\rho_{uv7,m,n}$	Shared instruments (same masts) Different masts, same make/model) Different masts, different make/model	1,0 0,9 0,7	
	Data acquisition for site calibration	$\rho_{udv,m,n}$	Shared DAQ Different DAQ of same make, same design Different DAQ of different make, same design Different DAQ of same make, different design Different DAQ of different make, different design	1,0 0,9 0,7 0,5 0,2	Data acquisition devices of the same make tend to have similar cat B error.
Tempera-ture	Temperature sensor	$\rho_{ut1,m,n}$	Shared instruments(same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	Temperature measurement devices of the same make tend to have similar cat B error.
	Radiation shielding	$\rho_{ut2,m,n}$	Shared instruments(same met mast) Same instrument make Different instrument make	1,0 0,9 0,6	Radiation shields tend to have the same method errors relative to the true value.
	Mounting effects	$\rho_{ut3,m,n}$	Shared instruments(same met mast) Same location and mounting Different location or mounting	1,0 0,9 0,1	
	Data acquisition	$\rho_{udt,m,n}$	Shared instruments(same met mast) Same instrument make Different instrument make	0,9 0,1	Data acquisition devices of the same make tend to have similar cat B error.

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Measured parameter	Source	Correlation coefficient	Condition	Value range	Notes
Pressure	Pressure sensor	$\rho_{ub1,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	Pressure measurement devices of the same make tend to have similar cat B error.
	Mounting effects	$\rho_{ub2,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	If using multiple instruments, mounting will likely be similar.
	Data acquisition	$\rho_{udb,m,n}$	Shared instrument (same met mast) Same instrument make Different instrument make	1,0 0,9 0,1	Data acquisition devices of the same make tend to have similar cat B error.
Method	Air density correction	$\rho_{um1,m,n}$	Same correction methodology for all turbines	1,0	
	Wind Conditions	$\rho_{um2,m,n}$	Same conditions for different turbines	1,0	
	Seasonal variation	$\rho_{um3,m,n}$	Testing occurs during the same time of year Testing occurs during different time of year	1,0 0,6	
Statistical	Variance in electrical power	$\rho_{sp,m,n}$		0,0	Inherently random and independent.

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Annex S
(informative)

Mast flow distortion correction for lattice masts

Annex S gives guidance regarding a possible method to determine a correction for flow distortion of side mounted anemometers. Such a correction is already discussed in 7.2.4 as well as 9.1.2. In this annex, a more detailed approach is presented for a lattice mast.

A similar method may work for other types of mast configuration but it is likely that specific changes need to be made to allow for the differences in the configuration. Other methods to determine a correction may be applied but shall be documented in sufficient detail to allow the results to be reproduced by a third party based on the reported information.

The starting point is to do a linear regression between two anemometers installed on different booms at the same measurement height. The residuals of the regression can be determined and plotted against wind direction for the full 0° to 360° sector. Other filters may be applied to ensure data quality. This plot will normally show two things:

a) for specific directions large flow distortions will be visible, indicated wakes operation from mast, guy wires or other sensors;

b) a slowly changing sine wave is normally visible with a period of 360°.

An example is given in Figure S.1 below. This example is for a goal-post design for the top of the mast but it illustrates the expected signal behaviour. As shown in the graph, it may be beneficial to also plot the expected wakes as determined from the geometric set-up as this will help to correctly interpret the plot. Care should be taken when there are too many and/or too strong wakes, from masts, guys and other sensors as the wakes may overshadow the sine-wave we are interested in and thereby make this method impractical or impossible to apply.

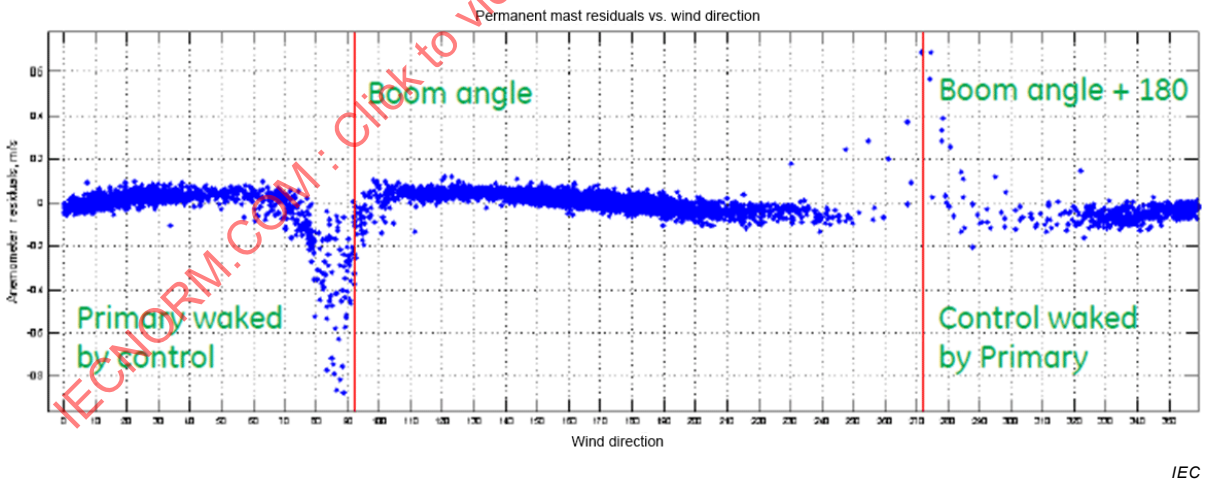

Figure S.1 – Example of mast flow distortion

The sine wave is the flow distortion from the mast and other hardware at the same measurement height that we aim at correcting. This is done by finding suitable values for the parameters in this equation:

$$V_1 = m \cdot V_2 + B + A\sin(\mathrm{WD} + Centre) \quad \text{(S.1)}$$

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where

V_1 is the wind speed from sensor one;

V_2 is the wind speed from the second sensor;

m is the slope of the regression between V_1 and V_2;

B is the offset of the regression between V_1 and V_2;

A is a scaling parameter;

WD is the wind direction.

Centre is the wind direction where the residuals are expected to be zero; In the above examples where the boom angles are 92° and 272°, *Centre* = 182°. Figure G.3, Figure G.6 and Figure G.8 may be useful in assessing the directions where flow distortion is equal at both sensor locations. Solutions within the measurement sector (or closest to) are most useful.

A is a scaling parameter that we need to solve for. A can be found by iteration; by first setting A to zero and picking another point in the data (keeping away from the wakes data), we can determine the current value for the residuals. In the graph above we see a residual value of 0,03 at 150° and a residual value of 0 at 182°. Now we define *Centre* = 182° and require a value of zero for V_1 at 150°. This determines value for A of 0,06 (note the negative sign for the sine at an angle of 150°+180° = 330°). Further checking of other points is recommended to make sure we have the right value for A and that this is not based on accidental outlier data.

A reflects the magnitude of the sum effect of the flow distortion on both anemometers. Therefore, each anemometer wind speed must be corrected by half of amplitude A according to Equations (S.2) and (S.3) below:

$$V_{1\text{corr}} = V_1 + \frac{A}{2}\sin(\text{WD} + Centre) \tag{S.2}$$

$$V_{2\text{corr}} = V_2 - \frac{A}{2}\sin(\text{WD} + Centre) \tag{S.3}$$

The flow distortion correction shown here does not correct to zero flow distortion but only normalizes to the direction where the flow distortion effect is the same at both anemometers. The direction at which the flow distortion is zero may be estimated from the flow speed graphs in Clause G.4, and the final flow correction can be adjusted accordingly.

The corrected wind speeds can now be used to recalculate residuals, which can be plotted in the same graph to show the improvement. The residuals of the corrected signal (in red) are clearly less depending on wind direction than the original (in blue), as shown in Figure S.2.

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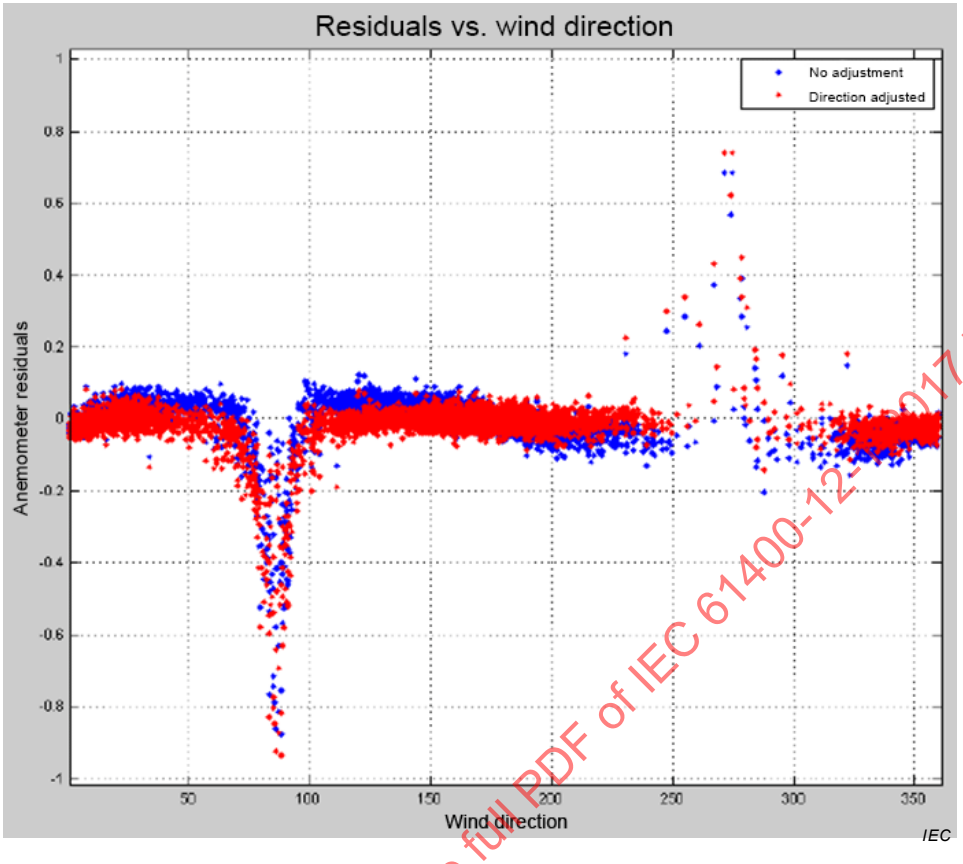

Figure S.2 – Flow distortion residuals versus direction

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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SYSTÈMES DE GÉNÉRATION D'ÉNERGIE ÉOLIENNE –

Partie 12-1: Mesures de performance de puissance des éoliennes de production d'électricité

AVANT-PROPOS

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La Norme internationale IEC 61400-12-1 a été établie par le comité d'études 88 de l'IEC: Systèmes de génération d'énergie éolienne.

Cette deuxième édition annule et remplace la première édition parue en 2005. Cette édition constitue une révision technique. Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) nouvelle définition de la vitesse du vent;
b) inclusion du cisaillement du vent et de la déviation de la trajectoire du vent;
c) correction de la masse volumique de l'air;
d) révision de l'étalonnage du site;
e) révision de la définition de la courbe de puissance;

f) interpolation de la méthode utilisant le centre de la tranche;
g) révision du modèle d'obstacle;
h) clarification des exigences relatives à la topographie;
i) nouvelle annexe sur la distorsion de l'écoulement produite par le mât;
j) révision de la classification des anémomètres;
k) inclusion des anémomètres à ultrasons;
l) ajout d'une annexe sur les climats froids;
m) modification de la base de données A en base de données spéciale;
n) révision de l'annexe sur l'incertitude;
o) inclusion de la télédétection.

L'IEC 61400-12-2 est un complément à l'IEC 61400-12-1.

Le texte de cette norme est issu des documents suivants:

FDIS	Rapport de vote
88/610/FDIS	88/617/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette norme.

Une liste de toutes les parties de la série IEC 61400, publiées sous le titre général *Systèmes de génération d'énergie éolienne*, peut être consultée sur le site web de l'IEC.

Les futures normes de cette série porteront dorénavant le nouveau titre général cité ci-dessus. Le titre des normes existant déjà dans cette série sera mis à jour lors de la prochaine édition.

Cette publication a été rédigée selon les Directives ISO/IEC, Partie 2.

Le comité est conscient que la mise en œuvre de cette révision est considérablement plus complexe, voire plus difficile. Néanmoins, le comité tente de traiter de son mieux les questions relatives à l'exploitation des grandes éoliennes sous un cisaillement du vent important et sur un terrain complexe. Le comité recommande que les nouvelles techniques présentées soient immédiatement validées par des laboratoires d'essais dans le cadre d'essais d'aptitude interlaboratoires. Le comité recommande de rédiger, dans les trois ans qui suivent la publication du présent document, un Rapport de Révision de maintenance contenant des recommandations, des clarifications et des simplifications qui amélioreront la mise en œuvre pratique de la présente norme. Si nécessaire, il convient de proposer une révision au moment de l'intégration de ces recommandations, clarifications et simplifications.

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Le comité a décidé que le contenu de cette publication ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous "http://webstore.iec.ch" dans les données relatives à la publication recherchée. A cette date, la publication sera

- reconduite,
- supprimée,
- remplacée par une édition révisée, ou
- amendée.

Le contenu des corrigenda de septembre 2019 et mars 2020 a été pris en considération dans cet exemplaire.

IMPORTANT – Le logo *"colour inside"* qui se trouve sur la page de couverture de cette publication indique qu'elle contient des couleurs qui sont considérées comme utiles à une bonne compréhension de son contenu. Les utilisateurs devraient, par conséquent, imprimer cette publication en utilisant une imprimante couleur.

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INTRODUCTION

L'objectif de la présente partie de l'IEC 61400 est de fournir une méthodologie uniforme qui garantira la cohérence, la précision et la reproductibilité de la mesure et de l'analyse de la performance de puissance des éoliennes. La présente norme a été établie en vue d'être appliquée par:

a) les fabricants d'éoliennes dans le cadre de leurs efforts pour satisfaire à des exigences de performance de puissance bien définies et/ou à un système de déclaration éventuel;

b) les acheteurs d'éoliennes lors de la spécification de telles exigences de performance;

c) les opérateurs d'éoliennes qui peuvent devoir vérifier que les unités neuves ou remises en état satisfont aux spécifications de performance de puissance indiquées, voire exigées;

d) les autorités d'urbanisme ou de régulation en matière d'éoliennes, qui doivent être en mesure de définir de manière juste et acceptable les caractéristiques de performance de puissance des éoliennes au titre de la réglementation ou des exigences relatives aux autorisations applicables aux installations neuves ou modifiées.

Le présent document fournit des lignes directrices sur la mesure, l'analyse et la consignation des rapports d'essai de performance de puissance des éoliennes. Le document concerne les parties impliquées dans la fabrication, la planification d'installation et la délivrance de permis, l'exploitation, l'utilisation et la réglementation des éoliennes. Il convient que toutes les parties appliquent les techniques de mesure et d'analyse techniquement précises recommandées dans la présente norme pour garantir le développement et l'exploitation en continu des éoliennes dans un climat de communication cohérente et exacte vis-à-vis de la performance des éoliennes. Le présent document décrit les procédures de mesure et de rapport qui sont réputées donner des résultats précis pouvant être reproduits par d'autres personnes. D'autre part, il convient que les utilisateurs de la présente norme soient informés des différences qui apparaissent en cas de variations importantes du cisaillement du vent et des turbulences. Par conséquent, il convient que les utilisateurs tiennent compte de l'influence de ces différences ainsi que des critères de choix des données par rapport à l'objectif de l'essai avant de procéder aux mesures de performance de puissance.

La mesure de la vitesse du vent constitue un élément fondamental des essais de performance de puissance. Pour mesurer le vent, le présent document prescrit l'utilisation d'anémomètres à coupelles, d'anémomètres à ultrasons ou de dispositifs de télédétection (RSD, *Remote Sensing Device*) utilisés en conjonction avec des anémomètres. Même si les procédures appropriées sont appliquées pour l'étalonnage/la validation et la classification, la nature même du principe de mesure de ces dispositifs peut altérer leur fonctionnement. Ces instruments sont résistants et ont été jugés appropriés pour ce type d'essai, à ceci près que certains d'entre eux sont limités à des classes spécifiques de terrains.

Sachant que la taille des éoliennes ne cesse d'augmenter, la vitesse du vent mesurée à une même hauteur est de moins en moins susceptible de représenter avec précision la vitesse du vent traversant le rotor de l'éolienne dans son ensemble. Par conséquent, la présente norme introduit une définition supplémentaire de la vitesse du vent. Auparavant, la vitesse du vent était mesurée à la hauteur du moyeu seulement. A présent, cette caractéristique peut être complétée par la vitesse du vent équivalente du rotor (REWS, *Rotor Equivalent Wind Speed*), déterminée par une combinaison arithmétique de mesures simultanées de la vitesse du vent à différentes hauteurs allant de l'extrémité inférieure à l'extrémité supérieure du rotor, couvrant ainsi la totalité du diamètre du rotor. Les courbes de puissance définies par la vitesse du vent à la hauteur du moyeu et par la REWS ne sont pas identiques; la courbe de puissance de la vitesse du vent à la hauteur du moyeu est toujours présentée à titre de comparaison lorsqu'une courbe de puissance de REWS est mesurée. En raison de cette différence de définition de la vitesse du vent, la production annuelle d'énergie (AEP) déduite à partir de la combinaison d'une courbe de puissance mesurée et d'une distribution des vitesses du vent utilise une courbe de puissance et une distribution des vitesses du vent qui appliquent la même définition de la vitesse du vent.

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Les procédures de classification des anémomètres à coupelles et à ultrasons sont données aux Annexes I et J. Les procédures de classification des dispositifs de télédétection sont données à l'Annexe L. Il convient de porter une attention particulière au choix des instruments utilisés pour mesurer la vitesse du vent car ce choix peut influencer le résultat de l'essai.

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SYSTÈMES DE GÉNÉRATION D'ÉNERGIE ÉOLIENNE –

Partie 12-1: Mesures de performance de puissance des éoliennes de production d'électricité

1 Domaine d'application

La présente partie de l'IEC 61400 spécifie une procédure de mesure des caractéristiques de performance de puissance d'une éolienne simple et s'applique aux essais d'éoliennes raccordées au réseau électrique de tous types et de toutes tailles. En outre, la présente norme décrit une procédure qui doit être utilisée pour déterminer les caractéristiques de performance de puissance des petites éoliennes (définies dans l'IEC 61400-2) raccordées soit au réseau électrique, soit à un banc de batteries. La procédure peut être utilisée pour évaluer la performance d'éoliennes spécifiques sur des sites spécifiques, mais la méthodologie peut également être utilisée pour procéder à des comparaisons génériques entre différents modèles d'éoliennes ou différents réglages d'éoliennes lorsque les influences des conditions spécifiques au site et du filtrage de données sont étudiées.

Les caractéristiques de performance de puissance des éoliennes sont déterminées par la courbe de puissance mesurée et la production annuelle d'énergie (AEP) estimée. La courbe de puissance mesurée, définie comme la relation entre la vitesse du vent et la puissance de sortie de l'éolienne, est déterminée en compilant des mesures simultanées des variables météorologiques (notamment la vitesse du vent), ainsi que des signaux d'éoliennes (notamment la puissance de sortie) sur le site d'essai pendant une période suffisamment longue pour constituer une base de données statistiquement significative sur une plage donnée de vitesses du vent et dans des conditions de vent et des conditions atmosphériques variables. La production annuelle d'énergie (AEP) est calculée en appliquant la courbe de puissance mesurée aux distributions de fréquence de vitesses du vent de référence, en prenant pour hypothèse une disponibilité de 100 %.

Le présent document décrit une méthodologie de mesure qui exige que les valeurs de la courbe de puissance mesurée et de la production d'énergie déduite soient complétées par une évaluation des sources d'incertitude et de leurs effets associés.

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2 Références normatives

Les documents suivants cités dans le texte constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60688:2012, *Transducteurs électriques de mesure convertissant les grandeurs électriques alternatives ou continues en signaux analogiques ou numériques*

IEC 61400-12-2:2013, *Eoliennes – Partie 12-2: Performance de puissance des éoliennes de production d'électricité basée sur l'anémométrie de nacelle*

IEC 61869-1:2007, *Transformateurs de mesure – Partie 1: Exigences générales*

IEC 61869-2:2012, *Transformateurs de mesure – Partie 2: Exigences supplémentaires concernant les transformateurs de courant*

IEC 61869-3:2011, *Transformateurs de mesure – Partie 3: Exigences supplémentaires concernant les transformateurs inductifs de tension*

ISO/IEC Guide 98-3:2008, *Incertitude de mesure – Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)*

ISO/IEC 17025:2005, *Exigences générales concernant la compétence des laboratoires d'étalonnages et d'essais*

ISO/IEC 17043:2010, *Evaluation de la conformité – Exigences générales concernant les essais d'aptitude*

ISO 2533:1975, *Atmosphère type*

ISO 3966:2008, *Mesurage du débit des fluides dans les conduites fermées – Méthode d'exploration du champ des vitesses au moyen de tubes de Pitot doubles*

3 Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
précision
étroitesse de la correspondance entre le résultat d'une mesure et une valeur vraie du mesurande

3.2
production annuelle d'énergie
AEP
estimation de la production totale d'énergie d'une éolienne pendant un an en appliquant la courbe de puissance mesurée à diverses distributions de fréquence de vitesses du vent de référence à la hauteur du moyeu, en supposant une disponibilité de 100 %

Note 1 à l'article: L'abréviation " *AEP* " est dérivée du terme anglais développé correspondant "*annual energy production*".

3.3
stabilité atmosphérique
mesure de la tendance du vent à stimuler ou inhiber le brassage vertical

Note 1 à l'article: Une atmosphère stable est caractérisée par un gradient de température élevé avec l'altitude, un fort cisaillement du vent, une éventuelle déviation de la trajectoire du vent et de faibles turbulences par rapport aux conditions instables. Une atmosphère neutre et instable se traduit généralement par de faibles gradients de température et un faible cisaillement du vent.

3.4
terrain complexe
terrain entourant le site d'essai, et présentant des variations topographiques notables et des obstacles (voir 3.18) pouvant entraîner une distorsion de l'écoulement de l'air

3.5
vitesse de démarrage
vitesse du vent la plus basse à laquelle une éolienne commence à fournir une puissance

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3.6
vitesse de coupure
vitesse à laquelle une éolienne est coupée du réseau électrique en raison d'une vitesse élevée du vent

3.7
ensemble de données
collection de données qui ont été échantillonnées sur une période continue

3.8
constante de distance
indication du temps de réponse d'un anémomètre définie comme la longueur de l'écoulement d'air qui doit passer à travers l'instrument afin que celui-ci indique 63 % de la valeur finale pour une variation en échelon de la vitesse du vent en entrée

3.9
courbe de puissance extrapolée
prolongement de la courbe de puissance mesurée obtenu en estimant la production de puissance entre la vitesse maximale du vent mesurée et la vitesse de coupure

3.10
distorsion de l'écoulement
changement dans l'écoulement de l'air causé par des obstacles, des variations topographiques ou par d'autres éoliennes, qui se traduit par un écart entre la vitesse du vent au point de mesure et la vitesse du vent à l'emplacement de l'éolienne

3.11
hauteur du moyeu (des éoliennes)
hauteur du centre de la surface balayée par le rotor de l'éolienne par rapport au sol au niveau du mât

Note 1 à l'article: Pour une éolienne à axe vertical, la hauteur du moyeu est la hauteur du centroïde de la surface balayée par le rotor par rapport au sol au niveau du mât.

3.12
courbe de puissance mesurée
tableau et graphique représentant la puissance de sortie nette d'une éolienne mesurée, corrigée et normalisée, en fonction de la vitesse du vent mesurée selon une procédure de mesure bien définie

3.13
période de mesure
période pendant laquelle une base de données statistiquement significative a été recueillie pour l'essai de performance de puissance

3.14
secteur de mesure
secteur des directions du vent dans lequel les données sont choisies pour la courbe de puissance mesurée

3.15
méthode des tranches
procédure de réduction des données selon laquelle les données d'essai pour un paramètre donné sont groupées en intervalles (tranches)

Note 1 à l'article: Pour chaque tranche, le nombre d'ensembles de données ou d'échantillons et leur somme sont enregistrés, et la moyenne de la valeur du paramètre à l'intérieur de chaque tranche est calculée.

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3.16
puissance électrique active nette
mesure de la puissance de sortie électrique de l'éolienne fournie au réseau électrique

3.17
maintenance normale
toute intervention effectuée conformément à un programme de maintenance régulière définie, indépendamment de tout essai de performance de puissance, par exemple un changement d'huile, un lavage des pales (s'il est nécessaire, indépendamment de l'essai de performance de puissance) et toute intervention ne relevant pas du programme de maintenance régulière, (par exemple la réparation d'un composant défectueux) et ne constituant pas une modification de configuration de la machine

3.18
obstacles
objets faisant obstacle au vent et créant une distorsion de l'écoulement, tels que des bâtiments et des arbres

3.19
angle de pas
angle entre la corde à un endroit défini du rayon de la pale (habituellement à 100 % du rayon de la pale) et le plan de rotation du rotor

3.20
coefficient de puissance
rapport de la puissance électrique nette d'une éolienne, à la puissance disponible dans le vent en écoulement libre sur la surface balayée par le rotor

3.21
performance de puissance
mesure de l'aptitude d'une éolienne à produire de la puissance et de l'énergie électriques

3.22
puissance assignée
quantité de puissance assignée, généralement par un fabricant, pour une condition d'exploitation spécifiée d'un composant, d'un dispositif ou d'un matériel

3.23
vitesse du vent équivalente du rotor
vitesse du vent correspondant au flux d'énergie cinétique traversant la surface balayée par le rotor en tenant compte de la variation de la vitesse du vent en fonction de la hauteur, représentée à l'Equation (5)

3.24
maintenance spéciale
toute intervention ne relevant pas du programme de maintenance régulière et ne constituant pas une modification de configuration de la machine, c'est-à-dire toute intervention effectuée dans le but d'améliorer la performance de puissance au cours d'une période d'essai, par exemple lavage des pales non programmé ou remplacement d'un composant essentiel

3.25
incertitude-type
incertitude du résultat d'une mesure exprimée sous la forme d'un écart-type

3.26
surface balayée
pour une éolienne à axe horizontal, surface projetée par le rotor mobile sur un plan perpendiculaire à l'axe de rotation

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Note 1 à l'article: Pour les rotors à balancier, il convient de prendre pour hypothèse que le rotor reste perpendiculaire par rapport à l'arbre primaire. Pour une éolienne à axe vertical, surface projetée par le rotor mobile sur un plan vertical.

3.27
site d'essai
emplacement de l'éolienne à l'essai et ses environs

3.28
incertitude de mesure
paramètre, associé au résultat d'un mesurage, qui caractérise la dispersion des valeurs qui pourraient raisonnablement être attribuées au mesurande

3.29
matériel de mesure du vent
mât météorologique ou dispositif de télédétection

3.30
cisaillement du vent
variation de la vitesse du vent en fonction de la hauteur sur le rotor de l'éolienne

3.31
exposant de cisaillement du vent
exposant α de la loi exponentielle définissant la variation de la vitesse du vent en fonction de la hauteur

Note 1 à l'article: Ce paramètre est utilisé comme mesure de l'amplitude du cisaillement du vent pour l'étalonnage du site de l'Annexe C et peut être utile à d'autres égards. L'équation exponentielle est la suivante:

$$v_{zi} = v_h \left(\frac{z_i}{H} \right)^{\alpha} \quad (1)$$

où

v_h est la vitesse du vent à la hauteur du moyeu;
H est la hauteur du moyeu (m);
v_{zi} est la vitesse du vent à la hauteur z_i
α est l'exposant de cisaillement du vent.

3.32
déviation de la trajectoire du vent
variation de la direction du vent en fonction de la hauteur sur le rotor de l'éolienne

4 Symboles et unités

A	surface balayée par le rotor de l'éolienne	[m^2]
A_i	surface du i^e segment du rotor de l'éolienne	[m^2]
A_w	facteur d'échelle de Weibull	[m/s]
AEP	production annuelle d'énergie	[Wh]
B	pression atmosphérique	[Pa]
B_{10min}	pression atmosphérique moyennée sur une période de 10 min	[Pa]
Ch	coefficient de la tête du tube de Pitot	
$C_{P,i}$	coefficient de puissance dans la tranche i	
C_{QA}	coefficient de couple aérodynamique généralisé	
C_T	coefficient de poussée	
c	facteur de sensibilité d'un paramètre (dérivée partielle)	

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$c_{B,i}$	facteur de sensibilité de la pression atmosphérique dans la tranche i	[W/Pa]
$c_{d,i}$	facteur de sensibilité du système d'acquisition de données dans la tranche i	
c_{index}	facteur de sensibilité du paramètre d'indice	
$c_{k,i}$	facteur de sensibilité de la composante k dans la tranche i	
$c_{T,i}$	facteur de sensibilité de la température de l'air dans la tranche i	[W/K]
$c_{V,i}$	facteur de sensibilité de la vitesse du vent dans la tranche i	[Ws/m]
$c_{\rho,i}$	facteur de sensibilité de la correction de la masse volumique de l'air dans la tranche i	[Wm^3/kg]
D	diamètre du rotor	[m]
D_e	diamètre équivalent du rotor	[m]
Dn	diamètre du rotor de l'éolienne voisine en exploitation	[m]
d	diamètre du mât météorologique	[m]
$F(V)$	fonction de distribution de probabilité cumulative de Rayleigh pour la vitesse du vent	
f_i	occurrence relative de la vitesse du vent dans un intervalle de vitesse du vent	
$f_{r,MM}$	facteur de correction du cisaillement du vent, mesuré à l'aide d'instruments montés sur le mât météorologique	
$f_{r,RSD}$	facteur de correction du cisaillement du vent, mesuré à l'aide d'un dispositif de télédétection	
H	hauteur du moyeu de l'éolienne	[m]
h	hauteur de l'obstacle	[m]
I	inertie du rotor de l'anémomètre à coupelles	[kgm^2]
k	numéro de classe	
k	facteur de forme de Weibull	
k_b	facteur de correction de l'obstruction	
k_c	facteur d'étalonnage de la soufflerie	
k_f	facteur de correction de la soufflerie par rapport aux autres souffleries (uniquement utilisé pour les estimations de l'incertitude)	
k_ρ	facteur de correction d'humidité par rapport à la masse volumique	
$K_{B,t}$	sensibilité du baromètre	[N/m^{2}V]
$K_{B,s}$	gain du baromètre	
$K_{B,d}$	conversion d'échantillonnage du baromètre	
$K_{T,t}$	sensibilité du transducteur de température	[K/A]
$K_{T,s}$	gain du transducteur de température	[A/V]
$K_{T,d}$	conversion d'échantillonnage du transducteur de température	
$K_{p,t}$	sensibilité du transducteur de pression	
$K_{p,s}$	gain du transducteur de pression	
$K_{p,d}$	conversion d'échantillonnage du transducteur de pression	
L_m	distance entre les pieds adjacents du mât météorologique en treillis	[m]
L	distance entre l'éolienne et le matériel de mesure du vent	[m]
L_e	distance entre l'éolienne ou le matériel de mesure du vent et un obstacle	[m]
L_n	distance entre l'éolienne ou le matériel de mesure du vent et une éolienne voisine en exploitation	[m]

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l_h	hauteur de l'obstacle	[m]
l_w	largeur de l'obstacle	[m]
M	nombre de composantes d'incertitude dans chaque tranche	
M_A	nombre de composantes d'incertitude de catégorie A	
M_B	nombre de composantes d'incertitude de catégorie B	
N	nombre de tranches	
N_h	nombre d'heures dans une année ≈ 8760	[h]
N_i	nombre d'ensembles de données de 10 min dans la tranche i de vitesse du vent	
N_j	nombre d'ensembles de données de 10 min dans la tranche j de direction du vent	
n	nombre d'échantillons dans un intervalle d'échantillonnage	
n_h	nombre de hauteurs de mesure disponibles	
P_o	porosité d'un obstacle (0: solide, 1: aucun obstacle)	
P_i	puissance de sortie normalisée et moyennée dans la tranche i	[W]
P_n	puissance de sortie normalisée	[W]
$P_{n,i,j}$	puissance de sortie normalisée de l'ensemble de données j dans la tranche i	[W]
P_{10min}	puissance moyennée sur une période de 10 min	[W]
P_w	pression de vapeur	[Pa]
Q_A	couple aérodynamique	[Nm]
Q_f	couple de frottement	[Nm]
R	rayon du rotor	[m]
R_0	constante des gaz pour l'air sec (287,05)	[J/kgK]
R_d	distance jusqu'au centre du mât météorologique	[m]
R_w	constante des gaz pour la vapeur d'eau (461,5)	[J/kgK]
RSD	dispositif de télédétection	
r	coefficient de corrélation	
s	composante d'incertitude-type de catégorie A	
s_A	incertitude-type de catégorie A sur le chronogramme de la vitesse du vent dans la soufflerie	
$s_{k,i}$	incertitude-type de catégorie A sur la composante k dans la tranche i	
s_i	incertitudes composées de catégorie A dans la tranche i	
$s_{P,i}$	incertitude-type de catégorie A sur la puissance dans la tranche i	[W]
s_{sc}	incertitude-type de catégorie A sur l'étalonnage du site	[m/s]
$s_{w,i}$	incertitude-type de catégorie A sur les variations climatiques	[Wh]
$s_{\alpha,j}$	incertitude-type de catégorie A sur les rapports de vitesses du vent dans la tranche j	
S	solidité du mât météorologique	
T	température absolue	[K]
TI	intensité des turbulences ("*turbulence intensity*")	
T_{10min}	température absolue de l'air moyennée sur une période de 10 min	[K]
t	temps	[s]
U	vitesse du vent	[m/s]
U_d	déficit de vitesse du vent de l'axe central	[m/s]
U_{eq}	vitesse horizontale du vent équivalente	[m/s]

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U_i	vitesse du vent dans la tranche i	[m/s]
U_t	seuil de vitesse du vent	[m/s]
U	vecteur de vitesse du vent	
u	composante d'incertitude-type de catégorie B	
u_{AEP}	incertitude-type composée sur la production annuelle d'énergie estimée	[Wh]
$u_{B,i}$	incertitude-type de catégorie B sur la pression atmosphérique dans la tranche i	[Pa]
$u_{c,i}$	incertitude-type composée sur la puissance dans la tranche i	[W]
u_i	incertitudes composées de catégorie B dans la tranche i	
u_{index}	incertitude-type de catégorie B sur le paramètre d'indice	
$u_{k,i}$	incertitude-type de catégorie B sur la composante k dans la tranche i	
$u_{P,i}$	incertitude-type de catégorie B sur la puissance dans la tranche i	[W]
$u_{V,i}$	incertitude-type de catégorie B sur la vitesse du vent dans la tranche i	[m/s]
$u_{T,i}$	incertitude-type de catégorie B sur la température de l'air dans la tranche i	[K]
$u_{\alpha,i,j}$	incertitude-type composée sur l'étalonnage du site dans la tranche i de vitesse du vent et dans la tranche j de direction du vent	[m/s]
$u_{\rho,i}$	incertitude-type de catégorie B sur la correction de la masse volumique de l'air dans la tranche i	[kg/m^3]
V	vitesse du vent	[m/s]
V_{ave}	moyenne annuelle de la vitesse du vent à la hauteur du moyeu	[m/s]
V_i	vitesse du vent normalisée et moyennée dans la tranche i	[m/s]
V_n	vitesse du vent normalisée	[m/s]
$V_{n,i,j}$	vitesse du vent normalisée de l'ensemble de données j dans la tranche i	[m/s]
V_{10min}	vitesse du vent moyennée sur une période de 10 min	[m/s]
v	composante de la vitesse du vent transversale	[m/s]
$\overline{v}$	vitesse moyenne de l'écoulement d'air	[m/s]
v_{eq}	vitesse du vent équivalente mesurée	[m/s]
$v_{eq,final}$	vitesse du vent équivalente du rotor finale	[m/s]
$v_{eq,MM}$	vitesse du vent équivalente mesurée à l'aide d'un mât météorologique	[m/s]
$v_{eq,RSD}$	vitesse du vent équivalente mesurée à l'aide d'un dispositif de télédétection	[m/s]
v_h	vitesse du vent à la hauteur du moyeu	[m/s]
$v_{h,MM}$	vitesse du vent mesurée à la hauteur du moyeu à l'aide d'un mât météorologique	[m/s]
v_{hn}	vitesse du vent normalisée mesurée à la hauteur du moyeu pour un profil spécifique de cisaillement du vent	[m/s]
$v_{h,RSD}$	vitesse du vent mesurée à la hauteur du moyeu à l'aide du dispositif de télédétection	[m/s]
v_i	vitesse du vent mesurée à la hauteur i	[m/s]
v_{zi}	vitesse du vent à la hauteur z_i	[m/s]
WME	matériel de mesure du vent ("*wind measurement equipment*")	
w	composante verticale de la vitesse du vent	[m/s]

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w_i	fonction de pondération pour la détermination de l'enveloppe des écarts	
X_k	paramètre moyenné sur une période de prétraitement	
X_{10min}	paramètre moyenné sur une période de 10 min	
x	distance en aval d'un obstacle jusqu'au matériel de mesure du vent ou jusqu'à l'éolienne	[m]
z	hauteur au-dessus du sol	[m]
z_i	hauteur du i^e segment du rotor de l'éolienne	[m]
α	exposant de cisaillement du vent calculé à l'aide de la loi exponentielle	[°]
$\varepsilon_{max,i}$	écart maximal pour toutes les tranches i de vitesse du vent dans la plage de vitesses du vent	[m/s]
θ	secteur perturbé	[°]
κ	constante de von Karman, 0,4	
λ	rapport de vitesses	
ρ	masse volumique de l'air	[kg/m^3]
ρ_0	masse volumique de l'air de référence	[kg/m^3]
ρ_{10min}	masse volumique de l'air déduite moyennée sur une période de 10 min	[kg/m^3]
$\sigma_{P,i}$	écart-type des données de puissance normalisées dans la tranche i	[W]
σ_{10min}	écart-type du paramètre moyenné sur une période de 10 min	
$\sigma_u/\sigma_v/\sigma_w$	écarts-types des vitesses longitudinale/transversale/verticale du vent	
Φ	humidité relative (plage de 0 % à 100 %)	
ω	vitesse angulaire	[s^{-1}]

5 Vue d'ensemble de la méthode de performance de puissance

Le cisaillement du vent et la déviation de la trajectoire du vent peuvent varier de manière considérable sur la hauteur du rotor des grandes éoliennes en conditions de stabilité atmosphérique, mais également en fonction de la topographie du site. L'occurrence de conditions extrêmes de stabilité atmosphérique est une problématique spécifique au site. Si elles surviennent lors d'un essai de performance de puissance, la courbe de puissance peut varier de manière significative.

La méthode de mesure de performance de puissance utilisée dans la présente norme s'appuie sur une définition de la courbe de puissance exprimant la puissance produite par rapport à la vitesse du vent, et qui représente le flux d'énergie cinétique effectif dans l'écoulement du vent sur la surface balayée par le rotor.

Le flux d'énergie cinétique (à un instant donné ou sur une période donnée, habituellement 10 min, en prenant pour hypothèse que la vitesse du vent ne varie pas pendant cette période[1]) sur la surface balayée verticale est généralement exprimé par l'équation suivante:

[1] Si la vitesse du vent varie (c'est-à-dire si l'intensité des turbulences > 0) pendant une période donnée, la puissance cinétique (moyennée sur la période donnée) est plus élevée que lorsque la vitesse du vent est constante; or une éolienne ne dispose que d'une capacité limitée à transformer cette énergie cinétique supplémentaire en puissance électrique supplémentaire. La présente norme ne traite pas cette question de manière approfondie. Pour des raisons de simplification, les Equations (2), (3) et (4) sont réputées valides, même en cas d'intensité des turbulences > 0. L'impact des variations de la vitesse du vent sur la puissance cinétique moyennée dans le temps et l'impact associé sur la courbe de puissance de l'éolienne sont traités par la procédure de normalisation des turbulences donnée à l'Annexe M.

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$$P_{\text{kin}} = \int_A \frac{1}{2}\rho V^3 \, \mathrm{d}A \tag{2}$$

Ici, la vitesse du vent V, mesurée en un point donné dans l'espace sur la surface du rotor, correspond à la vitesse horizontale du vent[2]. La vitesse horizontale du vent est définie comme l'amplitude moyenne de la composante horizontale de la vitesse vectorielle instantanée du vent, incluant uniquement les composantes de turbulences longitudinale et latérale (mais pas la composante verticale). Dans le cas d'une éolienne à axe horizontal, la déviation de la trajectoire du vent est également prise en compte et l'énergie cinétique du vent est corrigée en fonction de la direction du vent à la hauteur du moyeu:

$$P_{\text{kin}} = \int_A \frac{1}{2}\rho \left(V \cos\left(\varphi - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A \tag{3}$$

Ici, φ_{hub} est la direction du vent à la hauteur du moyeu. La déviation de la trajectoire du vent peut varier de manière considérable sur la hauteur du rotor des grandes éoliennes en conditions extrêmes de stabilité atmosphérique, mais également en fonction de la topographie du site.

Dans la présente norme, le cisaillement du vent et la déviation de la trajectoire du vent ne sont pas étudiés dans le plan horizontal. Par conséquent, la vitesse du vent équivalente de l'énergie, qui correspond à l'énergie cinétique du vent déduite par l'Equation (3), est généralement exprimée par l'équation suivante:

$$V_{\text{eq}} = \left(\frac{1}{A} \int_i \left(V_i \cos\left(\varphi_i - \varphi_{\text{hub}}\right)\right)^3 \mathrm{d}A_i \right)^{1/3} \tag{4}$$

Ici, l'indice i se réfère à la hauteur au sein de la surface du rotor[3].

Même si la vitesse horizontale du vent est réputée être le paramètre de vitesse du vent d'influence, sur les sites présentant un écoulement non horizontal significatif (écoulement ascendant ou descendant), une incertitude supplémentaire est associée d'une part à la mesure de la vitesse horizontale du vent et d'autre part à la réponse de l'éolienne.

Sur les sites présentant des cisaillements et des déviations de la trajectoire du vent faibles et homogènes sur la surface du rotor (ainsi que pour les éoliennes équipées de rotors de diamètre réduit dans des conditions d'écoulement du vent potentiellement plus complexes), la vitesse du vent mesurée à la hauteur du moyeu peut constituer un bon indicateur de l'énergie cinétique que le rotor doit capter. La vitesse du vent à la hauteur du moyeu est la vitesse du vent à partir de laquelle ont été définies les courbes de puissance dans toutes les éditions antérieures de la présente norme. Pour cette raison, la vitesse du vent mesurée à la hauteur du moyeu est la définition par défaut de la vitesse du vent et doit toujours être mesurée et consignée, même lorsque des mesures plus complètes sont disponibles sur la hauteur du rotor.

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2 La puissance de l'éolienne semble concorder davantage avec la définition de la vitesse horizontale du vent qu'avec la définition d'une vitesse vectorielle du vent pour une mesure de la vitesse du vent en un point donné à la hauteur du moyeu.

3 Cependant, lorsque la vitesse du vent est mentionnée dans le document, il s'agit par défaut de la vitesse du vent à la hauteur du moyeu, sauf spécification indiquant qu'il s'agit de la vitesse du vent équivalente de l'énergie.

Sur les sites et pendant les saisons où des conditions extrêmes de stabilité atmosphérique sont fréquemment attendues, il est recommandé de procéder à une mesure systématique du cisaillement du vent.

Si le cisaillement et la déviation de la trajectoire du vent ne sont pas mesurés sur la totalité de la hauteur du rotor, une incertitude supplémentaire est associée à la vitesse du vent équivalente. Cette incertitude diminue au fur et à mesure qu'augmente le nombre de hauteurs de mesure de la vitesse et de la direction du vent. Si les mesures se limitent à la hauteur du moyeu et que les parties les plus significatives du rotor n'ont pas fait l'objet d'une mesure du cisaillement du vent, cela entraîne une incertitude dans la détermination de la vitesse du vent équivalente.

Pour les petites éoliennes[4], pour lesquelles l'influence du cisaillement et de la déviation de la trajectoire du vent est négligeable, la vitesse du vent doit être déterminée en mesurant uniquement la vitesse du vent à la hauteur du moyeu, sans introduire une incertitude supplémentaire due à l'absence des mesures du cisaillement et de la déviation de la trajectoire du vent.

Pour les éoliennes à axe vertical, pour lesquelles la déviation de la trajectoire du vent n'a aucune influence, la déviation de la trajectoire du vent doit être ignorée.

Les conditions de vent à l'emplacement de l'éolienne d'essai et à l'emplacement de la mesure du vent peuvent varier de manière considérable si ces emplacements se trouvent dans le sillage d'éoliennes; de telles situations doivent donc être exclues de l'essai.

La masse volumique de l'air ρ varie également en fonction de la hauteur du rotor d'une grande éolienne. Néanmoins, cette variation est mineure. Pour la mise en œuvre pratique de la méthode de mesure de performance de puissance, il suffit de définir et de déterminer la masse volumique de l'air seulement à la hauteur du moyeu. La courbe de puissance est normalisée à la masse volumique de l'air moyenne sur le site de mesure pendant la période de mesure ou à la masse volumique de l'air de référence prédéfinie.

Les courbes de puissance sont également influencées par les turbulences sur le site d'essai, lesquelles peuvent varier sur la surface du rotor. Dans la présente norme, seules les turbulences du site à la hauteur du moyeu sont étudiées. Les fortes turbulences augmentent le rayon de courbure de la courbe de puissance au démarrage et au début de la régulation de puissance à la puissance nominale. En revanche, de faibles turbulences accentuent les angles de la courbe de puissance. Les turbulences du site doivent être mesurées et présentées comme un complément à la courbe de puissance. Si cela est nécessaire, les turbulences peuvent être normalisées à une valeur donnée à l'aide de la méthode donnée à l'Annexe M.

En résumé, la courbe de puissance selon la présente norme est une courbe de puissance spécifique au climat, où:

a) la vitesse du vent en un point donné dans l'espace est définie comme la vitesse horizontale du vent;

b) la vitesse du vent d'une courbe de puissance est définie comme la vitesse du vent à la hauteur du moyeu. A cette définition peut s'ajouter la vitesse du vent équivalente définie dans l'Equation (4) en tenant compte du cisaillement du vent vertical et de la déviation de la trajectoire du vent[5];

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4 Pour les petites éoliennes, voir l'IEC 61400-2.

5 Pour les éoliennes à axe vertical, la déviation de la trajectoire du vent est omise dans l'Equation (3) (en définissant $\varphi_i = \varphi_{\text{hub}}$).

c) la masse volumique de l'air est mesurée à la hauteur du moyeu, et la courbe de puissance est normalisée à la masse volumique de l'air moyenne du site pendant la période de mesure ou à la masse volumique d'air de référence prédéfinie;

d) les turbulences sont mesurées à la hauteur du moyeu, et la courbe de puissance est présentée sans normalisation des turbulences;

e) la courbe de puissance peut être normalisée selon une plage plus large de conditions climatiques (p. ex.: masse volumique de l'air spécifique, intensité des turbulences, cisaillement vertical et déviation de la trajectoire)[6].

La présente norme fournit toutes les procédures nécessaires pour la mesure, l'étalonnage, la classification, la correction, la normalisation des données et la détermination des incertitudes. Cependant, si tous les paramètres ne sont pas suffisamment mesurés, une incertitude doit être appliquée en raison de l'absence de mesures. Par exemple, cela s'applique à la mesure de la courbe de puissance d'une grande éolienne équipée uniquement d'un capteur de vitesse du vent à la hauteur du moyeu. Dans ce cas, une incertitude doit être appliquée pour la variabilité du cisaillement et de la déviation de la trajectoire du vent .

Les meilleurs résultats faisant suite à l'application de la norme sont obtenus en mesurant tous les paramètres exigés et en utilisant toutes les procédures adéquates. Néanmoins, si cela n'est pas possible, il existe d'autres options pour les montages de mesure et pour l'utilisation de ces procédures. Ces options sont décrites dans le Tableau 1. Les options se réfèrent à l'utilisation de matériel de mesure du vent, aux normalisations appliquées ainsi qu'aux incertitudes supplémentaires dues à l'absence de mesures.

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6 La normalisation de la courbe de puissance n'est valide que pour des plages limitées de conditions climatiques parmi les conditions réelles du site.

Tableau 1 – Vue d'ensemble des configurations de mesure du vent pour les mesures de la courbe de puissance qui satisfont aux exigences de la présente norme

Configuration de mesure du vent	1. Mât météorologique à la hauteur du moyeu et dispositif de télédétection à toutes les hauteurs	2. Mât météorologique en dessous de la hauteur du moyeu et dispositif de télédétection à toutes les hauteurs	3. Mât météorologique au-dessus de la hauteur du moyeu	4. Mât météorologique à la hauteur du moyeu
Application type	Grandes éoliennes[7] sur terrain plat (voir Annexe B)	Grandes éoliennes sur terrain plat (voir Annexe B)	Petites et grandes éoliennes sur tous types de terrains	Petites et grandes éoliennes sur tous types de terrains
Capteurs de mesure du vent	7.2.3, 7.2.5	7.2.3, 7.2.5	7.2.3, 7.2.4	7.2.3
Procédures de normalisation pour la détermination de la courbe de puissance spécifique au climat	Masse volumique de l'air, cisaillement du vent; 9.1.5 et 9.1.3.4	Masse volumique de l'air, cisaillement du vent; 9.1.5 et 9.1.3.4	Masse volumique de l'air, cisaillement du vent; 9.1.5 et 9.1.3.4	Masse volumique de l'air; 9.1.5
Incertitude supplémentaire due à l'absence de mesures du cisaillement du vent	Aucune incertitude supplémentaire liée à la couverture des hauteurs de mesure; E.11.2.2	Aucune incertitude supplémentaire liée à la couverture des hauteurs de mesure; E.11.2.2	Aucune incertitude supplémentaire liée à la couverture des hauteurs de mesure; E.11.2.2	Incertitude brute supplémentaire pour les grandes éoliennes liée à l'absence de mesures du cisaillement du vent vertical; E.11.2.2
Procédures de normalisation facultatives[8]	Turbulences, déviation de la trajectoire du vent et angle d'écoulement ascendant; 9.1.6 et 9.1.4	Turbulences, déviation de la trajectoire du vent et angle d'écoulement ascendant; 9.1.6 et 9.1.4	Turbulences, déviation de la trajectoire du vent et angle d'écoulement ascendant; 9.1.6 et 9.1.4 Distorsion de l'écoulement au niveau du mât météorologique; 9.1.2, étalonnage du site; Annexe C.	Turbulences et angle d'écoulement ascendant; 9.1.6. Etalonnage du site; Annexe C.

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7 Voir l'IEC 61400-2 pour la définition des petites et grandes éoliennes.

8 Les influences de l'écoulement ascendant influencent la courbe de puissance et peuvent être mesurées avec des anémomètres à ultrasons 3D ou des girouettes d'écoulement ascendant. Si une normalisation de l'angle d'écoulement ascendant est appliquée, il convient de documenter la méthode utilisée (l'incertitude sur l'écoulement ascendant est abordée à l'Annexe E). Toutefois, la présente norme ne décrit aucune procédure spécifique concernant la manière de normaliser l'angle d'écoulement ascendant.

6 Préparation de l'essai de performance

6.1 Généralités

Les conditions d'essai spécifiques concernant la mesure de performance de puissance de l'éolienne doivent être bien définies et documentées dans le rapport d'essai décrit à l'Article 10.

6.2 Eolienne et raccordement électrique

Comme décrit à l'Article 10, l'éolienne et le raccordement électrique doivent être décrits et documentés afin d'identifier de manière unique la configuration spécifique de la machine soumise à l'essai.

6.3 Site d'essai

6.3.1 Généralités

Sur le site d'essai, le matériel de mesure du vent doit être installé dans le voisinage de l'éolienne afin de déterminer la vitesse du vent qui entraîne l'éolienne.

Les caractéristiques de cisaillement du vent et de stabilité atmosphérique du site peuvent avoir une influence significative sur les mesures du vent et sur la performance de puissance réelle de l'éolienne. Un cycle diurne de stabilité atmosphérique est fréquemment observé, caractérisé par une atmosphère stable qui se forme la nuit et par une atmosphère neutre ou instable dans la journée lorsque le soleil réchauffe le sol, ce qui augmente les turbulences et le brassage dans la couche limite. Le cisaillement du vent, la déviation de la trajectoire du vent et les turbulences sont fonction de la stabilité atmosphérique, et affectent les relations entre la vitesse du vent à la hauteur du moyeu et la vitesse du vent équivalente du rotor. Des profils peu habituels peuvent également avoir une influence sur la conversion énergétique de l'éolienne. En outre, les effets de distorsion de l'écoulement peuvent engendrer une différence de la vitesse du vent à l'emplacement de la mesure et à l'emplacement de l'éolienne, en dépit de leur corrélation.

Les sources de distorsion de l'écoulement du vent doivent être évaluées sur le site d'essai afin de:

a) choisir l'emplacement approprié pour le matériel de mesure du vent;

b) définir un secteur de mesure approprié;

c) déterminer si un étalonnage du site est exigé, puis déterminer les corrections d'écoulement appropriées en procédant à une mesure conformément à l'Annexe C;

d) évaluer l'incertitude due à la distorsion de l'écoulement du vent.

En particulier, les facteurs suivants doivent être pris en compte:

1) les variations topographiques et la rugosité;

2) les autres éoliennes;

3) les obstacles (bâtiments, arbres, etc.).

Le site d'essai doit être documenté de la manière décrite à l'Article 10.

6.3.2 Emplacement du matériel de mesure du vent

Le choix de l'emplacement du matériel de mesure du vent doit faire l'objet d'une attention particulière. Le matériel de mesure du vent ne doit pas être situé trop près de l'éolienne, puisque la vitesse du vent sera influencée devant l'éolienne. Il ne doit pas non plus être situé trop loin de l'éolienne, car la corrélation entre la vitesse du vent et la puissance de sortie électrique en serait réduite. L'instrumentation de mesure de la vitesse du vent et l'éolienne

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doivent être placées à une distance comprise entre 2 fois et 4 fois le diamètre du rotor D de l'éolienne. Une distance égale à 2,5 fois le diamètre du rotor D est recommandée. Pour les éoliennes à axe vertical, voir l'Article H.4.

Avant de procéder à l'essai de performance de puissance et afin d'optimiser le choix de l'emplacement du matériel de mesure du vent, il convient de tenir compte de la nécessité d'exclure les mesures de tous les secteurs dans lesquels le matériel de mesure du vent ou l'éolienne seront soumis à une perturbation de l'écoulement.

Dans la plupart des cas, l'emplacement le plus approprié pour le matériel de mesure du vent sera du côté exposé au vent de l'éolienne, dans la direction d'où est censé venir le vent au cours de l'essai. Cependant, il peut parfois être plus approprié de placer le matériel de mesure du vent à côté de l'éolienne dans la mesure où les conditions de vent seront plus semblables, par exemple pour une éolienne située sur une crête.

6.3.3 Secteur de mesure

Le ou les secteurs de mesure doivent exclure les directions présentant des obstacles significatifs et d'autres éoliennes, tant pour les éoliennes à l'essai que pour le matériel de mesure du vent.

Pour l'ensemble des éoliennes et des obstacles significatifs du voisinage, les directions à exclure en raison des effets de sillage doivent être déterminées selon la procédure donnée à l'Annexe A. Les secteurs perturbés à exclure du fait que le matériel de mesure du vent se trouve dans le sillage de l'éolienne à l'essai sont représentés à la Figure 1 pour des distances de $2D$, $2{,}5D$ et $4D$. La réduction d'un ou de plusieurs secteurs de mesure peut être justifiée par des conditions topographiques spécifiques ou des données de mesure inattendues résultant de directions présentant des structures compliquées. Toutes les raisons de réduire le secteur de mesure doivent être clairement documentées.

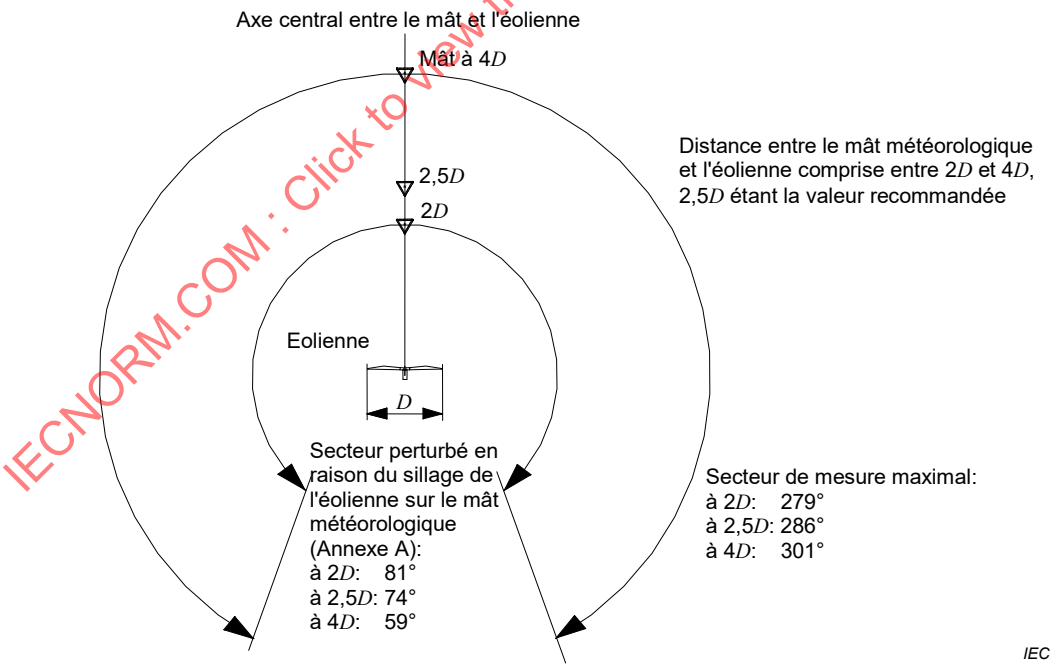

Figure 1 – Exigences de distance entre le matériel de mesure du vent et les secteurs de mesure maximaux admis

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6.3.4 Facteurs de correction et incertitude due à la distorsion de l'écoulement résultant de la topographie

Les sources de distorsion de l'écoulement du vent résultant de variations topographiques doivent être évaluées sur le site d'essai. L'évaluation décrite à l'Annexe B doit déterminer si la courbe de puissance peut être mesurée sans procéder à un étalonnage du site. Si les critères de l'Annexe B sont satisfaits, le régime d'écoulement du vent du site ne nécessite pas d'étalonnage du site. Cependant, en prenant pour hypothèse qu'aucune correction d'écoulement n'est nécessaire, l'incertitude appliquée due à la distorsion de l'écoulement du site d'essai doit correspondre au minimum à 2 % de la vitesse du vent mesurée si le matériel de mesure du vent est positionné à une distance comprise entre 2 fois à 3 fois le diamètre du rotor de l'éolienne, et à 3 % ou plus si la distance est comprise entre 3 fois à 4 fois le diamètre du rotor[9], à moins qu'une preuve tangible puisse démontrer l'estimation d'une incertitude différente.

Si les critères de l'Annexe B ne sont pas respectés ou qu'une incertitude due à la distorsion de l'écoulement du site d'essai moins élevée est souhaitée, un étalonnage du site expérimental doit être réalisé selon l'Annexe C. Les facteurs de correction d'écoulement mesurés pour chaque secteur doivent être utilisés.

7 Matériel d'essai

7.1 Puissance électrique

La puissance électrique nette de l'éolienne doit être mesurée en utilisant un dispositif de mesure de puissance (par exemple, un transducteur de puissance) et être fondée sur des mesures de courant et de tension sur chaque phase.

La classe des transformateurs de courant doit satisfaire aux exigences de l'IEC 61869-2, et la classe des transformateurs de tension, le cas échéant, doit satisfaire aux exigences de l'IEC 61869-3. Ils doivent être de classe 0,5 au moins.

Si le dispositif de mesure de puissance est un transducteur de puissance, la précision doit satisfaire aux exigences de l'IEC 60688 et doit être de classe 0,5 au moins. Si le dispositif de mesure de puissance n'est pas un transducteur de puissance, il convient alors que la précision soit équivalente à celle des transducteurs de puissance de classe 0,5. La plage de fonctionnement du dispositif de mesure de puissance doit être déterminée de manière à mesurer toutes les crêtes de puissance instantanée positives et négatives produites par l'éolienne. A titre indicatif, pour les éoliennes de grande puissance à contrôle actif, il convient de définir la plage complète du dispositif de mesure de puissance de –25 % à +125 % de la puissance assignée de l'éolienne[10]. Toutes les données doivent être revues périodiquement pendant l'essai afin de s'assurer que les limites de la plage du dispositif de mesure de puissance n'ont pas été dépassées. Le transducteur de puissance doit être étalonné d'après des normes traçables. Le dispositif de mesure de puissance doit être monté entre l'éolienne et le raccordement électrique afin de s'assurer que seule la puissance électrique active nette (c'est-à-dire, diminuée de la consommation propre) est mesurée. Il doit être indiqué si les mesures sont réalisées côté éolienne ou côté réseau du transformateur.

7.2 Vitesse du vent

7.2.1 Généralités

La vitesse du vent mesurée à la hauteur du moyeu (HH, *Hub Height*) seulement correspond à la définition par défaut de la vitesse du vent et doit toujours être utilisée. Elle peut être

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9 Ces incertitudes ont été déduites à partir d'une analyse WAsP (*Wind Atlas Analysis and Application Program, DTU Wind Energy*) d'une courbe gaussienne satisfaisant aux exigences de terrain de l'Annexe B.

10 Dans les autres cas, une plage plus élevée peut se révéler nécessaire. Ce fait doit être vérifié au cas par cas.

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considérée comme le cas limite de la vitesse du vent équivalente du rotor lorsqu'il n'y a qu'une hauteur de mesure et qu'il existe une incertitude supplémentaire due à l'absence de mesures du cisaillement du vent ou du profil de déviation de la trajectoire du vent (voir E.11.2.2). Il est recommandé de compléter la mesure de la vitesse du vent à la hauteur du moyeu par des mesures du cisaillement du vent dans la moitié inférieure du rotor afin de réduire l'incertitude liée à la vitesse du vent. Pour réduire davantage l'incertitude liée à la vitesse du vent, il convient d'utiliser la vitesse du vent équivalente du rotor (REWS) (voir 9.1.3.2 et Annexe Q) comme variable d'entrée pour la vitesse du vent sur la courbe de puissance.

Les configurations de mesure de la vitesse du vent sont répertoriées au Tableau 2, qui tient compte des limites propres à chaque technologie de mesure en fonction de la classe de complexité du terrain. Les dispositifs de télédétection qui prennent pour hypothèse que le volume analysé présente un écoulement horizontal uniforme limitent l'application de ces technologies à des conditions de terrain non complexe pour les essais de performance de puissance. Ainsi, seules les configurations du Tableau 2 doivent être appliquées.

Tableau 2 – Configurations de mesure de la vitesse du vent (X indique une configuration admissible)

Mesure de la vitesse du vent	HH	HH	REWS	REWS
Type de terrain	**Non complexe**	**Complexe**	**Non complexe**	**Complexe**
Mât météorologique à la hauteur du moyeu	X	X		
Mât météorologique à la hauteur du moyeu + RSD	X	X	X	
RSD + mât météorologique à une hauteur différente de celle du moyeu	X		X	
Mât météorologique couvrant des hauteurs supérieures à la hauteur du moyeu+ 2/3 R	X	X	X	X

Les différentes configurations de capteurs possibles comprennent les anémomètres montés en tête de mât météorologique, les anémomètres montés latéralement sur des mâts météorologiques et les dispositifs de télédétection. Ces instruments mesurent la vitesse du vent à la hauteur du moyeu, la vitesse du vent équivalente du rotor, ainsi que le profil de cisaillement du vent. Les Paragraphes 7.2.3 à 7.2.5 décrivent les exigences générales communes concernant les configurations d'anémomètres montés en tête de mât ou latéralement et les configurations de dispositifs de télédétection, tandis que les Paragraphes 7.2.6 à 7.2.8 décrivent les détails spécifiques à la réalisation des mesures à l'aide de ces configurations de capteurs.

7.2.2 Exigences générales concernant les anémomètres montés en tête de mât météorologique

Les exigences suivantes s'appliquent à toutes les applications des anémomètres à coupelles et à ultrasons décrites dans Paragraphes 7.2.3 à 7.2.8.

Le capteur doit satisfaire aux exigences de l'Annexe I concernant les anémomètres à coupelles et à ultrasons. Pour les mesures de performance de puissance, un anémomètre de classe 1,7A ou 1,7C au moins doit être utilisé. En outre, sur un terrain qui exige un étalonnage du site, un anémomètre de classe supérieure à 2,5B, 2,5D ou 1,7S doit être utilisé. Voir Annexe I et Annexe J.

L'anémomètre doit être étalonné au préalable et, si cela est exigé, être à nouveau étalonné après la campagne de mesure (post-étalonnage). Il est obligatoire de vérifier et de documenter que l'étalonnage de l'anémomètre demeure valide tout au long de la période de

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mesure. Cela peut être effectué en comparant les résultats de l'étalonnage initial aux résultats du post-étalonnage. A défaut, la comparaison des anémomètres in situ selon l'Annexe K est admise.

Lors de la réalisation d'un post-étalonnage, la différence entre les droites de régression d'étalonnage et de post-étalonnage doit être de l'ordre de ± 0,1 m/s dans la plage de valeurs de 4 m/s à 12 m/s. Seul l'étalonnage effectué avant la campagne de mesure doit être utilisé pour l'essai de performance. L'étalonnage de l'anémomètre doit être réalisé conformément à la procédure donnée à l'Annexe F. Si la différence maximale entre les droites de régression d'étalonnage et de post-étalonnage n'est pas de l'ordre de ± 0,1 m/s dans la plage de valeurs de 4 m/s à 12 m/s, l'incertitude-type de l'étalonnage de l'anémomètre $u_{VS,precal,i}$ doit être augmentée (au moins à sa différence maximale, mais sans dépasser ± 0,2 m/s). Si la différence est supérieure à ± 0,2 m/s, la comparaison des anémomètres in situ selon l'Annexe K doit être utilisée pour identifier le moment auquel s'est produit l'écart dans les données, et les données erronées qui s'ensuivent doivent être rejetées. Si l'essai in situ ne peut pas à déterminer le moment auquel a commencé l'écart, la différence de post-étalonnage est ajoutée en tant qu'incertitude.

En guise d'alternative, la procédure d'étalonnage in situ donnée à l'Annexe K doit être utilisée pour vérifier l'intégrité de l'anémomètre tout au long de la période de mesure. Lors de cette procédure, un anémomètre de commande est utilisé pour surveiller l'anémomètre primaire. Lorsqu'un anémomètre à coupelles est utilisé comme anémomètre primaire, un anémomètre à coupelles ou à ultrasons peut être utilisé comme anémomètre de commande. Lorsqu'un anémomètre à ultrasons est utilisé comme anémomètre primaire, l'anémomètre de commande doit être un anémomètre à coupelles. Dans le cas où une courbe de puissance déduite de la REWS est obtenue à partir de mesures réalisées sur un mât météorologique à une hauteur supérieure à celle du moyeu, un anémomètre primaire monté latéralement doit être installé sur le mât à la hauteur du moyeu, avec un anémomètre de commande associé satisfaisant aux exigences de montage de l'Annexe G.

L'incertitude de mesure de la vitesse du vent est déduite à partir de plusieurs sources d'incertitude spécifiées au Tableau D. L'incertitude d'étalonnage doit être déduite à partir de l'Annexe F. L'incertitude due aux caractéristiques d'exploitation doit être déduite selon l'Annexe I consacrée à la classification de l'anémométrie. L'incertitude due aux effets de montage doit être déterminée selon l'Annexe G.

7.2.3 Anémomètres montés en tête de mât

Pour mesurer la vitesse du vent à l'aide d'un anémomètre monté en tête de mât, les exigences de montage données à l'Annexe G doivent être respectées. La hauteur d'installation du capteur au-dessus du niveau du sol[11] doit être vérifiée par mesure. La méthode de mesure et son incertitude-type doivent être documentées[12]. L'incertitude-type de la mesure de la hauteur du capteur de vitesse du vent au-dessus du niveau estimé du sol doit être inférieure ou égale à 0,2 m. L'anémomètre de commande doit être monté conformément aux exigences données à l'Annexe G.

7.2.4 Anémomètres montés latéralement

Le montage doit satisfaire à l'exigence relative aux anémomètres montés latéralement selon l'Annexe G. La hauteur installée des anémomètres montés latéralement au-dessus du niveau du sol (voir note de bas de page 11) doit être vérifiée par mesure. La méthode de mesure et

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[11] Afin de déterminer le niveau du sol, une estimation de l'altitude moyenne peut être réalisée sur un rayon de 2 m autour de la base du mât ou sur un rayon de 5 m autour de la base de l'éolienne. Il convient que l'incertitude de mesure de la hauteur du capteur exclue l'incertitude de l'estimation du niveau du sol. En mer, il convient de considérer que le niveau du sol équivaut au niveau moyen de la mer.

[12] La mesure peut être réalisée à l'aide d'un dispositif de mesure avec un étalonnage traçable, comme un théodolite capable de déduire des hauteurs à partir d'une mesure d'angle sur le plan vertical.

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son incertitude doivent être documentées. L'incertitude-type de mesure de la hauteur doit être inférieure ou égale à 0,2 m.

La correction des anémomètres montés latéralement pour la distorsion de l'écoulement au niveau du mât météorologique est admise et décrite plus en détail en 9.1.2 et à l'Annexe S. Les fondements techniques et l'effet de la correction doivent être documentés. Les flèches doivent toutes avoir la même orientation afin de garantir une distorsion de l'écoulement similaire entre les différentes hauteurs. Il convient que la conception du mât météorologique et celle de la flèche présentent le même effet de distorsion de l'écoulement au niveau du capteur avec une différence maximale admise de distorsion de la vitesse du vent de 1 % entre les différentes hauteurs. Il convient que les dimensions de la section transversale du mât météorologique soient cohérentes pour chaque altitude. En cas de mâts météorologiques autoporteurs pour lesquels la surface de la section transversale est plus large aux altitudes inférieures, il convient de porter une attention particulière à l'application des recommandations données à l'Annexe G. Une autre option consiste à monter un deuxième anémomètre à chaque hauteur de mesure sur une flèche distincte et à limiter le secteur de mesure de telle sorte que les mesures de la vitesse du vent présentent un écart inférieur ou égal à 1 %.

7.2.5 Dispositif de télédétection (RSD)

Les dispositifs de télédétection qui prennent pour hypothèse que le volume analysé présente un écoulement horizontal uniforme limitent l'application de ces technologies à des conditions de terrain non complexe pour les essais de performance de puissance, comme décrit dans l'Annexe B. Le dispositif de télédétection doit être vérifié avant la campagne de mesure ou in situ, conformément à l'Article L.3. Le dispositif de télédétection peut être utilisé pour mesurer la vitesse du vent à la hauteur du moyeu, le profil de cisaillement du vent, la déviation de la trajectoire du vent et/ou la vitesse du vent équivalente du rotor en procédant à des mesures à plusieurs hauteurs (voir 7.2.8). Dans tous les cas, le dispositif de télédétection doit être comparé parallèlement à un anémomètre monté en tête de mât météorologique à une hauteur supérieure ou égale à la hauteur minimale de l'extrémité inférieure du rotor de l'éolienne ou à une hauteur de 40 m (voir Article L.1). Les exigences relatives aux anémomètres montés en tête de mât sont identiques à celles décrites en 7.2.3.

L'incertitude des mesures de la vitesse du vent des RSD doit être déduite selon l'Annexe L.

7.2.6 Mesure de la vitesse du vent équivalente du rotor

Si la vitesse du vent est mesurée à trois hauteurs ou plus sur le rotor de l'éolienne (voir 7.2.8), la vitesse du vent équivalente du rotor peut être calculée comme indiqué en 9.1.3. Il est à noter qu'il est recommandé d' utiliser plus de trois hauteurs de mesure. Les trois méthodes de mesure de la vitesse du vent équivalente du rotor sont décrites ci-dessous:

a) Lorsqu'un anémomètre monté en tête de mât à la hauteur du moyeu satisfaisant aux exigences de 7.2.3 est utilisé en conjonction avec un RSD satisfaisant aux exigences de 7.2.5 et que le terrain satisfait aux exigences de l'Annexe B, les mesures de l'anémomètre et du RSD à la hauteur du moyeu sont combinées afin de déterminer la vitesse du vent équivalente du rotor selon 9.1.3.

b) Lorsqu'un anémomètre monté à une hauteur différente de celle du moyeu, mais satisfaisant aux exigences relatives aux anémomètres montés en tête de mât de 7.2.3, est utilisé en conjonction avec un RSD satisfaisant aux exigences de 7.2.5 et que le terrain satisfait aux exigences de l'Annexe B, les mesures du RSD sont utilisées directement afin de déterminer la vitesse du vent équivalente du rotor selon 9.1.3.

c) Lorsqu'un mât météorologique situé à une hauteur supérieure à celle du moyeu est utilisé en conjonction avec des anémomètres montés latéralement répartis sur la hauteur du rotor, l'un d'eux se situant à la hauteur du moyeu, les mesures de la vitesse du vent des anémomètres montés latéralement peuvent être utilisées directement afin de mesurer la vitesse du vent équivalente du rotor selon 9.1.3.

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7.2.7 Mesure de la vitesse du vent à la hauteur du moyeu

Les trois méthodes de mesure de la vitesse du vent à la hauteur du moyeu sont décrites ci-dessous:

a) Lorsqu'un mât météorologique situé à la hauteur du moyeu est utilisé, les mesures de la vitesse du vent à la hauteur du moyeu doivent satisfaire aux exigences décrites en 7.2.3.

b) Si le terrain satisfait aux exigences de l'Annexe B, la vitesse du vent à la hauteur du moyeu peut être mesurée à l'aide d'un RSD satisfaisant aux exigences de 7.2.5, en particulier à l'exigence visant à comparer simultanément le RSD à un anémomètre monté en tête de mât.

c) Un mât météorologique situé à une hauteur supérieure à celle du moyeu peut être utilisé afin de mieux capturer les vitesses du vent sur la surface du rotor. Dans ce cas, la vitesse du vent à la hauteur du moyeu doit être mesurée à l'aide d'un capteur monté latéralement sur une flèche satisfaisant aux exigences décrites en 7.2.4.

Pour la définition de la vitesse du vent à la hauteur du moyeu, le fait que le cisaillement du vent vertical ou la déviation de la trajectoire du vent sur le rotor de l'éolienne ne sont pas connus doit être pris en compte en ajoutant un terme d'incertitude conformément à l'Annexe E, basé sur les estimations ou les mesures du cisaillement du vent ou de la déviation de la trajectoire du vent. Lorsque seule une mesure de la vitesse du vent à la hauteur du moyeu est disponible, une estimation du cisaillement du vent ou de la déviation de la trajectoire du vent en fonction des caractéristiques du site (p. ex.: rugosité), d'une mesure antérieure ou d'une modélisation du site (p. ex.: lors d'une campagne d'évaluation des ressources) doit être utilisée comme entrée pour l'analyse d'incertitude. Lorsque la vitesse du vent à la hauteur du moyeu est déterminée à l'aide d'un RSD ou d'un mât météorologique situé à une hauteur supérieure à celle du moyeu et équipé d'instruments de mesure montés latéralement sur le rotor, ou lorsque des instruments montés latéralement à une hauteur inférieure à celle du moyeu et satisfaisant aux exigences minimales décrites en 7.2.8 sont utilisés, le cisaillement du vent ou la déviation de la trajectoire du vent déduits à l'aide du RSD ou des instruments montés latéralement doivent être utilisés comme valeur d'entrée pour l'évaluation de l'incertitude.

7.2.8 Mesures du cisaillement du vent

Lorsque des mesures de la vitesse du vent sont disponibles sur une plage de hauteurs, le cisaillement du vent doit être mesuré et utilisé pour la détermination de la vitesse du vent équivalente du rotor ou de l'exposant de cisaillement du vent.

Les mesures du cisaillement du vent doivent être réalisées en utilisant soit des anémomètres montés latéralement (voir 7.2.4), soit un instrument de télédétection seul (voir 7.2.5). Des spécifications supplémentaires pour la mesure du cisaillement du vent à l'aide d'instruments de télédétection ou pour les mesures à l'aide de mâts météorologiques sont respectivement données à l'Annexe L et à l'Annexe G.

La mesure de la vitesse du vent équivalente du rotor doit inclure les mesures de la vitesse du vent à une hauteur supérieure à celle du moyeu. Pour appliquer une correction du cisaillement du vent fondée sur une mesure, au moins trois mesures de la vitesse du vent réparties sur la surface balayée par le rotor doivent être réalisées. Cependant, afin de réduire le plus possible l'incertitude de la vitesse du vent, il est recommandé de prévoir le plus grand nombre possible de hauteurs de mesure. Il convient de répartir les hauteurs de mesure de manière symétrique autour de la hauteur du moyeu et de façon régulière sur la plage verticale de la surface balayée par le rotor.

Les hauteurs de mesure doivent inclure au moins les hauteurs suivantes:

a) hauteur du moyeu ± 1,0 %;

b) hauteur entre $H - R$ et $H - 2/3R$;

c) hauteur entre $H + 2/3R$ et $H + R$,

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où H est la hauteur du moyeu de l'éolienne et R le rayon de la surface balayée par le rotor (voir Figure 2).

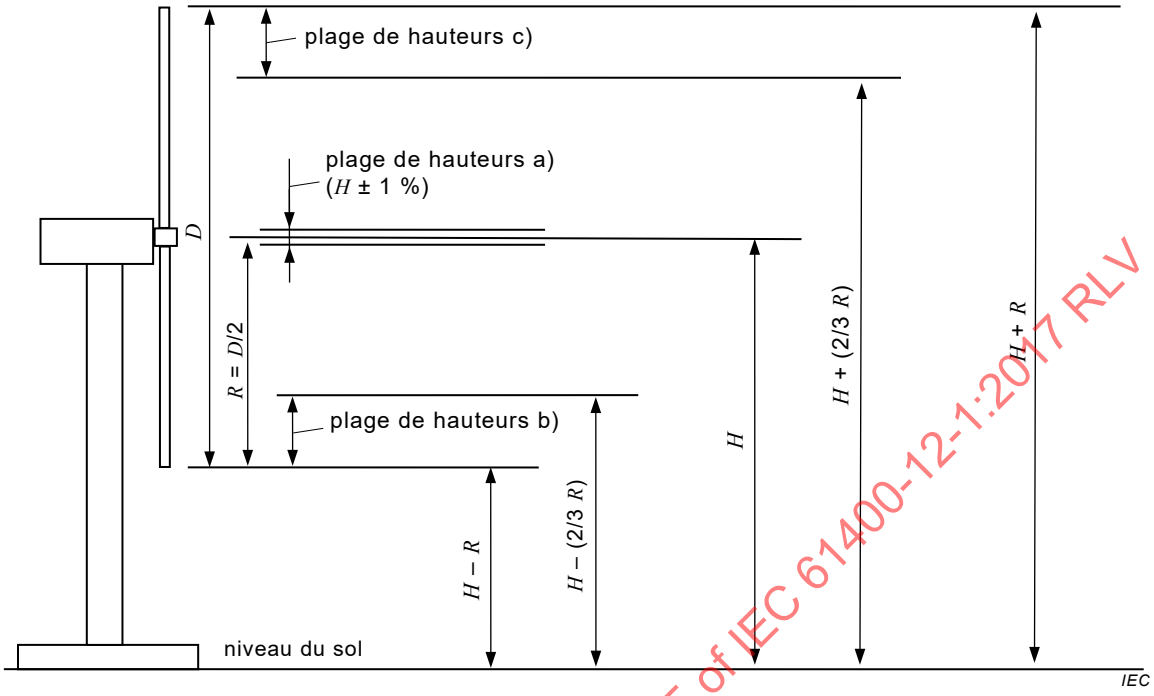

Figure 2 – Hauteurs de mesure du cisaillement du vent appropriées pour la mesure de la vitesse du vent équivalente du rotor

Si le mât météorologique se situe à la hauteur du moyeu ou légèrement au-dessus, aucune mesure de la vitesse du vent à une hauteur supérieure à celle du moyeu ne peut être disponible pour la mesure du cisaillement du vent. Dans ce cas, les mesures utilisées pour déduire le cisaillement du vent doivent inclure au moins les hauteurs suivantes:

a) un anémomètre monté latéralement le plus proche possible de la hauteur du moyeu satisfaisant aux exigences de l'Annexe G concernant la distance de séparation par rapport à l'anémomètre monté en tête de mât;

b) la distance entre $H - R$ et $H - 2/3R$ satisfaisant aux exigences de l'Annexe G concernant les anémomètres montés latéralement.

où H est la hauteur du moyeu de l'éolienne et R le rayon de la surface balayée par le rotor (voir Figure 3).

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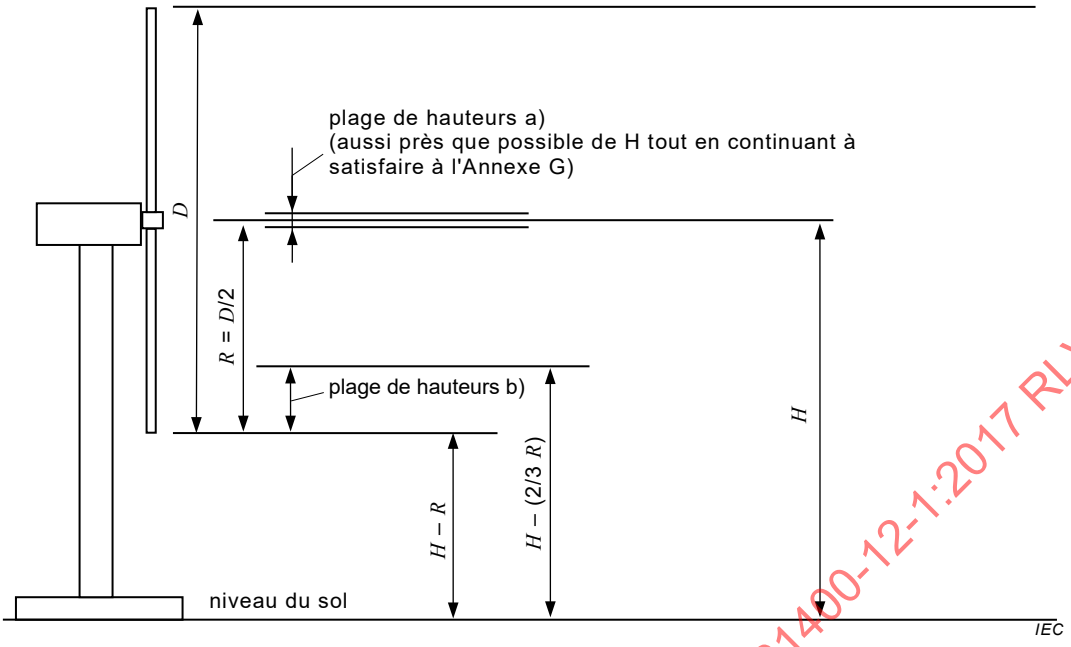

Figure 3 – Hauteurs de mesure du cisaillement du vent lorsqu'aucune mesure de la vitesse du vent à une hauteur supérieure à celle du moyeu n'est disponible (uniquement pour la détermination de l'exposant de cisaillement du vent)

7.3 Direction du vent

Les mesures de la direction du vent sont utilisées comme entrée pour l'étalonnage du site, le filtrage des données vers le secteur de direction valide et la détermination de la déviation de la trajectoire du vent. La direction du vent doit être mesurée à l'aide d'un capteur de direction du vent. Il peut s'agir d'une girouette, d'un anémomètre à ultrasons 2D ou 3D, ou d'un RSD. Un anémomètre à ultrasons doit être utilisé en conjonction avec une girouette conventionnelle, à des fins de contrôle. Si un RSD est utilisé, il convient de le soumettre à un essai de vérification de la direction du vent selon l'Annexe L.

La direction horizontale instantanée du vent doit être déterminée et moyennée sur une période de 10 min. Le moyennage vectoriel (moyennage des composantes cosinus et sinus des valeurs de directions instantanées du vent en prenant l'arc tangent des valeurs moyennes et ajusté à l'échelle allant de 0° à 360°) est une méthode permettant de déduire la direction moyenne du vent. Une autre méthode consiste à élargir l'échelle de direction du vent à des valeurs supérieures à 360° et à calculer la moyenne sur une période de 10 min, puis à ajuster la valeur moyenne à la plage allant de 0° à 360°. Les données mesurées dans la zone morte d'une girouette, correspondant en règle générale à l'indicateur du nord du corps du capteur de direction du vent, ne sont pas définies (circuit ouvert ou court-circuit) et doivent être exclues. L'incertitude-type composée sur l'étalonnage, l'exploitation et l'orientation pour la mesure de la direction du vent doit être inférieure à 5°. Le capteur de direction du vent doit être étalonné. L'Annexe N fournit des lignes directrices à ce sujet.

7.4 Masse volumique de l'air

La masse volumique de l'air doit être déduite à partir de la mesure de la température de l'air, de la pression atmosphérique et de l'humidité relative. A défaut d'une mesure de l'humidité, il est admis d'appliquer une valeur hypothétique de 50 % d'humidité relative. La masse volumique de l'air doit être calculée à l'aide de l'Equation (12) donnée en 9.1.5.

Le capteur de température de l'air doit être monté dans un rayon de 10 m de la hauteur du moyeu afin de représenter la température de l'air au niveau de l'axe central du rotor de l'éolienne. L'Annexe G définit les exigences de montage du capteur de température lorsqu'un mât météorologique dont la hauteur est inférieure à celle du moyeu est utilisé.

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Il convient de monter le capteur de pression atmosphérique dans un rayon de 10 m de la hauteur du moyeu afin de représenter la pression atmosphérique au niveau de l'axe central du rotor de l'éolienne. Les mesures de la pression atmosphérique doivent toujours être corrigées à la hauteur du moyeu appropriée, conformément à l'ISO 2533.

Il convient de monter le capteur d'humidité dans un rayon de 10 m de la hauteur du moyeu afin de représenter l'humidité au niveau de l'axe central du rotor de l'éolienne.

7.5 Vitesse de rotation et angle de pas

Il convient de mesurer la vitesse de rotation et l'angle de pas tout au long de l'essai si nécessaire, par exemple si les mesures doivent être appliquées en association avec des essais de bruit acoustique. Si ces valeurs sont mesurées, les mesures doivent être consignées conformément à l'Article 10.

7.6 Condition des pales

La condition des pales peut influencer la courbe de puissance, plus particulièrement dans le cas des éoliennes à régulation par décrochage. Il peut être utile de comprendre les caractéristiques de l'éolienne afin de surveiller les facteurs qui affectent la condition des pales, notamment les précipitations, le givrage et l'accumulation d'insectes et de boue.

7.7 Système de contrôle de l'éolienne

Des signaux d'état en nombre suffisant doivent être identifiés, vérifiés et surveillés afin de pouvoir appliquer les critères de rejet donnés en 8.4. Ces paramètres peuvent être obtenus à partir du système d'acquisition de données du système de contrôle de l'éolienne[13]. La définition de chaque signal d'état doit être consignée.

7.8 Système d'acquisition de données

Un système numérique d'acquisition de données ayant une fréquence d'échantillonnage par canal d'au moins 1 Hz doit être utilisé pour recueillir les mesures et stocker les données échantillonnées ou les statistiques relatives aux ensembles de données décrits en 8.3.

L'étalonnage et la précision de la chaîne du système d'acquisition de données (transmission, conditionnement du signal et enregistrement des données) doivent être vérifiés en injectant des signaux connus à partir d'une source traçable et étalonnée aux extrémités des transducteurs et en comparant ces entrées aux valeurs enregistrées. A titre de ligne directrice, il convient que l'incertitude du système d'acquisition de données soit négligeable par rapport à l'incertitude des capteurs.

8 Procédure de mesure

8.1 Généralités

L'objectif de la procédure de mesure est de collecter des données qui satisfont à un ensemble de critères clairement définis pour s'assurer que la quantité et la qualité des données suffisent pour déterminer avec précision les caractéristiques de performance de puissance de l'éolienne. La procédure de mesure doit être documentée, comme décrit à l'Article 10, de façon à ce que chaque étape du mode opératoire et chaque condition d'essai puisse être révisée et, si nécessaire, répétée.

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13 Un signal d'état de démarrage du générateur peut être utilisé pour vérifier l'hystérésis de la coupure dans l'algorithme de contrôle.

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La précision des mesures doit être exprimée en termes d'incertitude-type, comme décrit à l'Annexe D. Pendant la période de mesure, il convient de valider régulièrement les données pour garantir une haute qualité. Des journaux d'essai doivent être tenus à jour afin de documenter tous les événements importants pendant l'essai de performance de puissance.

8.2 Exploitation de l'éolienne

Pendant la période de mesure, l'éolienne doit être en fonctionnement normal conformément aux prescriptions du manuel d'exploitation de l'éolienne et la configuration de la machine ne doit pas être modifiée. L'état d'exploitation de l'éolienne doit être consigné comme décrit à l'Article 10. Une maintenance normale de l'éolienne doit être assurée tout au long de la période de mesure, mais ces travaux doivent être notés dans le journal d'essai. En particulier, toutes les actions de maintenance spéciale (par exemple, un lavage fréquent des pales) destinées à garantir une bonne performance pendant l'essai doivent être consignées. Il convient d'éviter de procéder à de telles actions de maintenance spéciale.

8.3 Collecte des données

Les données doivent être collectées en continu à une fréquence d'échantillonnage de 1 Hz ou plus. La température de l'air, la pression atmosphérique, l'humidité et les précipitations, si ces caractéristiques sont mesurées, peuvent être échantillonnées moins souvent, mais au moins une fois par minute.

Le système d'acquisition de données doit stocker les données échantillonnées ou bien les statistiques relatives aux ensembles de données comme suit:

a) la valeur moyenne;

b) l'écart-type;

c) la valeur maximale;

d) la valeur minimale.

Les ensembles de données choisis doivent être basés sur des périodes de 10 min déduites à partir de données mesurées de façon continue. Les données doivent être collectées jusqu'à ce que les exigences définies en 8.5 soient satisfaites.

8.4 Rejet des données

Pour s'assurer que seules les données obtenues lors de l'exploitation normale de l'éolienne sont utilisées pour l'analyse, mais aussi que les données ne sont pas corrompues, les ensembles de données doivent être exclus de la base de données dans les situations suivantes:

a) les conditions externes autres que la vitesse du vent sont en dehors de la plage de fonctionnement de l'éolienne;

b) l'éolienne ne peut pas fonctionner en raison d'un état de défaut;

c) l'éolienne est arrêtée manuellement ou dans un mode d'exploitation d'essai ou de maintenance;

d) le matériel de mesure est défaillant ou dégradé (par exemple, à cause du givrage);

e) la direction du vent est en dehors du ou des secteurs de mesure définis en 6.3.3;

f) les directions du vent sont en dehors des secteurs valides (complets) d'étalonnage du site;

g) toute condition atmosphérique particulière filtrée pendant l'étalonnage du site doit l'être également pendant l'essai de courbe de puissance.

Tout autre critère de rejet doit être clairement consigné.

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L'effet sur la courbe de puissance d'une large boucle d'hystérésis dans l'algorithme de contrôle de coupure peut être considérable. Cet effet ne doit pas être inclus dans la courbe de puissance. Quant à tous les ensembles de données correspondant au moment où l'éolienne a arrêté de produire de la puissance en raison d'une coupure due à une vitesse élevée du vent, ils doivent être exclus. Si le comportement de coupure a été atteint pendant la période de mesure, les mesures peuvent être présentées dans une base de données spéciale contenant tous les points de données de la base de données. La courbe de puissance doit refléter l'effet de l'hystérésis dans l'algorithme de contrôle du démarrage, mais aussi l'effet des pertes parasites en dessous de la vitesse de démarrage. L'hystérésis de coupure affecte les tranches de vitesse du vent les plus élevées; le fait de l'ignorer peut donc conduire à une surestimation de la production d'énergie, en particulier dans des scénarios présentant des vitesses de vent annuelles plus élevées.

Des sous-ensembles de la base de données collectés dans des conditions d'exploitation particulières (par exemple, forte rugosité des pales due à la poussière, sel, insectes, givrage ou si les conditions de raccordement varient de manière considérable) ou des conditions atmosphériques particulières (par exemple, précipitations, cisaillement du vent) qui se produisent pendant la période de mesure peuvent être choisis comme bases de données spéciales.

8.5 Base de données

Après normalisation des données (voir 9.1), les ensembles de données choisis doivent être triés selon la procédure de la "méthode des tranches" (voir 9.2). La plage de vitesses du vent doit être divisée en tranches contiguës de 0,5 m/s, centrées sur des multiples de 0,5 m/s. Les ensembles de données choisis doivent au moins couvrir une plage de vitesses du vent comprise entre 1 m/s en dessous de la vitesse de démarrage et 1,5 fois la vitesse du vent à 85 % de la puissance assignée de l'éolienne. A défaut, la plage de vitesses du vent doit s'étendre entre 1 m/s en dessous de la vitesse de démarrage et la vitesse du vent à laquelle l'"AEP mesurée" est supérieure ou égale à 95 % de l'"AEP extrapolée" (voir 9.3), l'"AEP mesurée" et l'"AEP extrapolée" étant déterminées sur la base des définitions cohérentes appropriées de la vitesse du vent (c'est-à-dire, la distribution des vitesses du vent et la courbe de puissance déduite à partir de la vitesse du vent à la hauteur du moyeu, ainsi que, lorsque la REWS est déduite, la distribution des vitesses du vent et la courbe de puissance déduite à partir de la REWS). Pour les éoliennes avec contrôle de pas actif, la courbe de puissance peut être considérée comme complète lorsque la puissance assignée a été atteinte, que la puissance moyenne ne varie pas de plus de 0,5 % de la puissance ou de 5 kW (la valeur retenue étant la plus élevée des deux) pendant trois tranches consécutives de vitesse du vent, et que la puissance ne tend pas à augmenter sur la moyenne de ces trois tranches. Le rapport doit indiquer lequel des trois critères de plage de vitesses du vent a été utilisé.

La base de données doit être considérée comme complète lorsqu'elle satisfait aux critères suivants:

a) chaque tranche comporte un minimum de 30 min de données échantillonnées;

b) la base de données comporte un minimum de 180 h de données échantillonnées.

Dans l'éventualité où une tranche incomplète empêcherait l'achèvement de l'essai, cette valeur de tranche peut être estimée par interpolation linéaire à partir des deux tranches complètes adjacentes.

La base de données doit être présentée dans le rapport d'essai décrit à l'Article 10.

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9 Résultats déduits

9.1 Normalisation des données

9.1.1 Généralités

Dans les paragraphes suivants, trois méthodes de normalisation sont décrites pour les principaux facteurs atmosphériques influençant les résultats de la courbe de puissance: la masse volumique de l'air, le cisaillement du vent et l'intensité des turbulences.

L'objectif de ces normalisations est d'améliorer la précision des résultats au moyen de formulations concrètes pour chaque variable. Cela permettra dans une certaine mesure de comparer les résultats de différents ensembles de données sur une échelle similaire.

Il convient d'appliquer les différentes normalisations conformément à l'organigramme de la Figure 4.

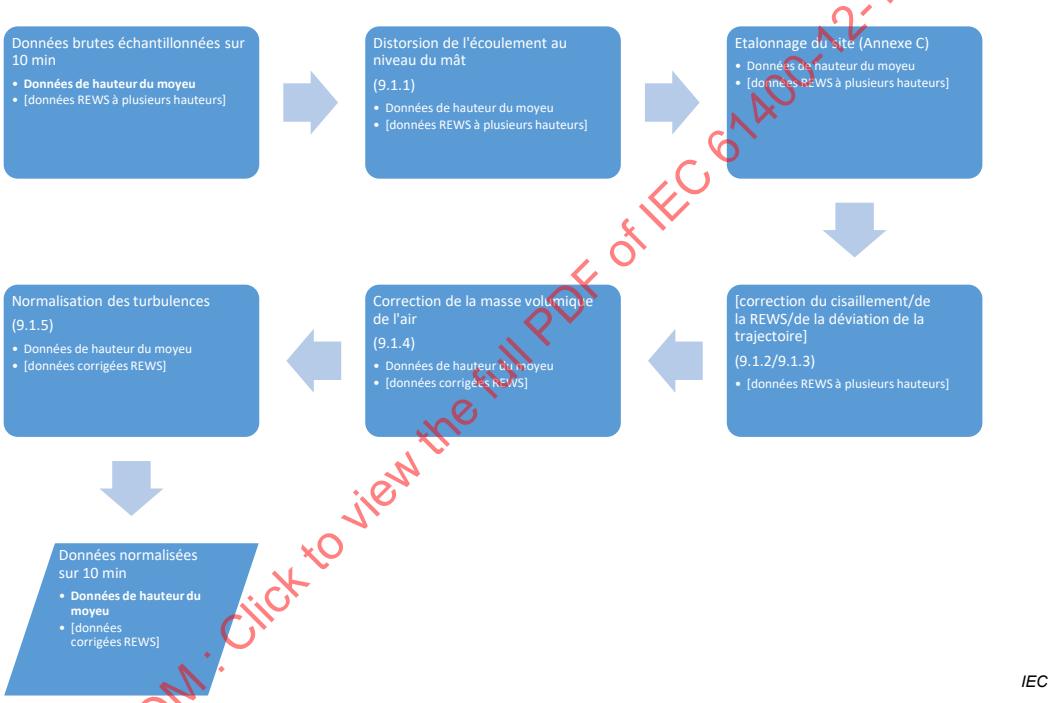

Figure 4 – Processus d'application des différentes normalisations [14]

9.1.2 Correction de la distorsion de l'écoulement au niveau du mât météorologique par les anémomètres montés latéralement

Concernant la distorsion de l'écoulement au niveau du mât météorologique, une correction des vitesses du vent par les anémomètres montés latéralement est admise (l'exigence de l'Annexe G pour un maximum de 1 % de distorsion de l'écoulement du mât météorologique avant application de la correction étant toujours valable). Toute méthode de correction doit être documentée et consignée conformément aux exigences de l'Article 10.

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14 Lorsque les mesures facultatives de la REWS sont disponibles, les données de REWS suivent une trajectoire de normalisation parallèle aux normalisations des données de hauteur du moyeu par défaut, représentées par les termes entre crochets. La normalisation des données REWS est réalisée séparément à chaque hauteur de mesure pour toutes les étapes de normalisation, jusqu'à l'étape à laquelle les résultats de chaque hauteur sont combinés dans la correction du cisaillement/de la REWS/de la déviation de la trajectoire. Une seule valeur corrigée de REWS est déduite pour chaque point de données de 10 min à chaque étape suivante, parallèlement aux corrections appliquées à chaque point de données de hauteur du moyeu.

L'impact de la distorsion de l'écoulement au niveau du mât météorologique sur la mesure du cisaillement du vent peut être diminué le plus possible en réduisant le secteur de mesure lorsque le niveau de distorsion de l'écoulement au niveau du mât météorologique est inférieur à une limite donnée. Les fondements techniques d'une telle réduction de la largeur du secteur doivent être documentés. L'Annexe S donne une méthode possible de détermination de la distorsion de l'écoulement pour un mât en treillis.

9.1.3 Correction du cisaillement du vent (lorsque des mesures de REWS sont disponibles)

9.1.3.1 Généralités

Si la vitesse du vent sur la surface du rotor de l'éolienne est constante, la vitesse du vent à la hauteur du moyeu sera représentative de la vitesse du vent sur le rotor de l'éolienne et l'utilisation de la vitesse du vent à la hauteur du moyeu sera justifiée. Néanmoins, l'hypothèse selon laquelle la vitesse du vent en un point (par exemple à la hauteur du moyeu) représente la vitesse du vent sur la surface du rotor de l'éolienne peut ne pas être représentative pour les grandes éoliennes. C'est pourquoi il est nécessaire d'introduire des corrections pour tenir compte de la vitesse du vent à la hauteur du moyeu, ainsi que des variations introduites par le cisaillement du vent sur le rotor de l'éolienne. Trois grandeurs sont définies ci-dessous:

a) la vitesse du vent équivalente du rotor;

b) le facteur de correction du cisaillement du vent;

c) la vitesse du vent corrigée du cisaillement du vent.

Le facteur de correction du cisaillement du vent peut être utilisé pour déduire une courbe de puissance spécifique à un climat, comme décrit à l'Annexe P. Cette correction est toutefois fondée sur l'hypothèse qu'une éolienne est capable de convertir toute l'énergie cinétique disponible.

9.1.3.2 Vitesse du vent équivalente du rotor

La vitesse du vent équivalente du rotor est la vitesse du vent correspondant au flux d'énergie cinétique qui traverse la surface balayée par le rotor, en tenant compte du cisaillement du vent vertical. Lorsque la vitesse du vent est disponible pour au moins trois hauteurs de mesure (voir 7.2.6), la vitesse du vent équivalente du rotor est définie comme suit:

$$v_{\mathrm{eq}} = \left(\sum_{i=1}^{n_{\mathrm{h}}} v_i^3 \frac{A_i}{A} \right)^{1/3} \tag{5}$$

où

n_{h} est le nombre de hauteurs de mesure disponibles ($n_{\mathrm{h}} \geq 3$);

v_i est la vitesse du vent mesurée à la hauteur i;

A est la surface totale balayée par le rotor (c'est-à-dire πR^2, R étant le rayon);

A_i est la surface du i^{e} segment, c'est-à-dire le segment pour lequel la vitesse du vent v_i est représentative, déduite à partir de l'Equation (6).

Les segments (avec les surfaces A_i) doivent être choisis de telle manière que la ligne de séparation horizontale entre deux segments se trouve au milieu des deux points de mesure. Les surfaces de segments sont ensuite déduites à l'aide de l'Equation (6):

$$A_i = \int_{z_i}^{z_{i+1}} c(z)\mathrm{d}z = g(z_{i+1}) - g(z_i) \tag{6}$$

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où

z_i est la hauteur de la i^e ligne de séparation de segment ($H–R<z_i<H+R$), numérotée dans le même ordre que v_i (de haut en bas ou de bas en haut).

La largeur du rotor à la hauteur z est:

$$\ell(z) = 2\sqrt{R^2 - (z-H)^2} \tag{7}$$

où

R est le rayon du rotor;

H est la hauteur du moyeu.

La fonction intégrée est:

$$g(z) = (z-H)\sqrt{R^2-(z-H)^2} + R^2 \arctan\left(\frac{z-H}{\sqrt{R^2-(z-H)^2}}\right) \tag{8}$$

Exemple de calcul REWS pour un profil de vitesse du vent sur 10 min

Cet exemple prend pour hypothèse une éolienne présentant une hauteur du moyeu de 80 m et un diamètre de rotor de 100 m. La vitesse du vent a été mesurée à 5 hauteurs à l'aide d'un mât météorologique. Si les hauteurs avaient pu être choisies, elles auraient été idéalement réparties de façon régulière (40 m, 60 m, 80 m, 100 m et 120 m). Cet exemple représente un cas dans lequel les hauteurs ont été déterminées indépendamment de l'objectif d'évaluation de la REWS. Les limites du segment ont été définies au milieu de deux mesures consécutives. La REWS obtenue est égale à 9,38 m/s (voir Tableau 3).

Tableau 3 – Exemple de calcul de REWS

Hauteurs de mesure [m]	Vitesse du vent [m/s]	Pondération du segment * [%]	Hauteur limite inférieure du segment (z_i) [m]	Hauteur limite supérieure du segment (z_{i+1}) [m]	Hauteur du segment [m]
116	11,46	16,31	108	130	22
100	10,43	21,04	90	108	18
80	9,24	25,29	70	90	20
60	7,81	23,12	50	70	20
40	6,05	14,24	30	50	20

* La pondération du segment est définie comme le rapport entre la surface du segment et la surface totale balayée par le rotor.

9.1.3.3 Facteur de correction du cisaillement du vent

9.1.3.3.1 Cas 1: Mât météorologique à hauteur du moyeu avec dispositif de télédétection ou dispositif de télédétection avec mât météorologique court (hauteur inférieure à celle du moyeu)

Un facteur de correction du cisaillement du vent mesuré à l'aide d'un dispositif de télédétection est défini comme le rapport de la vitesse du vent équivalente du rotor par rapport à la vitesse du vent mesurée à la hauteur du moyeu selon l'Equation (9):

$$f_{r,RSD} = v_{eq,RSD} / v_{h,RSD} \tag{9}$$

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où

$v_{eq,RSD}$ est la vitesse du vent équivalente du rotor mesurée à l'aide du dispositif de télédétection, selon l'Equation (5);

$v_{h,RSD}$ est la vitesse du vent mesurée à la hauteur du moyeu à l'aide du dispositif de télédétection.

9.1.3.3.2 Cas 2: Mât météorologique au-dessus de la hauteur du moyeu

Le facteur de correction du cisaillement du vent mesuré à l'aide d'un mât météorologique est défini comme le rapport de la vitesse du vent équivalente du rotor par rapport à la vitesse du vent mesurée à la hauteur du moyeu selon l'Equation (10)[15]:

$$f_{r,MM} = v_{eq,MM} / v_{h,MM} \tag{10}$$

où

$v_{eq,MM}$ est la vitesse du vent équivalente du rotor mesurée par les anémomètres sur le mât météorologique, selon l'Equation (5);

$v_{h,MM}$ est la vitesse du vent mesurée par l'anémomètre à la hauteur du moyeu.

9.1.3.4 Correction du cisaillement du vent

Si la vitesse du vent à la hauteur du moyeu et le cisaillement du vent sont mesurés à l'aide du même type de WME, la vitesse du vent équivalente du rotor est calculée selon l'Equation (5).

Si la vitesse du vent à la hauteur du moyeu est mesurée à l'aide d'un anémomètre monté sur un mât météorologique et que le cisaillement du vent est mesuré à l'aide d'un RSD, la vitesse du vent équivalente du rotor final est calculée selon l'Equation (11):

$$v_{eq,final} = f_{r,RSD} v_{h,MM} \tag{11}$$

9.1.4 Correction de la déviation de la trajectoire du vent

Comme expliqué à l'Annexe Q, le changement de direction du vent sur la plage de hauteurs du rotor (déviation de la trajectoire du vent) peut avoir un impact significatif sur la puissance de sortie de l'éolienne. Dans le cas des rotors de grandes éoliennes, il est recommandé d'appliquer la définition étendue de la vitesse du vent équivalente, en y incluant la déviation de la trajectoire du vent.

9.1.5 Normalisation de la masse volumique de l'air

La masse volumique de l'air doit être déterminée à partir de la mesure de la température de l'air, de la pression atmosphérique et de l'humidité relative, selon l'Equation (12):

$$\rho_{10min} = \frac{1}{T_{10min}} \left(\frac{B_{10min}}{R_0} - \Phi P_w \left(\frac{1}{R_0} - \frac{1}{R_w} \right) \right) \tag{12}$$

où

ρ_{10min} est la masse volumique de l'air moyennée déduite sur une période de 10 min;

T_{10min} est la température absolue de l'air moyennée sur une période de 10 min [K];

B_{10min} est la pression atmosphérique corrigée à la hauteur du moyeu moyennée sur une période de 10 min [Pa];

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[15] Il est à noter que $f_{r,MM}$ est utilisé aux fins du rapport seulement.

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R_0 est la constante des gaz pour l'air sec (287,05) [J/kgK];

Φ est l'humidité relative (plage de 0 % à 100 %);

R_w est la constante des gaz pour la vapeur d'eau (461,5) [J/kgK];

P_w est la pression de vapeur égale à 0,000 020 5 exp(0,0631 846 T_{10min}) [Pa];

La pression de vapeur P_w dépend de la température moyenne de l'air sur une période de 10 min.

Les ensembles de données choisis doivent être normalisés à au moins une masse volumique de l'air de référence. La masse volumique de l'air de référence doit correspondre à la moyenne de la masse volumique de l'air mesurée pour l'ensemble de données valide collecté sur le site pendant la période d'essai (voir 8.4) ou, à défaut, à une masse volumique de l'air nominale prédéfinie pour le site. La masse volumique de l'air moyenne mesurée doit être arrondie au 0,01 kg/m^3 le plus proche et être consignée conformément à l'Article 10.

Pour une éolienne à régulation par décrochage avec pas de pale constant et vitesse de rotation constante, la normalisation des données doit être appliquée à la puissance de sortie mesurée selon l'Equation (13):

$$P_n = P_{10min}\left(\frac{\rho_0}{\rho_{10min}}\right) \tag{13}$$

où

P_n est la puissance de sortie normalisée;

P_{10min} est la puissance moyennée sur une période de 10 min;

ρ_0 est la masse volumique de l'air de référence;

ρ_{10min} est la masse volumique de l'air déduite selon l'Equation (12) moyennée sur une période de 10 min.

Pour une éolienne avec contrôle de la puissance active, la normalisation doit être appliquée à la vitesse du vent selon l'Equation (14):

$$V_n = V_{10\,min}\left(\frac{\rho_{10\,min}}{\rho_0}\right)^{1/3} \tag{14}$$

où

V_n est la vitesse normalisée du vent;

V_{10min} est la vitesse du vent moyennée sur une période de 10 min.

9.1.6 Normalisation des turbulences

Les mesures de la courbe de puissance de l'éolienne sont influencées par l'intensité des turbulences. Une grande partie de l'effet de l'intensité des turbulences est causée par le moyennage de la puissance de sortie mesurée et la vitesse du vent mesurée sur des périodes de 10 min. Il est recommandé d'éliminer cet effet des mesures en normalisant les données de courbe de puissance à l'intensité des turbulences de référence conformément à l'Annexe M. L'intensité des turbulences de référence doit être définie avant l'essai de courbe de puissance. Elle peut être définie comme une fonction de la vitesse du vent à la hauteur du moyeu. Sauf indication contraire, une intensité des turbulences de référence de 10 % doit être appliquée. L'incertitude relative à la normalisation des turbulences doit être prise en compte. Si aucune normalisation des turbulences n'est appliquée aux données de courbe de puissance, l'incertitude sur la courbe de puissance due aux effets des turbulences doit être

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estimée. Il est recommandé d'utiliser la méthode de calcul de l'incertitude décrite à l'Annexe M[16].

9.2 Détermination de la courbe de puissance mesurée

La courbe de puissance doit être déterminée en fonction de la vitesse du vent à la hauteur du moyeu et, lorsqu'elle est mesurée, de la vitesse du vent équivalente du rotor. Toutefois, il convient de se rappeler que l'incertitude dans une courbe de puissance déduite à partir de mesures à hauteur du moyeu seulement est plus élevée en raison du fait qu'aucun autre paramètre influant sur les conditions du vent n'est connu. Pour tenir compte du cisaillement du vent vertical , de la déviation de la trajectoire du vent et de l'intensité des turbulences, mais aussi pour réduire l'incertitude de mesure de la courbe de puissance, il est recommandé de considérer la vitesse du vent équivalente du rotor comme la vitesse du vent représentative et la puissance de sortie normalisée des turbulences conforme à l'Annexe M comme la puissance de sortie pertinente. La dérivation des courbes de puissance à partir de la vitesse du vent normalisée pour un profil de cisaillement du vent spécifique (voir Annexe P) et la puissance de sortie normalisée des turbulences sont des options recommandées lorsqu'une comparaison entre différentes courbes de puissance est souhaitée ou que les courbes de puissance sont appliquées pour l'évaluation des ressources éoliennes.

Pour indiquer des moyennes sur des périodes de 10 min, il convient d'ajouter un indice j supplémentaire aux vitesses de vent respectives.

La courbe de puissance mesurée est déterminée en appliquant la "méthode des tranches" aux ensembles de données normalisés, en utilisant des tranches de vitesse du vent de 0,5 m/s et en calculant les valeurs moyennes de la vitesse normalisée du vent et de la puissance de sortie normalisée pour chaque tranche de vitesse du vent, selon les Equations (15) et (16):

$$V_i = \frac{1}{N_i}\sum_{j=1}^{N_i} V_{\mathrm{n},i,j} \tag{15}$$

$$P_i = \frac{1}{N_i}\sum_{j=1}^{N_i} P_{\mathrm{n},i,j} \tag{16}$$

où

V_i est la vitesse du vent normalisée et moyennée dans la tranche i;

$V_{\mathrm{n},i,j}$ est la vitesse du vent normalisée de l'ensemble de données j dans la tranche i;

P_i est la puissance de sortie normalisée et moyennée dans la tranche i;

$P_{\mathrm{n},i,j}$ est la puissance de sortie normalisée de l'ensemble de données j dans la tranche i;

N_i est le nombre d'ensembles de données de 10 min dans la tranche i.

La courbe de puissance mesurée doit être présentée et décrite comme indiqué à l'Article 10. Lorsque des courbes de puissance de la REWS sont mesurées, la courbe de puissance de la vitesse du vent à la hauteur du moyeu doit également être présentée.

9.3 Production annuelle d'énergie (*AEP*)

L'*AEP* doit être calculée de deux manières, l'une nommée "*AEP* mesurée", l'autre "*AEP* extrapolée". Si la courbe de puissance mesurée n'inclut pas les données jusqu'à la vitesse de coupure, la courbe de puissance doit être extrapolée entre la vitesse du vent maximale mesurée et la vitesse de coupure.

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16 Il convient de noter que l'intensité des turbulences est mesurée différemment par les anémomètres à coupelles, les dispositifs de télédétection et les anémomètres à ultrasons. Il convient d'en tenir compte lors de l'interprétation des résultats.

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De plus, l'AEP peut être définie comme une AEP générique ou une AEP spécifique au site. L'AEP générique est mesurée en appliquant la courbe de puissance mesurée aux différentes distributions de fréquence de vitesses du vent de référence. Pour une installation spécifique, les conditions nominales du site spécifiant le régime des vents sur le site peuvent être connues. Dans ce cas, une AEP spécifique au site peut également être consignée et calculée en se fondant sur les informations spécifiques à ce site.

Il est à souligner qu'une courbe de puissance déduite à partir des mesures de vitesse du vent à la hauteur du moyeu ne doit être combinée qu'à une distribution de fréquence de vitesses du vent fondée sur la définition de la vitesse du vent à la hauteur du moyeu pour déduire l'AEP, tandis qu'une courbe de puissance déduite à partir des mesures de la REWS ne doit être combinée qu'à une distribution de fréquence REWS pour déduire l'AEP. Déduire l'AEP à partir de la combinaison d'une courbe de puissance de la REWS et d'une distribution de fréquence de vitesses du vent à la hauteur du moyeu (et vice versa) ne constitue pas un calcul valide. Une distribution de Rayleigh, qui est identique à une distribution de Weibull avec un facteur de forme de 2, doit être utilisée comme distribution de fréquence de vitesses du vent de référence. Les estimations de l'AEP doivent être effectuées pour des moyennes annuelles de la vitesse du vent à la hauteur du moyeu égales à 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, 10 m/s et 11 m/s, selon l'Equation (17):

$$AEP = N_{\mathrm{h}} \sum_{i=1}^{N} \left[F(V_i) - F(V_{i-1})\right] \quad \left(\frac{P_{i-1} + P_i}{2}\right) \tag{17}$$

où

AEP est la production annuelle d'énergie;

N_{h} est le nombre d'heures dans une année ≈ 8 760;

n est le nombre de tranches;

V_i est la vitesse du vent normalisée et moyennée dans la tranche i;

P_i est la puissance de sortie normalisée et moyennée dans la tranche i.

$$F(V) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{V}{V_{\mathrm{ave}}}\right)^2\right) \tag{18}$$

où

$F(V)$ est la fonction de distribution de probabilité cumulative de Rayleigh pour la vitesse du vent;

V_{ave} est la moyenne annuelle de la vitesse du vent;

V est la vitesse du vent.

La sommation est initialisée en définissant $V_{i\text{-}1}$ sur V_i _ 0,5 m/s et $P_{i\text{-}1}$ sur 0,0 kW.

Pour un site spécifique, les conditions nominales spécifiant le régime des vents sur le site peuvent être connues. Dans ce cas, une AEP spécifique au site peut également être consignée et calculée en se fondant sur les informations spécifiques à ce site. Si la distribution du vent spécifique au site est connue et qu'elle est présentée sous une forme tabulaire, l'AEP spécifique au site peut être calculée en commençant par convertir la distribution du vent en une distribution cumulative correspondante. Le nombre d'heures jusqu'à chaque vitesse du vent mesurée de la courbe de puissance mesurée sera déduit par interpolation linéaire de deux valeurs adjacentes de la distribution cumulative. Ce nombre sera divisé par la somme des heures du tableau, qui correspond typiquement au nombre d'heures nominal d'une année calendaire. Enfin, l'AEP sera calculé à l'aide de l'Equation (17). La distribution tabulaire des vitesses du vent doit utiliser la même définition de vitesse du vent (hauteur du moyeu ou REWS) que la courbe de puissance mesurée, faute de quoi aucune AEP valide ne peut être déduite.

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Si la distribution du vent spécifique au site est présentée comme une distribution de Weibull avec des facteurs de forme et d'échelle connus, l'AEP peut être calculée selon l'Equation (17) et en remplaçant l'Equation de distribution cumulative de Rayleigh (18) par l'Equation de distribution de Weibull (19):

$$F(V) = 1 - e^{-\left(\frac{V}{A_W}\right)^k} \tag{19}$$

où

$F(V)$ est désormais la fonction de distribution de probabilité cumulative de Weibull pour la vitesse du vent;

V est la vitesse du vent;

A_W est le facteur d'échelle de Weibull;

k est le facteur de forme de Weibull.

L'AEP mesurée doit être obtenue d'après la courbe de puissance mesurée en prenant pour hypothèse une puissance nulle pour toutes les vitesses du vent supérieures et inférieures à la plage de la courbe de puissance mesurée, puis par sommation selon l'Equation (17).

L'AEP extrapolée doit être obtenue à partir de la courbe de puissance mesurée en prenant pour hypothèse une puissance nulle pour toutes les vitesses de vent inférieures à la vitesse la plus basse du vent sur la courbe de puissance mesurée et une puissance constante pour les vitesses de vent comprises entre la vitesse du vent la plus élevée sur la courbe de puissance mesurée et la vitesse de coupure. La puissance constante utilisée pour l'AEP extrapolée doit correspondre à la valeur de puissance de la tranche à la vitesse du vent la plus élevée sur la courbe de puissance mesurée.

L'AEP mesurée et l'AEP extrapolée doivent être présentées dans le rapport d'essai décrit à l'Article 10. Pour tous les calculs de l'AEP, la disponibilité de l'éolienne doit être définie à 100 %. Pour des moyennes annuelles données de la vitesse du vent, les estimations de l'AEP mesurée doivent être marquées comme "incomplètes" lorsque les calculs montrent que l'AEP mesurée est inférieure à 95 % de l'AEP extrapolée.

Des estimations de l'incertitude de mesure en termes d'incertitude-type sur l'AEP, conformément à l'Annexe D, doivent être consignées pour l'AEP mesurée pour l'ensemble des distributions des vitesses du vent utilisées.

Les incertitudes sur l'AEP, décrites ci-dessus, ne tiennent compte que des incertitudes issues de l'essai de performance de puissance; elles ne tiennent pas compte des incertitudes dues à d'autres facteurs importants associés à la production d'énergie réelle pour une installation donnée.

9.4 Coefficient de puissance

Le coefficient de puissance C_P de l'éolienne doit être ajouté aux résultats d'essai et présenté comme décrit à l'Article 10. C_P doit être déterminé à partir de la courbe de puissance mesurée, selon l'Equation (20):

$$C_{P,i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \tag{20}$$

où

$C_{P,i}$ est le coefficient de puissance dans la tranche i;

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V_i est la vitesse du vent normalisée et moyennée dans la tranche i (qui correspond à la vitesse du vent définie comme vitesse du vent équivalente du rotor ou vitesse du vent à la hauteur du moyeu);

P_i est la puissance de sortie normalisée et moyennée dans la tranche i;

A est la surface balayée par le rotor de l'éolienne;

ρ_0 est la masse volumique de l'air de référence.

10 Format de rapport

Le rapport d'essai doit contenir les informations suivantes:

a) Identification et description de la configuration spécifique de l'éolienne à l'essai (voir 6.2), notamment:

   1) la marque, le type, le numéro de série, l'année de production de l'éolienne;
   2) le diamètre du rotor et une description de la méthode de vérification utilisée ou un renvoi à la documentation relative au diamètre du rotor;
   3) la vitesse du rotor ou la plage de vitesses du rotor;
   4) la puissance assignée et la vitesse du vent assignée;
   5) les données relatives aux pales: marque, type, numéros de série, nombre de pales, pas fixe ou variable, angle(s) de pas;
   6) la hauteur du moyeu et le type de mât;
   7) une description du système de contrôle (dispositif et version logicielle) et une documentation des signaux d'état utilisés pour la réduction des données;
   8) une description des conditions de raccordement au réseau électrique au niveau de l'éolienne (tension, fréquence et tolérances associées), ainsi qu'un schéma indiquant l'emplacement auquel est raccordé le transducteur de puissance, à savoir un transformateur interne ou externe, ainsi que la consommation électrique propre de l'éolienne;

b) Description du site d'essai (voir 6.3), notamment:

   1) des photographies de tous les secteurs de mesure, prises de préférence depuis l'éolienne à la hauteur du moyeu;
   2) une carte du site d'essai représentant la surface des environs sur une distance radiale égale à au moins 20 fois le diamètre du rotor de l'éolienne et indiquant la topographie, l'emplacement de l'éolienne, le matériel de mesure du vent, les obstacles significatifs, les autres éoliennes ainsi que le secteur de mesure;
   3) les résultats de l'évaluation du site, c'est-à-dire les limites du ou des secteurs de mesure valides;
   4) si un étalonnage du site est effectué, les limites du ou des secteurs de mesure finals doivent également être consignées, y compris la justification des variations éventuelles résultant de l'évaluation du site;
   5) un tableau des coordonnées et de l'altitude de l'éolienne à l'essai, du matériel de mesure du vent et des éventuels obstacles significatifs étudiés lors de l'évaluation des obstacles;

c) Description du matériel d'essai (voir Article 7):

   1) l'identification de tous les capteurs, du matériel de mesure du vent et du système d'acquisition de données, y compris la documentation pour l'étalonnage des capteurs, du matériel de mesure du vent, des lignes de transmission du signal et du système d'acquisition de données;
   2) un croquis du montage du mât météorologique indiquant les dimensions du mât et le montage des instruments, conformément à l'Annexe G;

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3) une description de la méthode utilisée pour garantir que l'étalonnage du matériel de mesure du vent est resté valide pendant toute la durée de la période de mesure, ainsi qu'une documentation des résultats montrant que l'étalonnage est maintenu;

d) Description de la procédure de mesure (voir Article 8):

1) une documentation des étapes du mode opératoire, des conditions d'essai, de la fréquence d'échantillonnage, du temps de moyennage et de la période de mesure, y compris:

– la documentation des étalonnages, des corrections ou des fonctions de transfert appliquées par l'enregistreur de données et/ou par post-traitement;

2) un journal de bord d'essai consignant tous les événements importants qui se sont produits lors de l'essai de performance de puissance, y compris:

– une liste de toutes les activités de maintenance qui ont eu lieu pendant l'essai;

– une liste de toutes les actions spéciales (par exemple, un lavage des pales) qui ont été effectuées pour garantir une bonne performance;

3) une liste complète de tous les critères de filtrage utilisés pour produire le résultat consigné, y compris:

– le paramètre, la mesure, la durée ou une combinaison des paramètres filtrés;

– la plage ou le critère logique relatif au filtre;

– la justification du filtre;

– l'ordre dans lequel les filtres ont été appliqués doit être consigné, avec le nombre de points supprimé à chaque itération. A défaut, le nombre de points de données que le filtre supprimerait de la base de données par lui-même;

– le nombre initial d'ensembles de données dans la base de données et le nombre final d'ensembles de données après l'application de tous les filtres;

e) Présentation des données mesurées (voir 8.3 à 8.5). Les données de chaque ensemble de données choisi doivent être présentées au format tabulaire et graphique, ce qui permet de fournir des statistiques concernant la puissance de sortie mesurée en fonction de la vitesse du vent et de paramètres météorologiques importants (lorsque des mesures de la REWS sont disponibles, les données mesurées doivent être présentées séparément pour la hauteur du moyeu et la REWS), y compris:

1) des diagrammes de dispersion représentant les moyennes, les écarts-types, la puissance de sortie minimale et maximale en fonction de la vitesse du vent (les tracés doivent inclure des informations concernant la fréquence d'échantillonnage). Un exemple est donné à la Figure 5;

2) des diagrammes de dispersion représentant la vitesse moyenne du vent et l'intensité des turbulences en fonction de la direction du vent;

3) des diagrammes de dispersion représentant l'intensité des turbulences en fonction de la vitesse du vent (l'intensité des turbulences moyenne dans chaque tranche de vitesse du vent doit être représentée);

4) il convient également de présenter, comme décrit ci-dessus, les bases de données spéciales constituées de données recueillies dans des conditions d'exploitation ou dans des conditions atmosphériques particulières;

5) S'ils ont été mesurés, la vitesse de rotation et l'angle de pas doivent être représentés sous la forme d'un diagramme de dispersion incluant les valeurs de tranche en fonction de la vitesse du vent ainsi qu'un tableau des valeurs de tranche;

6) la définition des signaux d'état et des tracés des signaux d'état pendant la période de mesure;

7) des diagrammes de dispersion représentant la masse volumique de l'air en fonction de la direction du vent et de la vitesse du vent, y compris la moyenne par tranche;

8) un diagramme de dispersion représentant l'exposant de cisaillement du vent par rapport à l'heure du jour et en fonction de la vitesse du vent. L'exposant de cisaillement du vent dans la moitié inférieure du rotor et l'exposant de cisaillement du vent dans la moitié supérieure du rotor doivent être présentés séparément. En outre,

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les valeurs moyennes des deux exposants de cisaillement du vent par tranche de vitesse du vent doivent être représentées;

9) l'exposant moyen de cisaillement du vent ou une représentation équivalente des conditions de cisaillement du vent du site lors de l'essai;

10) le facteur de correction du cisaillement du vent, conformément à 9.1.3.3, si applicable, en fonction de la configuration de la mesure (utiliser l'Equation (9) ou l'Equation (10), en fonction de la configuration de la mesure);

11) la masse volumique de l'air moyenne mesurée lors de l'essai;

f) Présentation de la courbe de puissance mesurée pour la masse volumique de l'air de référence (voir 9.1 et 9.2), pour la courbe de puissance déduite à partir de la vitesse du vent à la hauteur du moyeu, ainsi que la courbe de puissance déduite de la REWS si elle est mesurée:

1) la courbe de puissance doit être représentée sous la forme d'un tableau similaire au Tableau 4[17]. Pour chaque tranche de vitesse du vent, le tableau doit répertorier:

– la vitesse du vent normalisée et moyennée;

– la puissance de sortie normalisée et moyennée;

– le nombre d'ensembles de données;

– la valeur C_P calculée;

– les incertitudes-types de catégorie A (voir Annexe D et Annexe E);

– les incertitudes-types de catégorie B (voir Annexe D et Annexe E);

– l'incertitude-type composée (voir Annexe D et Annexe E);

2) la courbe de puissance doit être représentée sous la forme d'un graphique similaire à la Figure 6. Le graphique doit représenter les caractéristiques suivantes en fonction de la vitesse du vent normalisée et moyennée:

– la puissance de sortie normalisée et moyennée;

– l'incertitude-type composée;

3) la courbe C_P doit être représentée sous la forme d'un graphique similaire à la Figure 7;

4) le graphique et le tableau doivent mentionner la masse volumique de l'air de référence utilisée pour la normalisation;

5) si la vitesse de coupure a été atteinte pendant la période de mesure, la courbe de puissance et la courbe C_P ou les parties des courbes influencées par l'hystérésis de coupure peuvent être présentées d'une manière similaire aux éléments 1), 2), 3) et 4).

g) Présentation des courbes de puissance mesurées recueillies dans des conditions d'exploitation et des conditions atmosphériques particulières:

1) les courbes de puissance déduites à partir des sous-ensembles de la base de données pour des conditions d'exploitation ou des conditions atmosphériques particulières peuvent également être consignées. Si tel est le cas, il convient de consigner une courbe de puissance de la même manière que pour la masse volumique de l'air de référence, mais selon la masse volumique déduite à partir de la moyenne de la masse volumique de l'air mesurée pour les sous-ensembles de la base de données ou, à défaut, en utilisant une masse volumique de l'air nominale prédéfinie pour le site.

h) Présentation de la production annuelle d'énergie estimée pour la masse volumique de l'air de référence (voir 9.3), pour la courbe de puissance déduite de la vitesse du vent à la

[17] En plus de représenter la courbe de puissance mesurée dans un tableau, conformément à f)1), la courbe de puissance mesurée peut être représentée sous la forme de valeurs au centre de la tranche. La méthode recommandée consiste à utiliser une fonction spline cubique pour l'interpolation entre les valeurs de tranches du tableau afin de représenter la vitesse du vent, la puissance et le coefficient de puissance mesurés au centre de la tranche.

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hauteur du moyeu, ainsi que la courbe de puissance déduite de la REWS si elle est mesurée:

1) un tableau similaire au Tableau 5 qui doit inclure pour chaque moyenne annuelle de la vitesse du vent à la hauteur du moyeu:
   – l'AEP mesurée;
   – l'incertitude-type de l'AEP mesurée (voir Annexe D et Annexe E);
   – l'AEP extrapolée;
2) le tableau doit également mentionner:
   – la masse volumique de l'air de référence;
   – la vitesse de coupure;
3) pour toute moyenne annuelle de la vitesse du vent, si l'AEP mesurée est inférieure à 95 % de la production annuelle d'énergie extrapolée, le tableau doit également inclure la mention "incomplet" dans la colonne des valeurs de l'AEP mesurée;

i) Présentation du coefficient de puissance mesuré (voir 9.4):
   1) il convient de représenter le coefficient de puissance mesuré en fonction de la vitesse du vent sous la forme d'un tableau et d'un graphique, où la surface balayée par le rotor doit être indiquée;

j) Présentation des résultats de l'étalonnage du site (voir Annexe C pour les exigences de consignation):
   1) si un étalonnage du site a été réalisé, il doit être consigné dans le rapport sous la forme d'un tableau;
   2) le tableau doit présenter pour chaque tranche de direction du vent:
      – les limites minimale et maximale de direction du vent;
      – la direction du vent moyennée par tranche;
      – les caractéristiques de la correction de la vitesse du vent;
      – le nombre d'heures de données;
      – l'incertitude-type composée du rapport de vitesses du vent pour 6 m/s, 10 m/s et 14 m/s;
   3) le rapport doit en outre inclure les graphiques et les tableaux exigés à l'Annexe C;

k) Incertitude de mesure (voir Annexe D):
   1) des hypothèses d'incertitude doivent être fournies pour toutes les composantes d'incertitude;

l) Ecarts par rapport à la procédure:
   1) tout écart par rapport aux exigences de la présente norme doit être clairement documenté dans un article distinct. Pour chaque écart doivent être fournies des justifications techniques, ainsi qu'une estimation de son effet sur les résultats d'essai.

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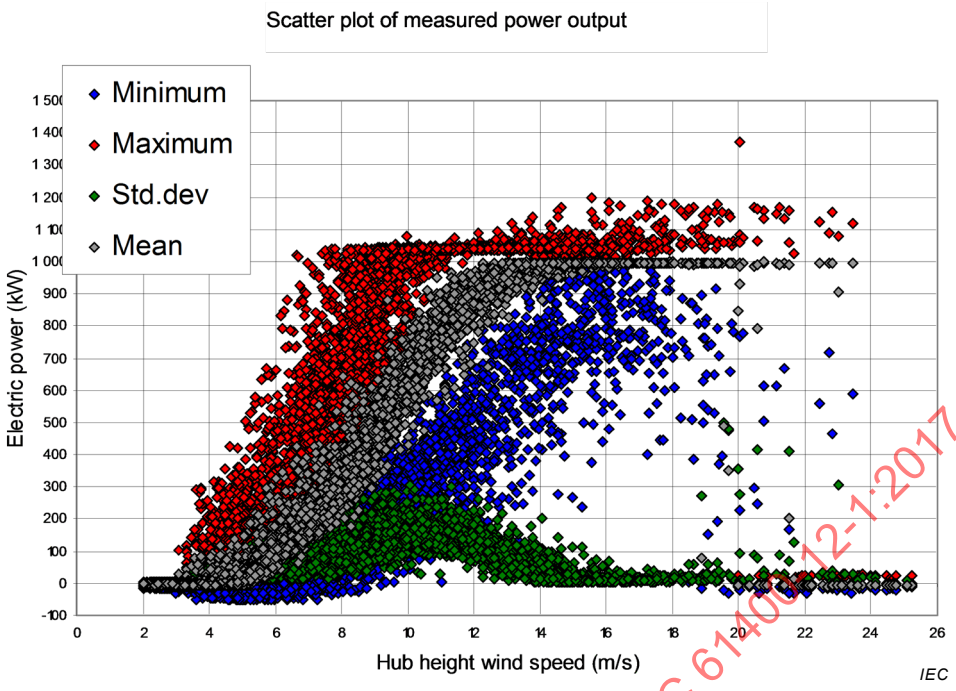

Anglais	Français
Scatter plot of measured power output	Diagramme de dispersion de la puissance de sortie mesurée
Minimum	Valeurs minimales
Maximum	Valeurs maximales
Std. dev	Ecarts-types
Mean	Moyennes
Electric power (kW)	Puissance électrique (kW)
Hub height wind speed (m/s)	Vitesse du vent à la hauteur du moyeu (m/s)

Figure 5 – Présentation d'un exemple de base de données: diagramme de dispersion de l'essai de performance de puissance échantillonné à 1 Hz (valeurs moyennes moyennées sur 10 min)

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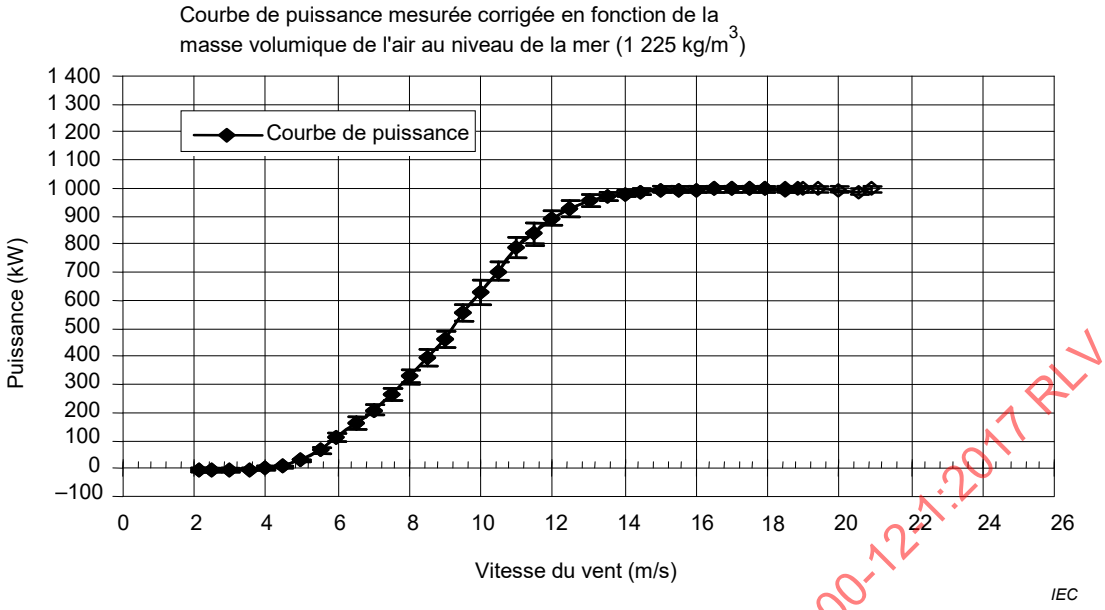

Figure 6 – Présentation d'un exemple de courbe de puissance mesurée

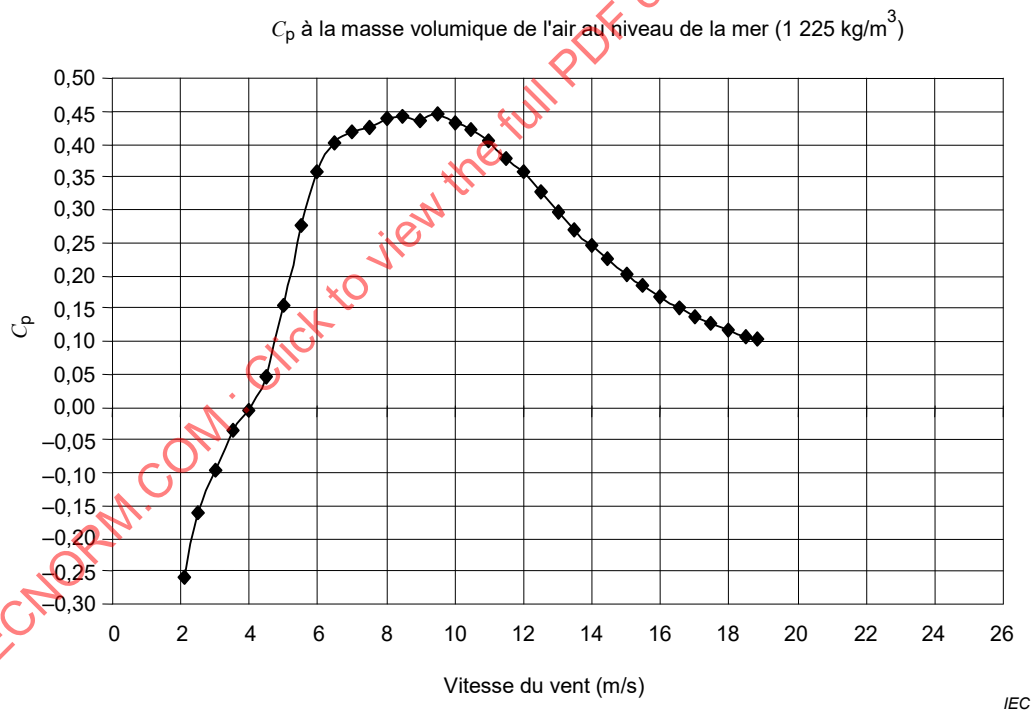

Figure 7 – Présentation d'un exemple de courbe C_P

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Tableau 4 – Exemple de présentation d'une courbe de puissance mesurée

Courbe de puissance mesurée							
Masse volumique de l'air de référence: 1,225 kg/m^3					Catégorie A	Catégorie B	Incertitude composée
N° de tranche	Vitesse du vent à la hauteur du moyeu [m/s]	Puissance de sortie [kW]	C_P	Nombre d'ensembles de données (moyennés sur 10 min)	Incertitude-type s_i [kW]	Incertitude-type u_i [kW]	Incertitude-type u_{ci} [kW]
4	2,1	–3,6	–0,26	138	0,05	6,3	6,3
5	2,5	–3,6	–0,16	275	0,04	6,3	6,3
6	3,0	–3,8	–0,10	270	0,13	6,3	6,3
7	3,5	–2,2	–0,03	320	0,56	6,3	6,3
8	4,0	–0,4	0,00	347	0,56	6,3	6,3
9	4,5	6,0	0,05	362	0,67	6,3	6,4
10	5,0	27,7	0,15	333	1,09	6,8	6,9
11	5,5	67,4	0,28	285	1,65	10,9	11,0
12	6,0	111,3	0,36	262	2,26	16,1	16,3
13	6,5	160,9	0,40	265	3,08	20,1	20,3
14	7,0	209,4	0,42	286	3,22	20,4	20,7
15	7,5	262,0	0,43	287	3,23	20,7	20,9
16	8,0	327,6	0,44	248	3,28	23,3	23,5
17	8,5	395,2	0,44	215	4,38	28,6	28,9
18	9,0	462,0	0,44	179	4,94	29,8	30,2
19	9,5	556,1	0,45	183	5,02	29,9	30,3
20	10,0	629,8	0,43	133	5,83	41,5	41,9
21	10,5	703,1	0,42	127	6,82	32,8	33,5
22	11,0	786,5	0,41	119	6,75	36,1	36,7
23	11,5	836,5	0,38	101	6,65	36,5	37,1
24	12,0	893,5	0,36	94	7,27	25,2	26,2
25	12,5	928,6	0,33	74	5,59	28,8	29,3
26	13,0	956,4	0,30	70	6,38	19,5	20,5
27	13,5	971,3	0,27	63	4,66	16,5	17,1
28	14,0	980,9	0,25	71	3,19	13,5	13,8
29	14,5	988,2	0,22	77	2,53	12,2	12,4
30	15,0	993,5	0,20	64	1,37	11,9	11,9
31	15,5	993,7	0,18	47	0,84	11,6	11,6
32	16,0	995,7	0,17	54	0,83	11,3	11,3
33	16,5	996,2	0,15	33	0,42	11,4	11,4
34	17,0	996,4	0,14	23	0,23	11,3	11,3
35	17,5	996,5	0,13	30	0,24	11,3	11,3
36	18,0	996,5	0,12	13	0,18	11,3	11,3
37	18,5	995,7	0,11	11	0,21	11,3	11,3
38	19,0	996,6	0,10	14	0,59	11,3	11,3
39	19,4	996,1	0,09	10	0,21	11,3	11,3
40	20,0	994,1	0,09	5	0,41	11,3	11,3

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Courbe de puissance mesurée							
Masse volumique de l'air de référence: 1,225 kg/m^3					Catégorie A	Catégorie B	Incertitude composée
N° de tranche	Vitesse du vent à la hauteur du moyeu [m/s]	Puissance de sortie [kW]	C_P	Nombre d'ensembles de données (moyennés sur 10 min)	Incertitude-type s_i [kW]	Incertitude-type u_i [kW]	Incertitude-type u_{ci} [kW]
41	20,5	987,4[18]	0,08	2	2,67	11,4	11,7
42	20,9	996,9	0,08	3	3,38	11,8	12,3

Tableau 5 – Exemple de présentation d'une production annuelle d'énergie estimée

Production annuelle d'énergie estimée Masse volumique de l'air de référence: 1,225 kg/m^3 Vitesse de coupure: 25 m/s (extrapolation par puissance constante après la dernière tranche)					
Moyenne annuelle de la vitesse du vent à la hauteur du moyeu (Rayleigh) m/s	*AEP* mesurée (courbe de puissance mesurée) MWh	Incertitude-type de l'*AEP* MWh	Incertitude-type de l'*AEP* %	*AEP* extrapolée (courbe de puissance extrapolée) MWh	
4	480	82	17	480	
5	1 081	113	10	1 081	
6	1 824	138	8	1 824	
7	2 595	155	6	2 603	
8	3 305	163	5	3 342	
9	3 889	165	4	3 995	
10	4 318	162	4	4 536	
11	4 592	157	3	4 954	Incomplet

NOTE Les chiffres d'incertitude-type dans les tableaux ci-dessus sont basés sur un facteur de couverture de 1. Cela implique que le niveau de confiance (soit le nombre de fois, en pourcentage, dans les mesures de la courbe de puissance répétées, où les intervalles contiendront la "vraie" valeur de l'*AEP*) est de l'ordre de 58 % à 68 %. Le niveau de confiance n'est qu'une estimation; en effet, la distribution de probabilité du mesurande n'est normalement pas connue en détail. La valeur supérieure (68 %) s'applique aux distributions normales, tandis que la valeur inférieure (58 %) s'applique aux distributions rectangulaires.

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[18] L'ensemble de données de la tranche 41 est incomplet (moins de 3 ensembles de données); la valeur de puissance dans la tranche 41 pour le calcul de l'*AEP* est donc interpolée à 995,7.

Annexe A
(normative)

Evaluation des influences des éoliennes et des obstacles présents sur le site d'essai

A.1 Généralités

L'Annexe A décrit une procédure permettant de déterminer un ou plusieurs secteurs qui ne sont pas aptes à l'essai car l'écoulement au niveau de l'éolienne à l'essai et/ou l'écoulement à l'emplacement du matériel de mesure du vent (WME, "*wind measurement equipment*": mât météorologique ou dispositif de télédétection) pourraient être affectés par une éolienne en exploitation et/ou par un obstacle.

La procédure comporte deux étapes, qui doivent être appliquées dans l'ordre suivant[19]:

a) évaluation des influences des éoliennes en exploitation (les éoliennes à l'essai, mais aussi les éoliennes voisines en exploitation), décrite à l'Article A.2;

b) évaluation des influences des obstacles décrite à l'Article A.3 (compte tenu des exigences spéciales pour les obstacles étendus, décrites à l'Article A.5).

Le secteur valide retenu à l'issue de cette procédure doit être utilisé pour l'évaluation du terrain conformément à l'Annexe B.

L'objectif de l'étalonnage du site est généralement de mesurer les variations intervenant dans la couche limite, car elles suivent l'orographie, qui est généralement un écoulement associé, alors que les obstacles produisent souvent des sillages plus turbulents, lesquels sont affectés par les bords saillants et les surfaces verticales qui peuvent entraîner une séparation de l'écoulement. En général, l'étalonnage du site ne permet donc pas de corriger correctement les effets de la séparation de l'écoulement. Il convient de tenir compte de ce fait au moment de décider de traiter un objet comme un obstacle ou comme un terrain, car la séparation de l'écoulement et les sillages très turbulents doivent être évités. En ce sens, il est recommandé de traiter comme un obstacle (y compris les éléments orographiques qui satisfont aux critères dimensionnels) un objet dont la hauteur est supérieure à plus de la moitié de sa largeur.

A.2 Exigences relatives aux éoliennes voisines en exploitation

Le WME ne doit pas être influencé par l'éolienne à l'essai.

L'éolienne à l'essai et le WME ne doivent pas être influencés par des éoliennes voisines en exploitation. Si une éolienne voisine fonctionne à un moment donné pendant l'essai de performance de puissance, son sillage doit être déterminé et pris en compte, comme décrit dans la présente annexe (à l'aide des calculs donnés à l'Article A.4). Les petites éoliennes dont la hauteur totale est inférieure à $(2/3)(H - D/2)$ doivent être traitées comme des obstacles et prises en compte comme décrit à l'Article A.3.

Si une éolienne est arrêtée à un moment donné pendant l'essai de performance de puissance, elle doit être considérée comme un obstacle et prise en compte comme décrit à l'Article A.3.

La distance minimale entre l'éolienne à l'essai et les éoliennes voisines en exploitation doit être égale à deux fois le diamètre du rotor D_n de l'éolienne voisine. La distance minimale

[19] Il est à noter que l'étape b) exige de connaître le secteur de mesure préliminaire, qui est le résultat de l'étape a).

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entre le WME et une éolienne voisine en exploitation doit être égale à deux fois le diamètre du rotor de l'éolienne en question. Les secteurs à exclure en raison des sillages des éoliennes voisines en exploitation doivent être choisis à partir de la Figure A.1. Les dimensions à prendre en compte sont la distance réelle L_n et le diamètre du rotor D_n de l'éolienne voisine en exploitation. Les secteurs à exclure doivent être déduits pour l'éolienne à l'essai et pour le WME; ils doivent également être centrés sur la direction entre l'éolienne voisine en exploitation et le WME ou l'éolienne. Un exemple est donné à la Figure A.2.

A.3 Exigences pour les obstacles

Les obstacles proches de l'éolienne à l'essai ou du WME doivent être évalués. Chaque obstacle doit être évalué comme élément de l'orographie (comme décrit à l'Annexe B[20]) ou, à défaut, conformément à la procédure décrite ci-après.

Aucun obstacle significatif (par exemple, des bâtiments, des arbres, des éoliennes immobilisées) ne doit être présent dans le secteur de mesure à une distance raisonnable de l'éolienne ou du WME. Seuls des petits bâtiments liés à l'exploitation de l'éolienne ou du matériel de mesure du vent sont acceptables. Lorsque des obstacles significatifs sont présents, le secteur de mesure doit être réduit, comme décrit aux Articles A.4 et A.5.

Le critère permettant de déterminer l'importance d'un obstacle (par rapport à l'éolienne à l'essai et/ou au WME) consiste à dépasser au moins l'une des limites données dans le Tableau A.1, le Tableau A.1 devant être appliqué pour tous les emplacements:

a) aux fins d'évaluation des environs de l'éolienne à l'essai (c'est-à-dire en utilisant le centre de l'éolienne à l'essai comme centre des cercles $2L$, $4L$, $8L$ et $16L$);

b) aux fins d'évaluation des environs du WME (c'est-à-dire en utilisant la ou les positions du matériel comme centre des cercles $2L$, $4L$, $8L$ et $16L$).

Tableau A.1 – Exigences relatives aux obstacles: pertinence des obstacles

Distance[a]	Secteur[b]	Hauteur maximale de l'obstacle par rapport à la surface du terrain[c]
$<2L$	360°	$<1/3\ (H - 0{,}5\ D)$
$\geq 2L$ et $< 4L$	Secteur de mesure préliminaire	$<2/3\ (H - 0{,}5\ D)$
$\geq 4L$ et $<8L$	Secteur de mesure préliminaire	$<(H - 0{,}5\ D)$
$\geq 8L$ et $<16L$	Secteur de mesure préliminaire	$<4/3\ (H - 0{,}5\ D)$
$\geq 2L$ et $<16L$	Clairement à l'extérieur du secteur de mesure préliminaire d'au moins 40°	Aucune limite de hauteur

[a] De l'obstacle à l'éolienne à l'essai ou de l'obstacle au WME, respectivement – L étant la distance horizontale entre l'éolienne à l'essai et le WME.

[b] Le *secteur de mesure préliminaire* doit être entendu ici comme le secteur valide restant après évaluation des éoliennes voisines en exploitation (comme décrit à l'Article A.2, selon le calcul donné à l'Article A.4), toutes les directions inférieures à 40° à l'extérieur devant également être prises en compte.

[c] H est la hauteur du moyeu, et D est le diamètre du rotor de l'éolienne à l'essai.

20 Généralement, envisager un obstacle de cette manière augmentera surtout la variation du terrain, tandis que les effets sur la pente pourraient être minimes (sauf pour les obstacles étendus, comme des forêts).

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A.4 Méthode de calcul des secteurs à exclure

L'influence du sillage de l'éolienne à l'essai sur le WME doit toujours être évaluée conformément à la Figure A.1.

L'influence du sillage d'une éolienne voisine en exploitation sur l'éolienne à l'essai doit toujours être évaluée conformément à la Figure A.1, de même que l'influence de son sillage sur le WME.

Concernant les éoliennes en exploitation, les dimensions à prendre en compte sont la distance réelle L_n (entre le centre de l'éolienne à l'essai et la position du WME) et le diamètre du rotor D_n de l'éolienne produisant le sillage[21].

L'influence du sillage d'un obstacle sur l'éolienne à l'essai doit être évaluée conformément à la Figure A.1 si l'obstacle est significatif par rapport à l'éolienne à l'essai selon le Tableau A.1.

L'influence du sillage d'un obstacle sur le WME doit être évaluée conformément à la Figure A.1 si l'obstacle est significatif par rapport au WME selon le Tableau A.1.

Concernant les obstacles, les dimensions à prendre en compte sont la distance horizontale réelle L_e (depuis le centre de l'éolienne à l'essai ou la position du WME, selon le cas) et un diamètre équivalent D_e du rotor de l'obstacle. Une éolienne voisine arrêtée peut être traitée comme un cylindre d'un diamètre égal à celui de la base du mât et d'une hauteur égale à celle de son extrémité supérieure. Le diamètre équivalent du rotor de l'obstacle doit être défini comme suit:

$$D_e = \frac{2 l_h l_w}{l_h + l_w} \tag{A.1}$$

où

D_e est le diamètre équivalent du rotor;

l_h est la hauteur de l'obstacle;

l_w est la largeur de l'obstacle examinée à partir de l'éolienne à l'essai ou du WME.

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21 L'influence de l'éolienne à l'essai sur le WME est évaluée à l'aide de L (distance entre l'éolienne à l'essai et le WME) et de D (diamètre du rotor de l'éolienne à l'essai).

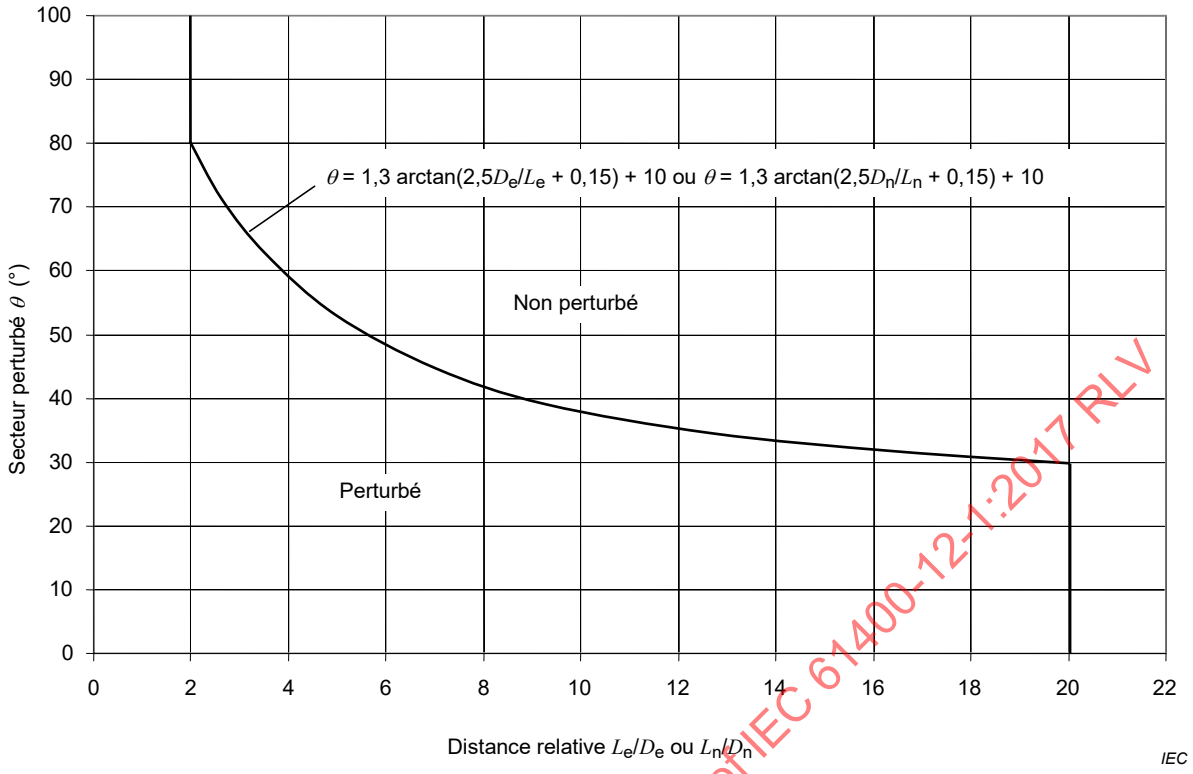

Figure A.1 – Secteurs à exclure en raison des sillages d'éoliennes voisines en exploitation et d'obstacles significatifs

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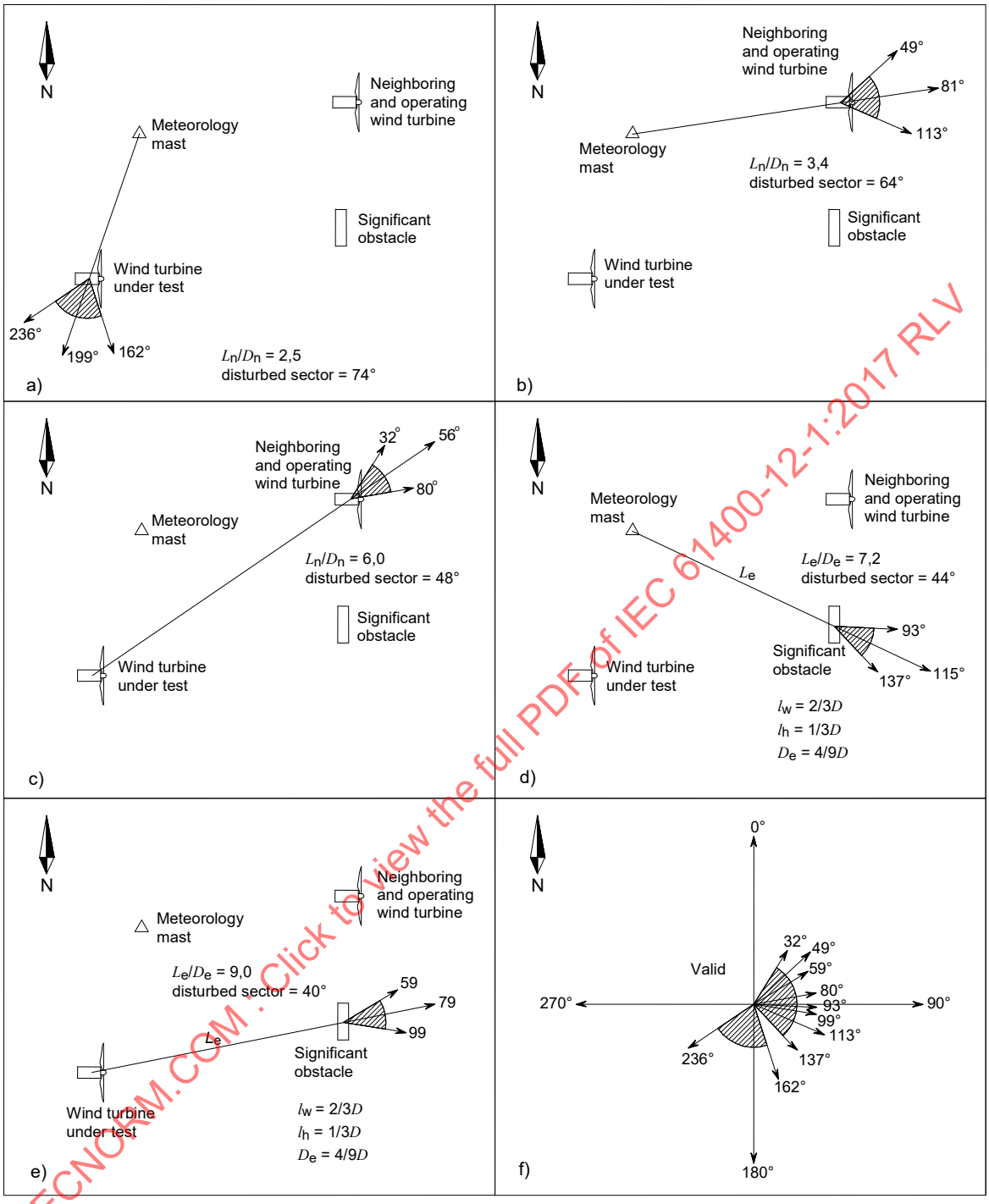

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Anglais	Français
Wind measurement equipment	Matériel de mesure du vent
Neighboring and operating wind turbine	Eolienne voisine en exploitation
Significant obstacle	Obstacle significatif
Wind turbine under test	Eolienne à l'essai
L_n/D_n = Disturbed sector =	L_n/D_n = Secteur perturbé =
Valid	Valide

Figure A.2 – Exemple de secteurs à exclure en raison des sillages de l'éolienne à l'essai, d'une éolienne voisine en exploitation et d'un obstacle significatif

Les figures représentent les secteurs à exclure si:

a) le WME (mât météorologique ou dispositif de télédétection) se trouve dans le sillage de l'éolienne à l'essai;

b) le WME se trouve dans le sillage de l'éolienne voisine en exploitation;

c) l'éolienne à l'essai se trouve dans le sillage de l'éolienne voisine en exploitation;

d) le WME se trouve dans le sillage de l'obstacle significatif;

e) l'éolienne à l'essai se trouve dans le sillage de l'obstacle significatif;

f) tous les effets a) à e) ci-dessus sont combinés.

NOTE L'exemple de la Figure A.2 est fondé sur l'hypothèse que l'obstacle est significatif (conformément au Tableau A.1) par rapport à l'éolienne à l'essai, mais aussi par rapport au matériel de mesure du vent.

A.5 Exigences spéciales relatives aux obstacles étendus

Les obstacles situés à une distance inférieure à $4L$ (depuis le centre de l'éolienne à l'essai ou le matériel de mesure du vent) qui s'étendent sur plus de 50 m dans toute direction horizontale doivent être divisés en obstacles partiels ne dépassant pas 50 m dans toute direction horizontale et s'étendant sur 50 m exactement pour les dimensions supérieures à 50 m. Ces obstacles partiels peuvent se chevaucher. La combinaison de ces obstacles partiels doit au moins[22] couvrir entièrement l'obstacle d'origine. Chaque obstacle partiel doit être évalué séparément. L'importance de chaque obstacle partiel doit être évaluée; si elle se révèle significative, le secteur à exclure doit être déterminé. Par exemple:

a) Un obstacle de 90 m sur 90 m est divisé en 4 obstacles partiels de 50 m sur 50 m chacun. Ces obstacles partiels sont choisis de telle manière qu'ils se chevauchent sur 10 m, afin que l'union définie des 4 obstacles partiels soit identique à l'obstacle d'origine.

b) Un obstacle de 70 m sur 10 m est divisé en 2 obstacles partiels de 50 m sur 10 m chacun. Ces obstacles partiels sont choisis de telle manière qu'ils se chevauchent sur 30 m, afin que l'union définie des 2 obstacles partiels soit identique à l'obstacle d'origine.

Un bosquet d'arbres ou une forêt doivent être traités de cette manière.

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22 A des fins pratiques, il est judicieux de créer des obstacles partiels qui ont tous la même forme (par exemple, des carrés de 50 m x 50 m). Il s'agit d'une approche prudente; par conséquent, elle est admise. (Dans ce cas, l'union définie de tous les obstacles partiels couvre une surface plus grande que l'obstacle d'origine.)

Annexe B
(normative)

Evaluation du terrain sur le site d'essai

Pour les essais réalisés sans étalonnage du site (sur un terrain défini comme "terrain plat"), les critères suivants doivent être observés (voir Figure B.1 et Tableau B.1 pour plus d'informations):

– l'orographie sur le site d'essai ne peut montrer que des variations mineures par rapport à un plan qui passe par la base du mât de l'éolienne, et par le terrain dans le secteur concerné;

– aucun de ces plans ne doit dépasser une certaine limite pour la pente.

Le terrain doit être évalué à l'aide d'un modèle numérique du terrain avec une résolution de 30 m ou plus fine.

Le Tableau B.1 doit être appliqué pour les emplacements ci-dessous concernant le secteur de mesure:

a) à des fins d'évaluation des environs de l'éolienne à l'essai (c'est-à-dire en utilisant le centre de l'éolienne à l'essai comme centre des cercles $2L$, $4L$, $8L$ et $16L$);

b) à des fins d'évaluation des environs du WME (c'est-à-dire en utilisant la ou les positions du matériel comme centre des cercles $2L$, $4L$, $8L$ et $16L$).

Si le terrain satisfait à toutes les exigences du Tableau B.1 dans les deux cas, aucun étalonnage du site n'est exigé[23] en raison de l'orographie. Sinon, le terrain est défini comme "terrain complexe" et une mesure de l'étalonnage du site est exigée.

Dans le Tableau B.1, L est la distance entre l'éolienne et le WME, H est la hauteur du moyeu et D est le diamètre du rotor (de l'éolienne à l'essai).

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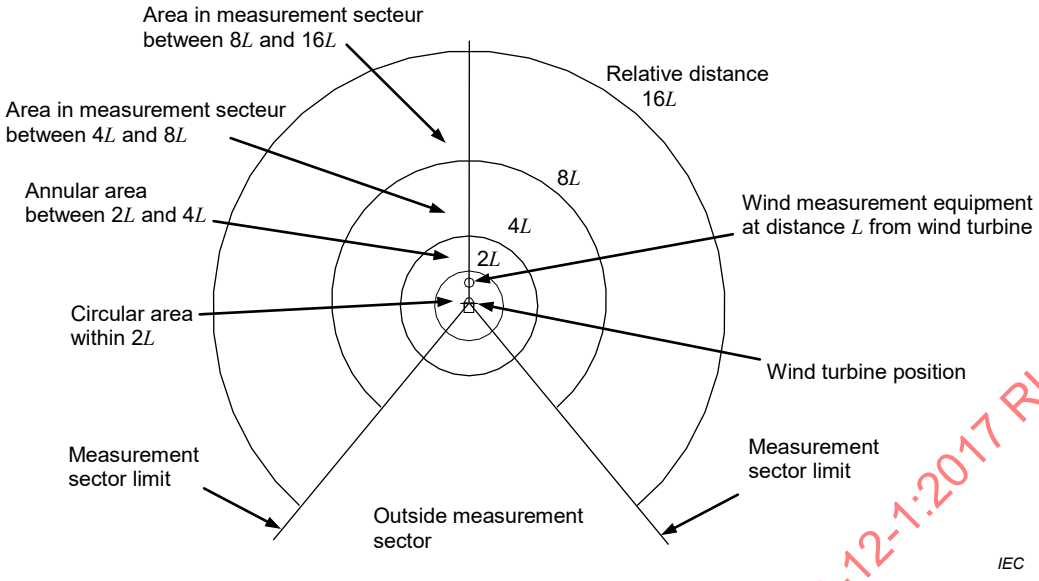
23 D'autres aspects du terrain, comme la rugosité, la distance par rapport au bord de la mer, mais aussi d'autres considérations, peuvent toutefois conduire à la conclusion qu'un étalonnage du site est recommandé.



Anglais	Français
Area in measurement sector between 8L and 16L	Surface du secteur de mesure située entre 8L et 16L
Area in measurement sector between 4L and 8L	Surface du secteur de mesure située entre 4L et 8L
Annular area between 2L and 4L	Surface annulaire située entre 2L et 4L
Circular area within 2L	Surface circulaire située à moins de 2L
Measurement sector limit	Limite du secteur de mesure
Relative distance 16L	Distance relative 16L
Wind measurement equipment at distance L from wind turbine	Matériel de mesure du vent situé à une distance L de l'éolienne
Wind turbine position	Emplacement de l'éolienne
Measurement sector limit	Limite du secteur de mesure
Outside measurement sector	Hors du secteur de mesure

Figure B.1 – Représentation de la surface à évaluer, vue de dessus

Tableau B.1 – Exigences relatives au site d'essai: variations topographiques

Distance	Secteur[a]	Pente maximale %	Variation maximale du terrain par rapport au plan
<2L	360°	<3[b]	<1/3 (H – 0,5 D)
≥2L et < 4L	Secteur de mesure	<5[b]	<2/3 (H – 0,5 D)
≥2L et <4L	A l'extérieur du secteur de mesure	<10[c]	Non applicable
≥4L et <8L	Secteur de mesure	<10[b]	< (H – 0,5 D)
≥8L et <16L	Secteur de mesure	<10[c]	Non applicable

[a] Le secteur de mesure est entendu ici par défaut comme le secteur valide restant après l'exécution de la procédure décrite à l'Annexe A, l'utilisation d'un secteur de mesure de moindres dimensions étant également admise[24].

[b] La pente maximale du plan, qui constitue la pente idéale pour le terrain dans le secteur envisagé et qui traverse la base du mât. Voir exemple à la Figure B.2.

[c] La ligne de la pente la plus inclinée qui relie la base du mât aux points individuels du terrain à la surface du terrain dans les limites du secteur. Voir exemple à la Figure B.3.

[24] Il est en outre recommandé de vérifier si une variation significative du terrain existe légèrement à l'extérieur des limites du secteur. Dans ce cas, il convient que le secteur final envisagé pour l'essai de performance de puissance maintienne une distance directionnelle claire par rapport à ces directions critiques.

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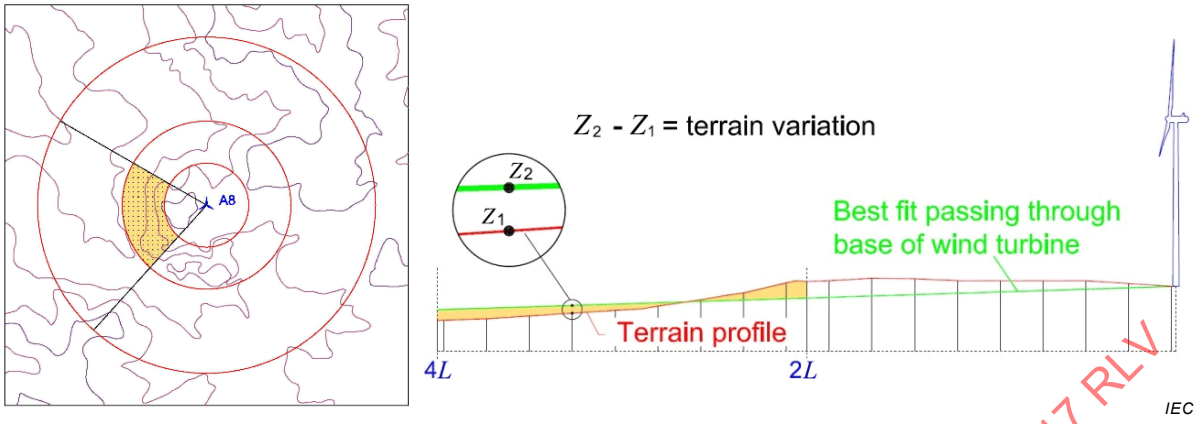
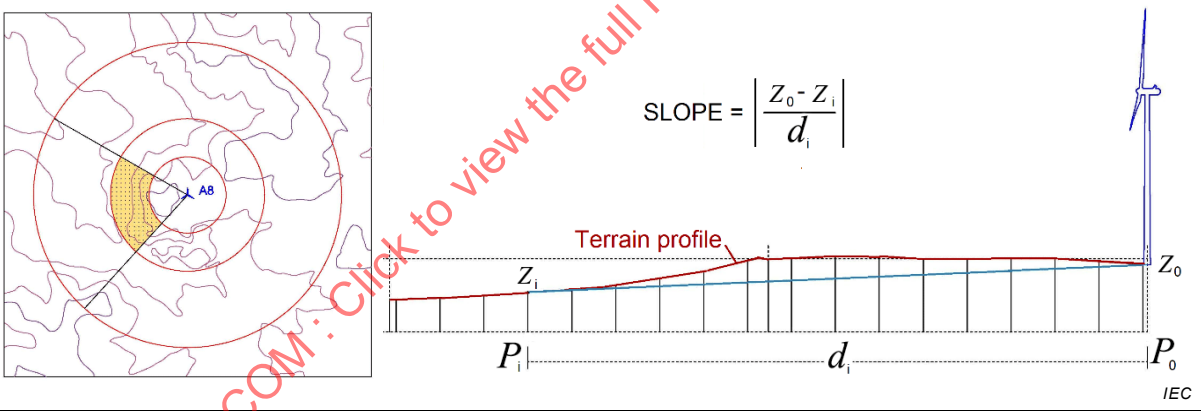


Anglais	Français
$Z_2 - Z_1$ =terrain variation	$Z_2 - Z_1$ = variation du terrain
Best fit passing through base of wind turbine	Plan idéal passant par la base de l'éolienne
Terrain profile	Profil du terrain

Figure B.2 – Exemple de détermination de la pente et de la variation du terrain par rapport au plan idéal pour la distance "2L à 4L" et le cas "secteur de mesure" (Tableau B.1, ligne 2)

NOTE 1 Cette figure ne représente qu'une direction. Toutes les directions dans les limites du secteur de mesure sont prises en compte pour le calcul du plan le mieux adapté, puis la variation maximale du terrain par rapport à ce plan est déterminée en analysant toutes les directions, comme représenté plus haut.



Anglais	Français
SLOPE	PENTE
Terrain profile	Profil du terrain

Figure B.3 – Détermination de la pente pour les distances "2L à 4L" et "8L à 16L" et le cas "à l'extérieur du secteur de mesure" (Tableau B.1, ligne 3 et ligne 5)

NOTE 2 Cette figure ne représente qu'une direction. Toutes les directions à l'extérieur du secteur de mesure sont analysées de la même manière; le résultat le plus défavorable (c'est-à-dire, la pente la plus élevée) est envisagé.

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Annexe C
(normative)

Procédure d'étalonnage du site

C.1 Généralités

Un étalonnage du site quantifie et, éventuellement, réduit les effets du terrain sur la mesure de performance de puissance. Le terrain peut provoquer une différence systématique de la vitesse du vent entre l'emplacement du mât météorologique auquel l'anémomètre de performance de puissance est monté et la hauteur équivalente au-dessus du sol au centre du rotor à l'emplacement de l'éolienne. En outre, la relation entre la vitesse du vent au niveau du mât météorologique de référence et la vitesse du vent à l'emplacement de l'éolienne peut également être affectée par les variations de stabilité atmosphérique et/ou le profil de cisaillement. Le cisaillement du vent, c'est-à-dire la variation de la vitesse du vent en fonction de la hauteur par rapport au sol, peut également être un paramètre d'influence sur cette relation. En effet, différents profils de cisaillement peuvent provoquer une relation différente entre les points de mesure, notamment si l'éolienne et le mât météorologique présentent différentes altitudes.

Considérations saisonnières: la stabilité atmosphérique, les turbulences et le cisaillement du vent peuvent varier en fonction des conditions saisonnières. Les effets des variations de la rugosité dues aux modifications de la végétation dans la surface d'essai ou directement provoquées par différentes caractéristiques saisonnières de surface (eau/sol par rapport à glace/sol, neige, cultures, etc.) posent également problème. Par conséquent, il convient de réaliser l'étalonnage du site et la mesure de la courbe de puissance pendant la ou les mêmes saisons. Si les mesures sont réalisées lors de différentes saisons, une incertitude supplémentaire doit être appliquée de la manière décrite à l'Article C.7.

Les résultats de l'étalonnage du site sont les suivants:

a) un tableau des corrections de l'écoulement pour toutes les directions du vent dans le ou les secteurs de mesure; et

b) une estimation de l'incertitude-type de ces corrections de l'écoulement.

L'étalonnage du site peut être évalué à l'aide de deux méthodes distinctes. Une seule méthode est exigée. Cette méthode est choisie en analysant les données permettant d'évaluer le cisaillement (voir C.5.1). Pour chaque méthode, les résultats sont les suivants:

1) Paragraphe C.5.2 – Etalonnage du site compte tenu du cisaillement: les corrections de l'écoulement sont représentées par une matrice des tranches de direction du vent et des tranches de cisaillement du vent dans laquelle un facteur de correction unique du rapport de vitesses du vent est calculé pour chaque point de la matrice;

2) Paragraphe C.5.3 – Etalonnage du site lorsque le cisaillement n'a pas une influence significative: les corrections de l'écoulement sont représentées par une pente et une valeur d'ordonnée à l'origine pour chaque tranche de direction du vent. Le coefficient de détermination, r^2, à savoir la valeur de la régression, doit également être consigné.

Cette procédure est donnée pour la vitesse du vent définie comme la vitesse du vent à la hauteur du moyeu. Ainsi, la procédure n'impose pas de mesures à la hauteur de l'extrémité supérieure du mât météorologique, qui impliquent un coût élevé et qui peuvent ne pas être pratiques car les dispositifs de télédétection peuvent ne pas être adaptés pour des mesures sur un terrain complexe. Cependant, lorsqu'une courbe de puissance doit être déduite pour la définition de la vitesse du vent comme REWS, la procédure est répétée pour chaque paire de hauteurs de mesure et non pour la hauteur du moyeu de chaque mât météorologique uniquement.

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C.2 Vue d'ensemble de la procédure

Avant l'installation de l'éolienne (ou après son enlèvement si elle existait déjà), deux mâts météorologiques doivent être érigés. L'un des mâts météorologiques est le mât météorologique à l'emplacement de référence. Il sera également utilisé pour l'essai de performance de puissance. Le second mât météorologique est un mât météorologique représentant l'éolienne et se situe à l'emplacement de l'éolienne.

Cette procédure vise à caractériser la corrélation des vitesses du vent entre ces deux emplacements. Des recommandations supplémentaires pour le choix de ces emplacements sont données en C.3.1.

L'organigramme de la Figure C.1 fournit une vue d'ensemble générale du processus de préparation et d'analyse.

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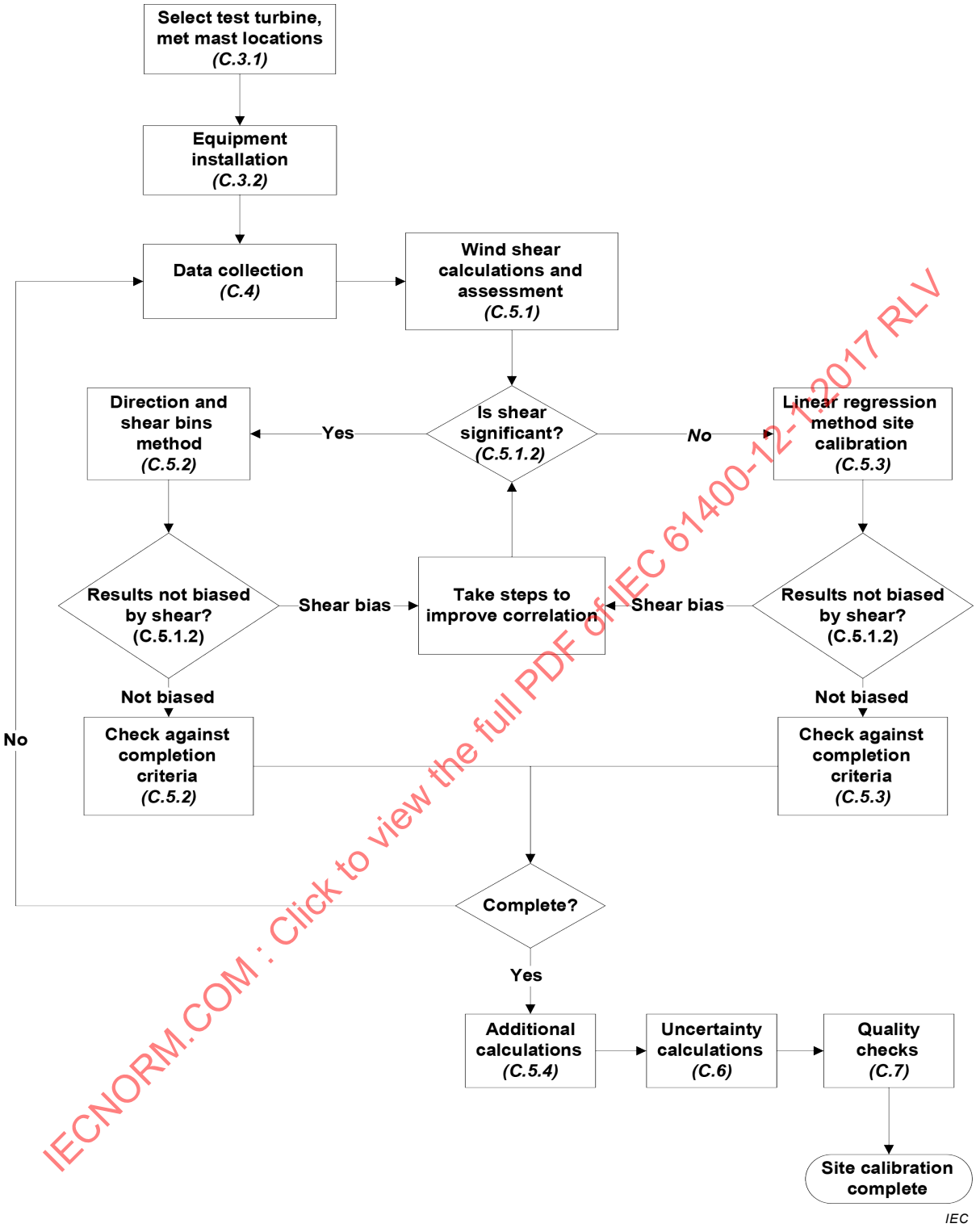

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Anglais	Français
Select test turbine, met mast locations *(C.3.1)*	Choix de l'éolienne d'essai et de l'emplacement du mât météorologique *(C.3.1)*
Equipment installation *(C.3.2)*	Installation du matériel *(C.3.2)*
Data collection *(C.4)*	Collecte des données *(C.4)*
Wind shear calculations and assessment *(C.5.1)*	Evaluation et calculs du cisaillement du vent *(C.5.1)*
Is shear significant? *(C.5.1.2)*	Le cisaillement est-il significatif? *(C.5.1.2)*
Yes	Oui

Anglais	Français
No	Non
Direction and shear bins method *(C.5.2)*	Méthode des tranches de direction et de cisaillement du vent *(C.5.2)*
Linear regression method site calibration *(C.5.3)*	Etalonnage du site selon la méthode de régression linéaire *(C.5.3)*
Results not biased by shear? *(C.5.1.2)*	Les résultats sont-ils polarisés par le cisaillement? *(C.5.1.2)*
Shear bias	Polarisation due au cisaillement
Take steps to improve correlation	Etapes à suivre pour améliorer la corrélation
Shear bias	Polarisation due au cisaillement
Results not biased by shear? *(C.5.1.2)*	Les résultats sont-ils polarisés par le cisaillement? *(C.5.1.2)*
Not biased	Pas de polarisation
Check against completion criteria *(C.5.2)*	Contrôler par rapport aux critères d'achèvement *(C.5.2)*
Check against completion criteria *(C.5.3)*	Contrôler par rapport aux critères d'achèvement *(C.5.3)*
Complete?	Terminé?
Additional calculations *(C.5.4)*	Calculs supplémentaires *(C.5.4)*
Uncertainty calculations *(C.6)*	Calculs d'incertitude *(C.6)*
Quality checks *(C.7)*	Contrôles de la qualité *(C.7)*
Site calibration complete	Etalonnage du site terminé

Figure C.1 – Organigramme d'étalonnage du site

C.3 Montage d'essai

C.3.1 Considérations relatives au choix de l'éolienne à l'essai et de l'emplacement du mât météorologique

Le mât météorologique de référence doit être le mât météorologique utilisé pour la mesure de la courbe de puissance. Le mât météorologique représentant l'éolienne doit être situé aussi près que possible de l'emplacement auquel l'éolienne à l'essai sera ou a été placée. Il doit se trouver à 0,2 H ou moins de l'axe central de l'éolienne, H étant la hauteur du moyeu de l'éolienne. Il est recommandé que l'éolienne et les mâts météorologiques de référence soient du même type et disposent de la même géométrie de flèche afin d'obtenir des effets de montage similaires sur le matériel de mesure du vent.

Plusieurs facteurs peuvent affecter l'étalonnage du site. Les facteurs les plus importants sont le terrain, l'emplacement du mât météorologique et les conditions atmosphériques, notamment le cisaillement du vent, les turbulences et la stabilité. Ils peuvent varier de manière significative d'un emplacement à un autre, mais sont souvent corrélés entre eux.

Il convient de choisir l'emplacement de l'éolienne à l'essai de manière à optimiser la collecte de données valides et à favoriser la corrélation entre les mâts météorologiques de référence et représentant l'éolienne. L'objectif de l'étalonnage du site est de mesurer les variations intervenant dans la couche limite, car le vent suit l'orographie du terrain, qui est généralement un écoulement associé, alors que les obstacles produisent davantage de sillages turbulents, lesquels sont affectés par les bords saillants et les surfaces verticales qui peuvent entraîner une séparation de l'écoulement. En outre, certaines particularités de terrains, comme les falaises ou les collines pentues, peuvent également provoquer une séparation de l'écoulement et ainsi entraîner une faible corrélation. A titre indicatif, il convient de prendre en considération le type de terrain lors du choix des emplacements de l'éolienne à l'essai et du mât météorologique de référence. Les types de terrains dont il est question dans le présent document constituent des descriptions informatives et qualitatives destinées à apporter une aide dans le choix des emplacements de l'éolienne à l'essai et du mât météorologique de

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référence, ainsi qu'à fournir des informations sur ce à quoi il faut s'attendre lors de la réalisation de mesures sur ces types de terrains. Des exemples de ces types de terrains sont donnés à la Figure C.2.

Type A:

Le terrain de type A est le type de terrain le moins complexe. En règle générale, un site de type A ne présente pas de variations significatives d'altitude par rapport à la hauteur du moyeu de l'éolienne ou de pentes particulièrement raides sur de longues distances. Les terrains qui satisfont aux exigences de l'Annexe B, les collines en pente douce et éventuellement les éoliennes situées sur une crête située face à une plaine sont des exemples de terrains de type A.

Lorsque des étalonnages sont réalisés sur des sites de type A, les conditions de cisaillement du vent à l'emplacement du mât météorologique de référence peuvent être différentes des conditions de cisaillement du vent à l'emplacement de l'éolienne. Le cas échéant, les résultats d'étalonnage du site seront susceptibles de dépendre du cisaillement et de la direction du vent.

Type B:

Le terrain de type B correspond à un terrain de complexité modérée à élevée. Les terrains de type B incluent les montagnes, les bords de crêtes, les grandes collines et les sites vallonnés avec des pentes modérées à raides. Ils présentent des variations significatives d'altitude par rapport à la hauteur du moyeu de l'éolienne. En règle générale, le cisaillement du vent sur des sites de type B est faible et relativement constant, bien qu'il puisse parfois être négatif. Par conséquent, il n'est pas prévu que le cisaillement du vent constitue un facteur aussi significatif que pour les sites de type A. Néanmoins, les résultats d'étalonnage sur les sites de type B dépendent souvent à la fois de la vitesse et de la direction du vent, en particulier si la différence d'altitude entre le mât météorologique de référence et l'éolienne à l'essai est supérieure à 10 m. Une correction de régression linéaire est donc fréquemment appropriée pour les sites de type B.

La composante écoulement ascendant/vitesse verticale du vent qu'impliquent les terrains de type B peut avoir un impact considérable sur l'incertitude, en fonction de la réponse des anémomètres à l'écoulement ascendant. Une mesure de la vitesse verticale du vent peut servir à évaluer l'angle d'écoulement ascendant, qui peut ensuite être utilisé en association avec le rapport de classification des anémomètres dans le but de calculer les caractéristiques d'exploitation d'un anémomètre de type S avec des plages des paramètres d'influence définies par les utilisateurs et décrites à l'Article I.3.

Type C:

Les terrains de type C sont les terrains les plus extrêmes du point de vue de la réalisation de mesures. Les sites de type C présentent généralement un élément de terrain pentu (p. ex.: montagne ou canyon) qui peut provoquer la séparation de l'écoulement directement du côté exposé au vent de l'éolienne à l'essai et créer une zone de recirculation à son emplacement. L'ampleur de la séparation de l'écoulement est définie par cet élément de terrain et peut perturber la corrélation de la vitesse du vent entre l'éolienne à l'essai et le mât météorologique de référence, même si l'élément de terrain est situé à une distance de plus de $16L$ de l'éolienne à l'essai. En règle générale, le terrain de type C est si complexe que la corrélation entre les vents au niveau du mât météorologique de référence et de l'éolienne à l'essai peut être faible. Les corrections de l'écoulement peuvent différer de manière significative entre les tranches adjacentes de direction du vent. Une attention particulière doit être prêtée au choix des éoliennes à l'essai pour les emplacements situés sur des terrains de type C dans le sens où les données seront généralement très dispersées et présenteront une grande incertitude de résultat.

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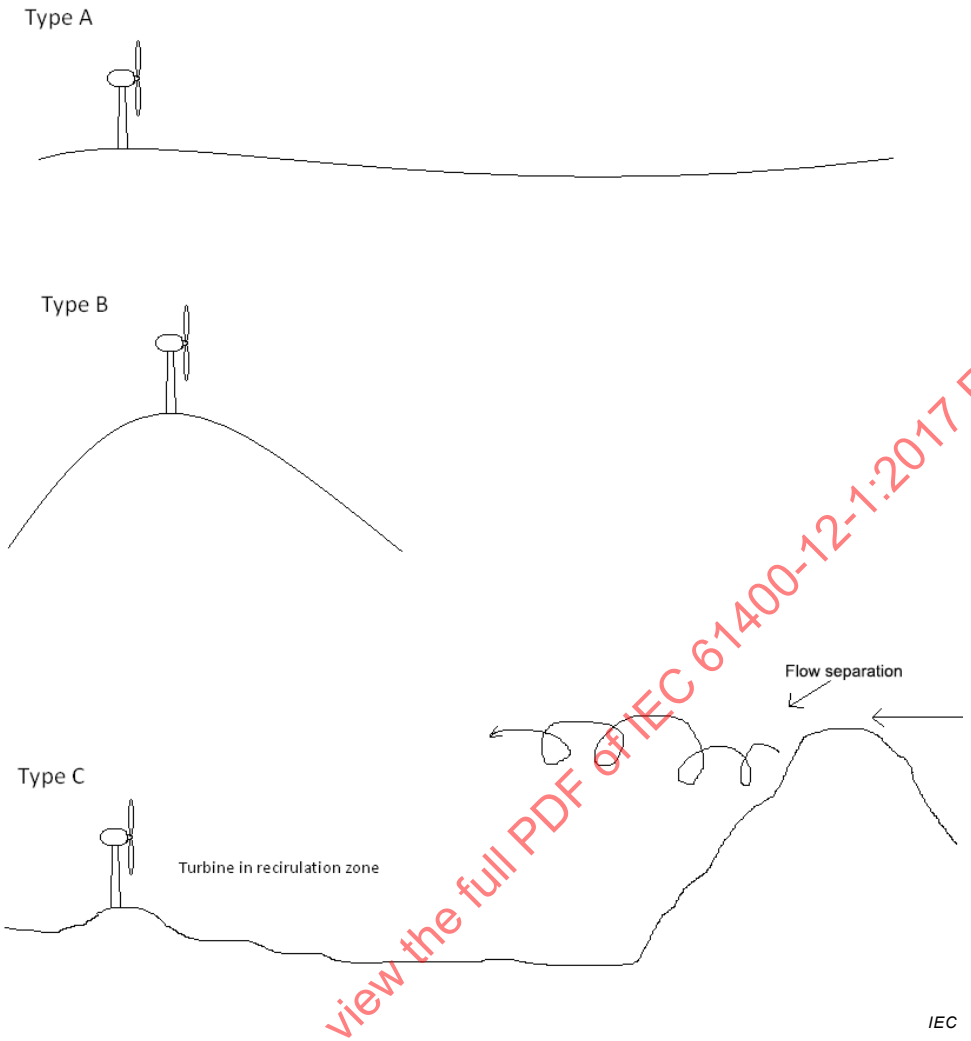

Anglais	Français
Type A	Type A
Type B	Type B
Type C	Type C
Flow separation	Séparation de l'écoulement
Turbine in recirculation zone	Eolienne située dans une zone de recirculation

Figure C.2 – Types de terrains

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Afin d'améliorer la corrélation, il convient de placer le mât météorologique de référence de façon à ce qu'il ait une altitude et des conditions de vent similaires à celles de l'éolienne à l'essai. Par exemple, si l'éolienne à l'essai est située sur une crête, il est recommandé de positionner le mât météorologique de référence sur cette crête à côté de l'éolienne plutôt qu'à une altitude inférieure face à l'éolienne.

C.3.2 Instrumentation

Le montage d'essai exige au minimum la réalisation des mesures de la vitesse du vent à la hauteur du moyeu, de la direction du vent à proximité de la hauteur du moyeu et du cisaillement du vent au niveau des deux mâts météorologiques conformément à 7.2.8.

Le WME utilisé pour l'étalonnage du site doit satisfaire aux exigences de 7.2 et suivre les lignes directrices relatives au montage données à l'Annexe G. Les anémomètres doivent être du même type, présenter des caractéristiques d'exploitation identiques et doivent également

être étalonnés dans la même soufflerie. Les anémomètres doivent être du même type et présenter des caractéristiques d'exploitation identiques pour la mesure de la courbe de puissance et pour l'étalonnage du site.

En fonction des caractéristiques du site, des mesures supplémentaires sont recommandées afin de fournir davantage d'informations sur les conditions du site. Elles ne sont par conséquent pas normatives. Ces mesures peuvent également être utilisées pour améliorer la qualité générale de l'étalonnage du site et de la mesure de la courbe de puissance en identifiant des conditions atmosphériques inhabituelles qui se corrèlent avec les valeurs aberrantes ou peuvent être utilisées pour déterminer une classification pertinente des instruments et, en association avec le rapport de classification correspondant, quantifier l'incertitude-type des caractéristiques d'exploitation des anémomètres spécifiques au site.

a) Une mesure de la vitesse verticale du vent (p. ex.: avec un anémomètre à ultrasons 3D) est recommandée dans les 10 % de la hauteur du moyeu ou dans les 5 m de la hauteur du moyeu pour les petites éoliennes afin de ne pas enfreindre les exigences de montage des capteurs montés en tête de mât données à l'Annexe G. Cette mesure peut être utilisée pour déterminer la classe pertinente pour la classification des instruments et, en association avec le rapport de classification correspondant, pour quantifier l'incertitude due aux caractéristiques d'exploitation, conformément à l'Annexe I.

b) Une mesure de la déviation de la trajectoire du vent est recommandée pour la direction du vent mesurée au point le plus bas à 10 m ou moins de la mesure de la vitesse du vent à la hauteur de l'extrémité inférieure.

c) Si des conditions de givrage sont prévues pendant la campagne d'étalonnage du site, un capteur de température ou d'autres moyens de détection du givrage sont recommandés à proximité de la hauteur du moyeu.

De plus, afin d'éviter l'introduction d'une polarisation dans la mesure de la direction du vent en raison de l'incertitude liée à l'installation du capteur de direction du vent, il convient de ne pas retirer le mât météorologique de référence ni son/ses capteurs de direction du vent entre l'étalonnage du site et la mesure de la courbe de puissance. Si le capteur principal de direction du vent est enlevé ou remplacé, une composante d'incertitude supplémentaire doit être incluse (voir C.7.4). Si le mât météorologique de référence est retiré puis installé à nouveau entre l'étalonnage du site et la mesure de la courbe de puissance, les instruments doivent être montés selon la même configuration et avec des angles de flèche identiques pendant ces deux périodes afin d'obtenir des effets de montage similaires.

C.4 Acquisition de données et critères de rejet

Les données doivent être recueillies en continu à la même fréquence d'échantillonnage que pour l'essai de performance de puissance. Les ensembles de données doivent être fondés sur des périodes de 10 min déduites à partir de données mesurées de façon continue. Pour chaque période de 10 min, la valeur moyenne, l'écart-type, la valeur minimale et la valeur maximale doivent être déduits et stockés.

La taille de la tranche de direction du vent doit être égale à 10°.

Des ensembles de données doivent être rejetés de la base de données dans les circonstances suivantes:

a) le matériel d'essai est défaillant ou dégradé (par exemple, à cause du givrage);

b) la direction du vent est en dehors du ou des secteurs de mesure définis en 6.3.3;

c) la vitesse moyenne du vent sur le mât météorologique représentant l'éolienne est inférieure à 4 m/s ou supérieure à 16 m/s;

d) toutes les autres conditions atmosphériques particulières dont il s'avère qu'elles influent sur les résultats d'étalonnage du site et qui sont donc choisies comme critères de rejet;

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e) les conditions atmosphériques particulières qui doivent être utilisées comme critères de rejet au cours de l'essai de performance de puissance et dont il s'avère qu'elles influent sur l'étalonnage du site.

Toute condition atmosphérique particulière filtrée pendant l'étalonnage du site doit l'être également pendant l'essai de courbe de puissance.

C.5 Analyse

L'étalonnage du site mesure la relation des vitesses du vent à deux points spécifiques dans l'espace. L'orographie exerce une influence statique sur cette relation (le terrain est fixe dans le temps) alors que le cisaillement du vent lui apporte un élément dynamique, puisque le gradient de la vitesse du vent peut varier de manière significative avec la hauteur, ou peut ne pas varier si le site présente uniquement un cisaillement relativement stable sur une plage limitée.

La première étape du processus d'étalonnage du site consiste donc à évaluer les conditions de cisaillement sur le site. Pour cela, les calculs et tracés de C.5.1 sont réalisés en premier. Ensuite, en fonction des résultats obtenus, C.5.2 ou C.5.3 est appliqué pour calculer les corrections de l'écoulement. A la suite du calcul des corrections de l'écoulement conformément à C.5.2 ou C.5.3, la procédure se poursuit avec les calculs supplémentaires de C.5.4, qui permettront de réaliser les calculs d'incertitude de l'Article C.6 et les contrôles de qualité de l'Article C.7.

C.5.1 Evaluation des conditions de cisaillement du site

C.5.1.1 Calculs et tracés de caractérisation du cisaillement

Pour chaque point de données sur 10 min, les calculs suivants doivent être effectués:

a) le rapport de vitesses du vent, soit la vitesse du vent à la hauteur du moyeu à l'emplacement de l'éolienne divisée par la vitesse du vent à la hauteur du moyeu à l'emplacement du mât météorologique de référence;

b) l'exposant de cisaillement aux deux mâts météorologiques, qui doit être calculé à l'aide de la loi exponentielle (voir 3.31);

c) l'heure du jour selon un système horaire sur 24 h, qui doit être déterminée à partir de l'horodatage et de tout décalage par rapport à l'heure locale du site. Tout réglage des horloges locales pour passer de l'heure d'été à l'heure d'hiver (avancement d'une heure pour l'heure d'été) doit être consigné s'il est appliqué aux horodatages de l'enregistreur de données.

La méthode d'analyse doit dépendre de la détermination ou non du cisaillement du vent comme un facteur significatif sur le site. Un cisaillement élevé, ou plus spécifiquement une large plage de valeurs de cisaillement, est généralement provoqué par un cycle diurne avec une atmosphère stable la nuit et une atmosphère instable au cours de la journée. A des fins de représentation des conditions de cisaillement sur le site et d'aide à l'évaluation du cisaillement, les diagrammes de dispersion suivants doivent être générés pour les données de l'emplacement de l'éolienne ainsi que de l'emplacement du mât météorologique de référence à partir de la base de données filtrée:

1) diagramme de dispersion de l'exposant de cisaillement du vent par rapport à l'heure du jour;

2) diagramme de dispersion de l'exposant de cisaillement du vent par rapport à la direction du vent;

3) diagramme de dispersion de l'exposant de cisaillement du vent par rapport à la vitesse du vent;

4) diagramme de dispersion de la vitesse du vent par rapport à l'heure du jour.

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Il est à noter qu'il convient d'utiliser l'heure du jour avec précaution. L'objectif réel est de prendre en compte les heures de lever et de coucher du soleil locales, car celles-ci influencent fortement la stabilité atmosphérique. Or, en particulier pour les ensembles de données les plus longs et les latitudes les plus élevées, la corrélation entre le lever du soleil, le coucher du soleil et l'heure du jour est assez faible.

En règle générale, pour un site sur lequel ces effets se produisent, les exposants de cisaillement observés au cours de la journée seront faibles tant que le soleil réchauffe le sol, provoquant des turbulences et un brassage des couches, puis seront élevés la nuit. Par conséquent, une large plage d'exposants de cisaillement ainsi qu'une variation considérable des exposants de cisaillement entre la journée et la nuit peuvent être observées sur ces sites.

C.5.1.2 Evaluation de l'importance du cisaillement

Indépendamment de la stabilité atmosphérique, le cisaillement doit être considéré comme un facteur significatif si plus de 25 % des points de données affichent un exposant de cisaillement supérieur à 0,25.

Il doit être confirmé que le cisaillement est un paramètre significatif si la corrélation avec la vitesse du vent s'améliore après la répartition en tranches en fonction de la direction et du cisaillement conformément à la Méthode 1 de C.5.2. A défaut, l'étalonnage du site peut être évalué d'après la Méthode 2 décrite en C.5.3 (méthode de régression linéaire).

La division du secteur de mesure pour permettre l'application de méthodologies différentes à divers secteurs est admise. Elle peut être utile si, par exemple, le terrain d'une partie du secteur de mesure est de type A, mais correspond au type B en provenance d'une autre direction.

L'objectif est de garantir que l'étalonnage du site n'est pas polarisé par des conditions de cisaillement inhabituelles. En effet, soit la méthode d'étalonnage du site tient compte de l'impact du cisaillement, soit les conditions peu communes sont filtrées. Les résultats de l'étalonnage du site effectué à l'aide de la méthode de C.5.2 ou de C.5.3 peuvent être évalués avec la méthode de C.5.4, laquelle applique les corrections d'étalonnage du site à la vitesse du vent au niveau du mât permanent avant de réaliser une comparaison avec la vitesse du vent à l'emplacement de l'éolienne. La comparaison entre les résidus d'étalonnage du site et le cisaillement du vent ou d'autres indicateurs de stabilité atmosphérique révélera si la méthode choisie corrige avec précision la vitesse du vent à l'emplacement permanent, quelles que soient les conditions, ou si des actions supplémentaires sont nécessaires pour améliorer sa qualité et réduire l'incertitude. Plus spécifiquement:

a) il convient que le paramètre de cohérence interne (Equation (C.3) en C.5.4) moyenné par tranche de vitesse du vent soit compris entre 0,98 et 1,02 dans la plage de valeurs de 4 m/s à 16 m/s au sein de chaque secteur;

b) il convient qu'une régression linéaire de $V_{\text{Turb_predicted}}$ (Equation (C.1)) par rapport à $V_{\text{Turb_measured}}$ ait une valeur de $R^2 > 0{,}95$ au sein de chaque secteur.

C.5.1.3 Etablissement d'une corrélation du cisaillement entre les emplacements

S'il est établi que le cisaillement est significatif sur le site et s'il existe une exigence imposant de filtrer le cisaillement à l'emplacement de l'éolienne, alors il doit être établi que le cisaillement à l'emplacement de l'éolienne peut être prédit à partir du cisaillement mesuré à l'emplacement du mât météorologique de référence. Pour cela, la méthode la plus simple consiste à établir le tracé du cisaillement à l'emplacement de l'éolienne par rapport au cisaillement à l'emplacement du mât de référence, puis à appliquer la méthode de régression linéaire des moindres carrés ordinaires. Cela doit être effectué à l'aide de la base de données filtrée. Il est à noter que cette régression peut être utilisée pendant la mesure de la courbe de puissance dans le but de prédire le cisaillement à l'emplacement de l'éolienne.

Si le cisaillement à l'emplacement de l'éolienne et le cisaillement à l'emplacement du mât de référence ne sont pas corrélés dans tous les cas, des actions supplémentaires doivent être

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entreprises pour que les données soient systématiquement corrélées. Par exemple, une non-corrélation peut apparaître lorsqu'une différence significative d'altitude entre l'emplacement du mât de référence et celui de l'éolienne à l'essai est observée en association avec un cisaillement élevé, lui-même souvent corrélé avec l'heure du jour. Le cas échéant, la méthode suggérée pour obtenir des résultats corrélés consiste à filtrer les données en fonction de l'heure du jour afin de supprimer les données de cisaillement élevé relevées pendant la nuit, bien que d'autres méthodes de suppression des données non corrélées soient admises. Le filtre de l'heure du jour peut être établi à partir des tracés de l'exposant de cisaillement en fonction de l'heure du jour. Différentes méthodes, entre autres la réduction du secteur de mesure visant à étudier uniquement les directions présentant des conditions d'écoulement similaires, le filtrage ou le fractionnement de l'étalonnage du site en fonction des saisons, peuvent être utilisées pour obtenir un ensemble de données parfaitement corrélé. Les tracés de l'exposant de cisaillement du vent en fonction de la direction du vent peuvent être utiles pour déterminer les secteurs à utiliser.

Chaque filtre supplémentaire appliqué aux résultats de l'étalonnage du site doit également être appliqué lors de la mesure de la courbe de puissance. Si un filtre de l'heure du jour est utilisé, il peut être ajusté en fonction des saisons afin de tenir compte de la longueur des jours, à savoir plus longs en été et plus courts en hiver. Il convient de n'utiliser que les données correspondant au mât de référence pour tous les filtres supplémentaires, car les données à l'emplacement de l'éolienne ne pourront pas être filtrées lors de la mesure de la courbe de puissance.

Le cisaillement, les turbulences et la vitesse du vent sont souvent corrélés. Les tracés de l'exposant de cisaillement du vent par rapport à la direction du vent, de l'exposant de cisaillement du vent par rapport à la vitesse du vent et de la vitesse du vent par rapport à l'heure du jour peuvent être utilisés pour évaluer l'impact potentiel de ces filtres sur les données de la courbe de puissance en ce qui concerne les données réduites à des vitesses du vent spécifiques. Par exemple, si l'application d'un filtre de l'heure du jour entraîne la perte de la plupart des données pour des vitesses élevées du vent, ce filtre peut ne pas être pratique. En dernier recours, une solution pourrait consister à réaliser plusieurs étalonnages du site, chacun d'entre eux étant valide pour une plage spécifique de conditions atmosphériques.

C.5.2 Méthode 1: tranches de direction du vent et tranches de cisaillement du vent

Pour déterminer si les facteurs de correction de l'étalonnage du site sont influencés par le cisaillement sur le site, les données doivent être réparties en tranches de direction du vent et de cisaillement du vent. La taille des tranches de direction du vent doit être de 10° et ne doit pas être inférieure à l'incertitude du capteur de direction du vent. Les données doivent être filtrées aux limites des extrémités du secteur de mesure. Par exemple, lorsque le secteur de mesure se termine à 43°, l'étalonnage du site à l'extrémité du secteur sera évalué de 35° à 43° uniquement. Le choix de la définition du centre de la tranche de direction (p. ex.: tranches centrées sur des multiples entiers de 10° ou tranches commençant par des multiples entiers de 10°) doit être réalisé de manière cohérente de l'étalonnage du site à l'essai de courbe de puissance. Les tranches de cisaillement du vent doivent augmenter par incréments de 0,05 pour l'exposant de cisaillement et être centrées sur des multiples entiers de 0,05.

Les rapports de vitesses du vent au sein de chaque tranche de direction du vent et de cisaillement du vent doivent être moyennés.

Les critères d'achèvement pour les tranches de direction du vent et de cisaillement du vent sont les suivants:

a) Au sein de chaque tranche de direction du vent, le nombre total minimal de points de données dans toutes les tranches de cisaillement du vent doit être de 144 (24 h de données). Des tranches de cisaillement du vent incomplètes peuvent être incluses dans ce nombre total. En outre, chaque tranche de direction du vent doit contenir au moins 6 h au-dessus de 8 m/s et 6 h en dessous de cette même valeur.

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b) Chaque tranche de cisaillement du vent au sein d'une tranche de direction du vent complète doit contenir au moins 3 points de données.

c) Les tranches de cisaillement du vent dans les secteurs de direction du vent incomplets qui contiennent au moins 6 h de données peuvent également être considérées comme complètes.

Après réalisation de la matrice, s'il est observé que les corrections de l'étalonnage du site ne varient pas à mesure que le cisaillement du vent augmente, alors les tranches de cisaillement du vent peuvent être éliminées et les données évaluées sur la seule base d'une tranche de direction du vent, conformément à C.5.3. Le niveau de variation doit être évalué par rapport à l'incertitude statistique de l'étalonnage du site.

Si la variation entre les tranches de cisaillement du vent provoque une variabilité des facteurs de l'étalonnage du site supérieure à deux fois l'incertitude statistique de l'étalonnage du site dans une ou plusieurs tranches de direction du vent, les tranches de cisaillement du vent doivent être incluses dans l'analyse au même titre que les tranches de direction du vent.

Si la variation entre les tranches de cisaillement du vent provoque une variabilité des facteurs de l'étalonnage du site inférieure à deux fois l'incertitude statistique de l'étalonnage du site dans une ou plusieurs tranches de direction du vent, les tranches de cisaillement du vent peuvent être éliminées et les données évaluées sur la seule base de la direction du vent conformément à C.5.3.

Au cours de la mesure de la courbe de puissance, les données doivent être réparties dans des tranches de direction du vent. Pour chaque point de données sur 10 min, l'exposant de cisaillement du vent au niveau du mât de référence doit être calculé. La correction appliquée à la vitesse du vent à la hauteur du moyeu doit être le rapport de vitesses du vent interpolé à la valeur de cisaillement du vent mesurée à partir des valeurs moyennes de la tranche de cisaillement du vent et de l'exposant de cisaillement du vent mesuré pour cette tranche de direction du vent. L'extrapolation est admise pour les exposants de cisaillement du vent se trouvant dans les dernières tranches de cisaillement complètes. Par exemple, si la dernière tranche de cisaillement complète pour l'étalonnage du site est la tranche de cisaillement de 0,6, une extrapolation est admise pour les valeurs mesurées de l'exposant de cisaillement comprises entre 0,600 et 0,625 (0,625 étant l'extrémité supérieure de la tranche de cisaillement du vent de 0,6, pour une largeur de tranche de 0,05 et une plage de 0,575 à 0,625). L'interpolation entre deux tranches de cisaillement du vent complètes sur une tranche de cisaillement incomplète est admise. L'interpolation entre des tranches de direction du vent n'est pas admise.

C.5.3 Méthode 2: méthode de régression linéaire lorsque le cisaillement n'a pas une influence significative

Les ensembles de données doivent être répartis en tranches de direction du vent. La taille des tranches de direction du vent doit être de 10°. Le choix de la définition du centre de la tranche de direction (p. ex.: tranches centrées sur des multiples entiers de 10° ou tranches commençant par des multiples entiers de 10°) doit être réalisé de manière cohérente de l'étalonnage du site à l'essai de courbe de puissance. Les données doivent être filtrées aux limites des extrémités du secteur de mesure. Par exemple, lorsque le secteur de mesure se termine à 43°, l'étalonnage du site à l'extrémité du secteur sera évalué de 35° à 43° uniquement.

Pour chaque tranche de direction du vent, la méthode de régression linéaire des moindres carrés ordinaires doit être appliquée, la vitesse du vent à l'emplacement de l'éolienne étant la variable dépendante et la vitesse du vent de référence étant la variable indépendante. Par conséquent, chaque tranche de direction du vent présentera une pente et une ordonnée à l'origine.

Chaque tranche de direction du vent doit compter un total d'au moins 24 h de données, et doit compter au moins 6 h de données lorsque la vitesse du vent est supérieure à 8 m/s ou inférieure à 8 m/s. Il convient d'étendre la répartition des vitesses du vent au sein de la

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tranche afin d'obtenir une bonne corrélation (voir C.7.2). Il est par conséquent recommandé d'utiliser des données relatives aux vitesses du vent allant jusqu'à 11 m/s, voire plus. Il est à noter que les valeurs aberrantes sont fortement pondérées par la méthode de régression linéaire des moindres carrés ordinaires. Il convient d'analyser et de documenter les valeurs aberrantes ayant un impact significatif sur la régression.

Pour représenter la corrélation entre la vitesse du vent à l'emplacement de référence et à l'emplacement de l'éolienne, les tracés suivants doivent être générés pour chaque tranche de direction du vent complète au sein du secteur de mesure:

> Vitesse du vent au niveau du mât de l'éolienne par rapport à la vitesse du vent au niveau du mât de référence, avec indication des coefficients de régression linéaire et de corrélation (communément appelés valeur R^2);

Sur un axe unique, effectuer les tracés ci-après. Un exemple est donné à la Figure C.11 à l'Article C.9:

a) rapport de vitesses du vent par rapport à la vitesse du vent de référence;

b) moyennes des tranches des rapports de vitesses du vent en tranches de vitesse du vent de 0,5 m/s;

c) courbe $y = m+b/x$ où m est la pente de la régression linéaire, b est l'ordonnée à l'origine, x est la vitesse du vent de référence et y est la vitesse du vent prédite à l'emplacement de l'éolienne normalisée à la vitesse du vent au niveau du mât de référence, c'est-à-dire y = rapport de vitesses du vent;

d) ligne horizontale indiquant la moyenne de tous les rapports de vitesses du vent au sein de la tranche de direction du vent.

C.5.4 Calculs supplémentaires

Les corrections de l'écoulement dictées par l'étalonnage du site doivent être appliquées aux données du mât météorologique de référence pour calculer la vitesse du vent prédite à l'emplacement de l'éolienne pour chaque point de données. Cela doit être effectué à l'aide de la base de données filtrée.

$$V_{\text{Turb_predicted}} = F(WD, \alpha) \times V_{\text{PM}} \quad \text{(C.1)}$$

où

$V_{\text{Turb_predicted}}$ est la vitesse du vent prédite à l'emplacement de l'éolienne

$F(WD,\alpha)$ est la correction de l'écoulement dictée par l'étalonnage du site définie en C.5.2;

V_{PM} est la vitesse du vent au niveau du mât météorologique de référence;

WD est la tranche de direction du vent;

α est l'exposant de cisaillement du vent, le cas échéant.

Un résidu d'étalonnage du site doit être calculé de la manière décrite ci-dessous pour chaque point de données sur 10 min. Il correspond à la différence entre la vitesse du vent prédite à l'emplacement de l'éolienne et la vitesse du vent mesurée au niveau du mât météorologique représentant l'éolienne.

$$residual = V_{\text{Turb_predicted}} - V_{\text{Turb_measured}} \quad \text{(C.2)}$$

Un paramètre de cohérence interne doit être calculé de la manière décrite ci-après pour chaque point de données sur 10 min: diviser la vitesse du vent prédite à l'emplacement de l'éolienne par la vitesse du vent réelle au niveau du mât météorologique représentant l'éolienne.

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$$self_consistency_paramenter = \frac{V_{\text{Turb_predicted}}}{V_{\text{Turb_measured}}} \quad \text{(C.3)}$$

Les résidus et le paramètre de cohérence interne sont utilisés pour évaluer la variation et les éventuelles polarisations des résultats. La moyenne des résidus et le paramètre de cohérence interne reflètent une polarisation moyenne. Les valeurs moyennes respectives de 0 et 1,0 correspondent à une polarisation nulle. L'écart-type de ces paramètres indique la variation de la polarisation moyenne. Il est utilisé pour le calcul de l'incertitude statistique de l'étalonnage du site.

Outre pour le calcul de l'incertitude statistique, qui s'appuie sur la variation d'une polarisation moyenne réputée nulle, ces paramètres sont utilisés pour le calcul de l'incertitude supplémentaire qui doit être ajoutée à certains scénarios énumérés à l'Article C.7. Ces scénarios sont élaborés à partir d'évaluations de la polarisation moyenne estimée qu'ils introduisent, et qui se reflète dans les décalages par rapport à la moyenne de ces paramètres, différant respectivement de 0 et de 1,0.

C.6 Incertitude d'étalonnage du site

C.6.1 Incertitude d'étalonnage du site de catégorie A

C.6.1.1 Analyse par validation croisée en k échantillons de l'étalonnage du site

L'étalonnage du site exploite un modèle de prédiction de la vitesse du vent à l'emplacement de l'éolienne en fonction de la vitesse du vent à l'emplacement du mât météorologique. Pour éviter le risque de sous-estimation de l'incertitude de catégorie A en raison d'un ajustement excessif du modèle aux données, l'incertitude de catégorie A doit être calculée à l'aide de la validation croisée en k échantillons, où k = 10. Il est à noter que, dans le secteur éolien, la lettre "k" a différentes significations. Toutefois, son utilisation dans le présent document coïncide avec son utilisation en apprentissage statistique, la méthode appliquée étant appelée *validation croisée en k échantillons*.

L'ensemble final de données filtrées doit être divisé en k échantillons (divisions) de taille égale en fonction de l'horodatage.

Pour chaque échantillon (k = 1 à 10):

a) les corrections d'étalonnage du site doivent être calculées conformément à l'Article C.5, en utilisant uniquement les données des 9 autres échantillons;

b) les corrections d'étalonnage du site doivent être utilisées pour calculer la vitesse du vent prédite à l'emplacement de l'éolienne en utilisant les vitesses du vent mesurées au niveau du mât de référence pour un échantillon k;

c) les vitesses du vent prédites à l'emplacement de l'éolienne pour un échantillon k doivent être comparées aux vitesses du vent réelles mesurées au niveau de l'éolienne pour un échantillon k conformément aux paramètres de résidus et de cohérence interne définis en C.5.4;

d) l'incertitude statistique pour un échantillon k doit être déterminée conformément à C.6.1.2.

L'incertitude totale de catégorie A correspond à la racine carrée de la somme des carrés de l'incertitude calculée pour chaque échantillon divisée par la racine carrée de k.

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$$s_{\mathrm{sc}} = \sqrt{\frac{\sum_{i=1}^{k} s_{\mathrm{sc},i}^2}{k}} \tag{C.4}$$

Une valeur de k = 10 est choisie afin d'augmenter la probabilité de disposer de suffisamment d'informations dans les ensembles restants pour couvrir la plage de vitesses du vent présente dans l'ensemble de données en cours d'évaluation. Toutefois, d'autres valeurs de k sont admises, du moment que $k \geq 2$.

Les échantillons sont répartis par horodatage plutôt que choisis au hasard. En effet, il est prévu que les variations de relation des vitesses du vent entre les deux emplacements puissent être corrélées avec des événements météorologiques, eux-mêmes corrélés avec le temps. Ainsi, les échantillons répartis en fonction du temps sont plus susceptibles de mieux détecter les variations entre les conditions au cours des périodes d'étalonnage du site et de mesure de la courbe de puissance.

C.6.1.2 Incertitude statistique d'étalonnage du site pour chaque échantillon

Pour chaque échantillon de la validation croisée en k échantillons, l'écart entre la vitesse du vent corrigée après l'étalonnage du site à l'emplacement de l'éolienne et la vitesse du vent mesurée au niveau du mât météorologique représentant l'éolienne est calculé pour chaque période de 10 min. L'écart-type de l'écart de vitesse du vent sur toutes les périodes de 10 min est calculé comme suit:

$$d_{\mathrm{std},k} = \sqrt{\frac{\sum_{j=1}^{N} \left(d_{j,k} - \overline{d}_k\right)^2}{N_k - 1}} \tag{C.5}$$

où

$d_{j,k}$ est le résidu de la j^{e} période de 10 min d'un échantillon k, voir Equation (C.2);

$\overline{d}_k$ est la valeur moyenne des résidus dans un échantillon k;

N_k est le nombre d'ensembles de données dans un échantillon k;

$d_{\mathrm{std},k}$ est l'écart-type des résidus d'étalonnage du site pour un échantillon k.

Seules les données qui ont été intégrées à l'évaluation de l'étalonnage du site doivent être incluses dans le calcul de l'écart-type.

L'incertitude-type statistique de catégorie A d'un échantillon k est la suivante:

$$s_{\mathrm{sc},k} = d_{\mathrm{std},k} \cdot \frac{\sqrt{N_k - 1}}{\sqrt{f \cdot N_k}} \tag{C.6}$$

où

f est le nombre de degrés de liberté de l'étalonnage du site.

Le nombre f correspond à la différence entre le nombre de périodes de 10 min incluses dans l'étalonnage du site et le nombre total de paramètres de l'algorithme d'étalonnage du site. Si les corrections de l'écoulement dictées par l'étalonnage du site se présentent sous la forme de rapports de vitesses du vent moyennés par tranche, le nombre de paramètres de l'algorithme d'étalonnage du site par sous-secteur de direction du vent est égal au nombre de

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tranches de cisaillement du vent. f correspond alors à la différence entre N_k et le nombre de sous-secteurs de direction du vent (en règle générale, un nombre de secteurs ayant une largeur de 10°). Si les corrections de l'écoulement dictées par l'étalonnage du site se présentent sous la forme de régressions linéaires (pentes et décalages), le nombre de paramètres de l'algorithme d'étalonnage du site est de 2 par sous-secteur de direction du vent. f correspond alors à la différence entre N_k et deux fois le nombre de tranches de direction du vent. Si les corrections de l'écoulement dictées par l'étalonnage du site se présentent sous la forme de rapports de vitesses du vent moyennés par tranche en fonction de la direction du vent et de la tranche de cisaillement du vent, f correspond à la différence entre N_k et la somme des nombres de toutes les tranches de cisaillement du vent dans tous les sous-secteurs de direction du vent.

C.6.2 Incertitude d'étalonnage du site de catégorie B

Il convient de considérer les composantes d'incertitude suivantes comme étant indépendantes les unes des autres lors de l'évaluation de l'incertitude-type composée de catégorie B.

$u_{\mathrm{VT,precal},i}$: Etalonnage de l'anémomètre – l'incertitude-type de l'étalonnage de l'anémomètre doit être issue des étalonnages. Lorsque les étalonnages de l'anémomètre au niveau du mât météorologique de référence et du mât météorologique représentant l'éolienne ont été réalisés dans la même soufflerie, les incertitudes estimées sont dans une certaine mesure corrélées. Il en va de même pour les étalonnages du ou des anémomètres utilisés pour les essais de performance de puissance. Une approche pratique consiste à inclure l'amplitude d'une incertitude d'étalonnage si les étalonnages sont effectués dans la même soufflerie. Lorsque les étalonnages ont été réalisés dans des soufflerie différentes ou lorsque différents modèles d'anémomètres sont utilisés, les incertitudes sont indépendantes et doivent être prises en compte en tant que telles.

$u_{\mathrm{VT,class},i}$: Caractéristiques d'exploitation de l'anémomètre – l'incertitude-type d'exploitation de l'anémomètre au niveau du mât météorologique représentant l'éolienne doit être prise en considération dans les calculs de l'incertitude d'étalonnage du site. La corrélation des caractéristiques d'exploitation au cours de l'étalonnage du site doit être étudiée afin de déterminer dans quelle mesure les incertitudes des caractéristiques d'exploitation au niveau de l'éolienne et de l'anémomètre de référence doivent être prises en considération. En fonction des différences entre les conditions environnementales au cours de la mesure de la courbe de puissance et au cours de l'étalonnage du site, une augmentation de l'incertitude des caractéristiques d'exploitation peut être exigée. Au cours de l'étalonnage du site, il convient de prendre totalement en compte l'incertitude opérationnelle de l'anémomètre de l'éolienne.

$u_{\mathrm{VT,mnt},i}$: Effets de montage – les incertitudes-types de montage de l'anémomètre au niveau du mât météorologique de référence et de l'anémomètre au niveau du mât météorologique représentant l'éolienne doivent être prises en considération dans l'évaluation de l'incertitude d'étalonnage du site.

$u_{\mathrm{dVT},i}$: L'incertitude-type de la vitesse du vent relative au système d'acquisition de données doit être estimée conformément à l'Annexe D et à l'Annexe E.

C.6.3 Incertitude composée

Il convient de considérer les composantes d'incertitude de catégorie A et de catégorie B comme étant indépendantes les unes des autres lors de l'évaluation de l'incertitude composée de l'étalonnage du site.

La restriction du secteur de mesure à des fins de réduction de l'incertitude par élimination des tranches de direction du vent présentant une incertitude plus élevée est admise.

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C.7 Contrôles de la qualité et incertitudes supplémentaires

C.7.1 Contrôle de la convergence

Pour chaque tranche de direction du vent, un contrôle de la convergence doit être réalisé à l'aide du paramètre de cohérence interne issu de l'Equation (C.3). Pour cela, le graphique le plus représentatif montre un tracé de la moyenne cumulative du paramètre de cohérence interne par rapport au nombre d'heures par tranche de direction du vent. Il convient de vérifier que les moyennes cumulatives convergent dans les 0,5 % de la moyenne finale pour 16 h de données ou 25 % du nombre total de points de données dans cette tranche (la valeur retenue étant la plus élevée des deux). Si ces critères ne sont pas satisfaits, d'autres actions, par exemple un filtrage supplémentaire, peuvent être appliquées dans le but d'essayer de justifier et de corriger la non-convergence. Si ces actions n'aboutissent pas à une convergence, la vérification de la cohérence interne conformément à l'Article C.8 peut être réalisée au cours de la mesure de la courbe de puissance afin d'évaluer si la non-convergence représente un problème ou non. Si l'essai de courbe de puissance ne satisfait pas aux critères de vérification de la cohérence interne, la tranche doit être exclue du secteur de mesure.

Il convient que la méthode de validation croisée en k échantillons utilisée pour calculer l'incertitude statistique pour l'étalonnage du site reflète une incertitude d'essai plus élevée pour tout cas de non-convergence, afin qu'aucune pénalité d'incertitude ne soit appliquée pour cette vérification.

C.7.2 Contrôle de corrélation pour la régression linéaire (voir C.5.3)

Pour chaque tranche de direction du vent, le niveau de corrélation doit être évalué à partir du coefficient de corrélation de la régression, communément appelé valeur r. Cette évaluation doit être incluse dans le rapport.

C.7.3 Variation de correction entre des tranches de direction du vent adjacentes

Il est recommandé d'éliminer les tranches de direction du vent des secteurs de mesure lorsque les corrections de l'écoulement varient de plus de 2 % entre les tranches adjacentes. Ces variations doivent être évaluées par application de la méthode du paramètre de cohérence interne donnée en C.5.4, de la manière suivante:

a) évaluer les données et calculer les corrections de l'écoulement dictées par l'étalonnage du site;

b) créer un décalage des corrections de l'écoulement dictées par l'étalonnage du site de l'ordre d'un secteur de direction, de manière à ce que les corrections ou régressions de l'écoulement soient appliquées à la tranche adjacente de direction du vent. Par exemple, si la correction de l'écoulement appliquée à la tranche à 290° est $1{,}024x + 0{,}1$, appliquer plutôt cette correction à la tranche à 280°;

c) en utilisant les corrections de l'écoulement dictées par l'étalonnage du site ajustées à l'étape précédente et les données d'étalonnage du site, calculer la vitesse du vent prédite à l'emplacement de l'éolienne pour chaque période de 10 min, puis calculer le paramètre de cohérence interne avec l'Equation (C.3);

d) moyenner les paramètres de cohérence interne pour chaque tranche de direction du vent. Si la moyenne est inférieure à 0,98 ou supérieure à 1,02, il convient d'éliminer ces tranches de direction du vent. Si ces tranches de direction du vent ne sont pas éliminées, l'incertitude qu'elles présentent doit être augmentée par la valeur de 1 moins la moyenne du paramètre de cohérence interne multipliée par 100 % et divisée par 2 et la racine carrée de 3. Si cela s'applique à un secteur à partir de ses deux secteurs adjacents, l'augmentation de l'incertitude correspond à la moyenne des deux.

Cette méthode doit être appliquée à la fois par addition et par soustraction à la tranche de direction du vent, en appliquant par exemple les résultats de la tranche à 290° aux deux tranches à 280° et à 300°. Le réglage d'incertitude pour les tranches ne se situant pas à une extrémité doit correspondre à l'impact de déplacement moyen d'une tranche adjacente dans chacune des directions.

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$$u_{VT,\mathrm{coc},i,j} = \frac{1}{2} \cdot \left(\frac{\left|1 - \mathrm{sccp}_{j,j-1}\right|}{2\sqrt{3}} + \frac{\left|1 - \mathrm{sccp}_{j,j+1}\right|}{2\sqrt{3}} \right) \quad \text{(C.7)}$$

où

$u_{VT,\mathrm{coc},i,j}$ est l'incertitude-type due à la variation de la correction dans la tranche j de direction du vent;

$\mathrm{sccp}_{j,j-1}$ est le paramètre de cohérence d'étalonnage du site pour la tranche j de direction du vent à l'aide des corrections d'étalonnage du site dans la tranche j –1;

$\mathrm{sccp}_{j,j+1}$ est le paramètre de cohérence d'étalonnage du site pour la tranche j de direction du vent à l'aide des corrections d'étalonnage du site dans la tranche j +1.

Pour les sous-secteurs situés aux extrémités du secteur de mesure, l'incertitude doit être uniquement évaluée par application de la correction à partir des sous-secteurs adjacents respectifs.

C.7.4 Suppression du capteur de direction du vent entre l'étalonnage du site et l'essai de performance de puissance

Si le capteur de direction du vent est supprimé entre l'étalonnage du site et l'essai de performance de puissance, une erreur peut être introduite en raison de l'incertitude d'alignement du capteur de direction du vent entre les deux installations. Une composante d'incertitude supplémentaire doit être appliquée pour chaque tranche de direction du vent. Pour chaque tranche de direction du vent, cette composante d'incertitude doit être calculée de la manière suivante:

a) Pour chaque tranche de direction du vent, appliquer la méthode décrite en C.7.3, à la différence que l'incertitude sera également appliquée lorsque la moyenne des paramètres de cohérence interne est comprise entre 0,98 et 1,02.

b) Déterminer l'incertitude relative des mesures de la direction du vent.

c) Multiplier le résultat obtenu au point a) par le rapport entre l'incertitude relative des mesures de la girouette et la taille totale de la tranche de direction du vent.

Par exemple, la girouette présente une défaillance et est remplacée par un modèle similaire entre l'étalonnage du site et la mesure de la courbe de puissance. L'incertitude sur les alignements de la girouette est déterminée à 3° et la taille de la tranche est de 10°. Multiplier la variation de la correction entre les tranches adjacentes d'après C.7.3 par $\frac{3}{10}$. Cette incertitude est appliquée en plus de toute incertitude appliquée d'après C.7.3.

$$u_{VT,\mathrm{rmv},i,j} = u_{VT,\mathrm{coc},i,j} \cdot \left(\frac{u_{w,i}}{\mathrm{BinSize}_j} \right) \quad \text{(C.8)}$$

où

$u_{w,i}$ est l'incertitude de direction du vent calculée conformément à l'Article E.12;

BinSize est la taille de la tranche j de direction du vent, par exemple 10°.

Il est à noter que $u_{w,i}$ peut être évaluée sur une base relative, c'est-à-dire que les composantes d'incertitude qui sont entièrement corrélées entre l'étalonnage du site et la mesure de la courbe de puissance peuvent être négligées. Par exemple, si le mât

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météorologique reste en place et que seul le capteur est remplacé sur la même flèche et monté avec une marque et un modèle identiques, $u_{WVbo,i}$ *et* $u_{WVoe,i}$ peuvent être négligées.

C.7.5 Etalonnage du site et mesures de performance de puissance lors de différentes saisons

En raison des variations saisonnières des conditions de vent et les variations de rugosité de la surface dues à la végétation, aux précipitations (neige et glace) et au gel de l'eau, les corrections de l'écoulement dictées par l'étalonnage du site peuvent dépendre de la saison. Par conséquent, il est recommandé de réaliser l'étalonnage du site et les mesures de performance de puissance à la même période de l'année, par exemple en été. Pour en évaluer l'impact éventuel, les étapes ci-après doivent être suivies.

Les conditions de vent moyennes au niveau du mât météorologique de référence au cours de l'étalonnage du site (cisaillement du vent, turbulences, écoulement ascendant) doivent être comparées aux conditions de vent moyennes au niveau de ce même mât météorologique au cours de la mesure de performance de puissance pour les directions du vent au sein du secteur de mesure. Une incertitude supplémentaire liée aux variations saisonnières doit être calculée si l'une des conditions suivantes associées à une tranche de direction du vent diffère d'une valeur supérieure aux valeurs indiquées:

a) 0,05 pour l'exposant de cisaillement du vent;

b) 3 % pour l'intensité des turbulences;

c) si l'écoulement ascendant est mesuré, une limite de variation de ± 2° est recommandée pour l'écoulement ascendant vertical.

L'incertitude supplémentaire liée aux variations saisonnières doit être égale à un tiers de l'amplitude de la correction de l'écoulement dictée par l'étalonnage du site.

C.8 Vérification des résultats

Un exemple de méthode de vérification des résultats à partir d'une mesure de performance de puissance avec ou sans étalonnage du site consiste à utiliser les données mesurées de puissance électrique pour déduire une vitesse du vent représentative pour l'éolienne pour chaque période de 10 min incluse dans la mesure de la courbe de puissance. Cette vitesse du vent est comparée à la vitesse du vent mesurée par l'anémomètre ou par le RSD. Idéalement, il convient que ce rapport ne varie pas en fonction de la direction du vent. Il convient d'analyser, voire d'exclure, les tranches de direction du vent pour lesquelles le rapport varie fortement. Si la courbe de puissance est fonction de la vitesse du vent équivalente du rotor, il convient d'appliquer ladite vitesse à la vérification de la cohérence interne.

a) La courbe de puissance inversée est définie comme la vitesse du vent moyennée par tranche en fonction de la puissance de sortie pour les ensembles de données qui ont été utilisés pour l'évaluation de la courbe de puissance. Pour les éoliennes avec contrôle actif, la vitesse du vent normalisée en fonction de la masse volumique de l'air est utilisée pour l'évaluation de la courbe de puissance inversée. Pour les éoliennes avec contrôle non actif, la puissance de sortie normalisée en fonction de la masse volumique de l'air est appliquée pour l'évaluation de la courbe de puissance inversée. Si un étalonnage du site a été réalisé, il convient d'utiliser la vitesse du vent étalonnée du site et, le cas échéant, normalisée en fonction de la masse volumique de l'air pour l'analyse par tranches. Il convient d'inclure les données de puissance aux résultats utilisés lorsque la puissance maximale n'atteint pas la puissance assignée nominale mesurée et lorsque la vitesse du vent normalisée est supérieure à 4 m/s.

b) La courbe de puissance inversée (RPC, *Reverse Power Curve*) est appliquée pour évaluer la vitesse du vent représentative du rotor de l'éolienne d'après la mesure de la puissance active sur chaque intervalle de 10 min dans lequel l'éolienne à l'essai fonctionne. Pour cela, la vitesse du vent est interpolée de manière linéaire entre les tranches de la RPC conformément à la puissance active mesurée. Le résultat donne la vitesse du vent

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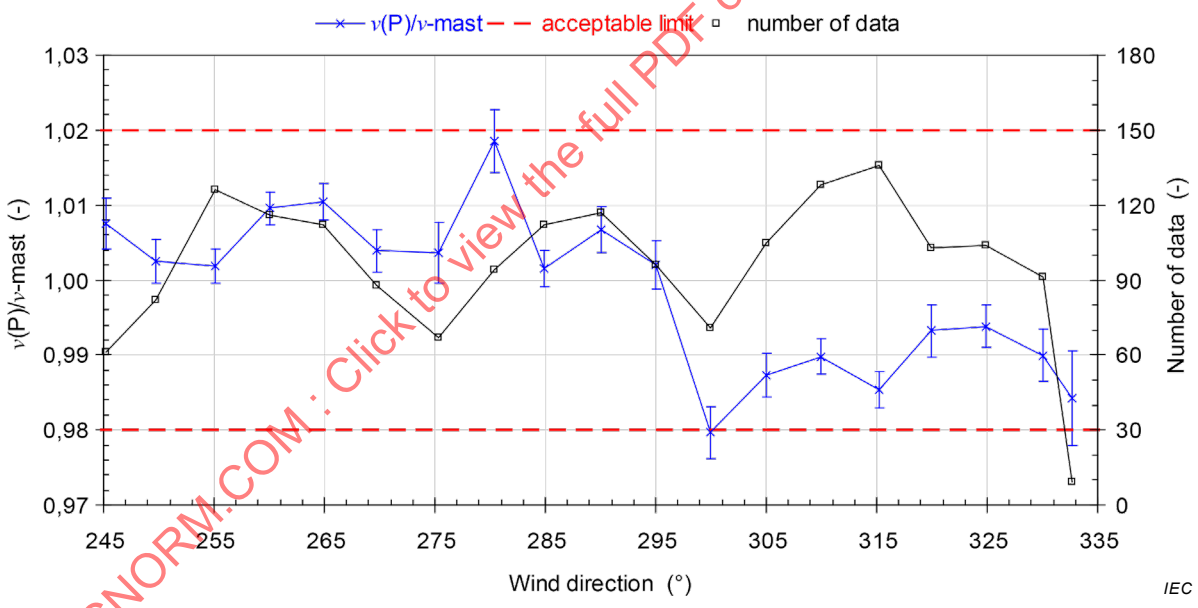
représentative du rotor de l'éolienne. Pour les éoliennes avec contrôle actif, le résultat est la vitesse du vent ambiante normalisée en fonction de la masse volumique représentative du rotor de l'éolienne. Pour les éoliennes avec contrôle non actif, il convient d'utiliser la puissance de sortie normalisée en fonction de la masse volumique de l'air pour l'évaluation de la vitesse du vent ambiante.

c) Il convient de moyenner par tranche le rapport des deux vitesses du vent (déduites/mesurées) en fonction de la direction du vent en secteurs de 5°.

d) Il est prévu que la vitesse du vent déduite et la vitesse du vent mesurée soient en adéquation pour le secteur de mesure. Ainsi, il convient que le rapport soit proche de l'unité. Des effets du site, des imperfections liées à la procédure d'étalonnage du site ou l'influence des variables environnementales sur la courbe de puissance peuvent donner lieu à des écarts par rapport à l'unité. Les secteurs pour lesquels la vitesse du vent déterminée à l'aide du mât météorologique n'est pas représentative de l'éolienne à l'essai peuvent clairement être identifiés comme des variations du rapport moyenné par tranche. Il convient d'analyser les écarts plus élevés de manière plus approfondie. Il convient d'exclure ces secteurs de l'essai de courbe de puissance final si les effets du site sont identifiés comme à l'origine de ces écarts.

e) Il convient d'évaluer à nouveau la courbe de puissance pour le secteur restant. La vérification de la cohérence interne peut être répétée avec la RPC recalculée. Il convient que le secteur de mesure soit ajusté, si nécessaire, conformément aux résultats de l'essai répété.

Un exemple de résultat d'essai de vérification est donné à la Figure C.3.



Anglais	Français
V(P)/v-mast	V(P)/v-mât
Acceptable limit	Limite acceptable
Number of data	Quantité de données
V(P)/v-mast [-]	V(P)/v-mât (-)
Wind direction [°]	Direction du vent (°)

Les barres d'erreur indiquent l'incertitude-type de catégorie A sur les rapports moyennés par tranche de v_P et v_{mast}. Les plages acceptables sont les suivantes: rapports de 0,98 à 1,02 pour L < 3 diamètres de rotor et rapports de 0,97 à1,03 pour L compris entre 3 et 4 diamètres de rotor.

Figure C.3 – Exemple de résultats d'essai de vérification

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C.9 Exemples d'étalonnage du site

C.9.1 Exemple A

Description du site:

La mesure de la courbe de puissance doit être réalisée sur un site se trouvant en bord de crête (terrain de type B). Le bord de crête est perpendiculaire à la direction du vent de principe face à une plaine et la hauteur de la crête est supérieure d'environ 40 m à 60 m par rapport au plan. La hauteur du moyeu des éoliennes est de 80 m. Elles sont placées sur une seule ligne au sommet de la crête.

Le type de terrain est entre un terrain de type A et un terrain de type B. Le caractère relativement plat du terrain de la crête face au vent implique qu'un cisaillement élevé du vent peut représenter un problème en raison de la stabilité atmosphérique. Cependant, le terrain local des éoliennes s'apparente plus à un site de type B dans lequel des angles d'écoulement ascendant élevés peuvent également poser problème. Les emplacements de l'éolienne à l'essai et du mât météorologique sont donc choisis dans le but de réduire le plus possible l'angle d'écoulement ascendant possible (pente de terrain local plus faible) et la différence d'altitude entre les deux emplacements (ce qui augmentera le plus possible la corrélation des corrections de l'écoulement de la vitesse du vent selon différents profils de cisaillement du vent) en fonction de l'implantation de l'éolienne et des contraintes du terrain.

Montage d'étalonnage du site:

Le mât météorologique de référence est situé sur la crête, à côté de l'éolienne à l'essai mais à une altitude légèrement moins élevée, soit 10 m plus bas environ que l'altitude de l'éolienne.

En plus des anémomètres à coupelles montés côte à côte en tête de mât à la hauteur du moyeu, les mesures du cisaillement du vent sont incluses dans la forme des anémomètres situés à une altitude de 43 m sur les deux mâts météorologiques. Un anémomètre à ultrasons 3D est monté sur chaque mât météorologique pour évaluer les caractéristiques d'exploitation des anémomètres à la hauteur du moyeu afin de quantifier l'incertitude en fonction de la complexité du terrain.

Evaluation de l'étalonnage du site:

Les données sont recueillies sur plusieurs mois. Les données recueillies sont filtrées en fonction du secteur de mesure, des vitesses du vent allant de 4 m/s à 16 m/s enregistrées au niveau du mât météorologique de référence, du dysfonctionnement du capteur et du givrage de l'anémomètre.

Pour chaque période de 10 min, les éléments suivants sont calculés, conformément à C.5.1:

a) le rapport entre la vitesse du vent à la hauteur du moyeu à l'emplacement de l'éolienne et la vitesse du vent à la hauteur du moyeu à l'emplacement du mât météorologique de référence;

b) les exposants de cisaillement du vent au niveau de chaque mât météorologique sont calculés à l'aide de la loi exponentielle à l'aide des mesures de la vitesse du vent à 80 m et à 43 m;

c) une balise représentant l'heure du jour dans un système horaire sur 24 h est calculée à partir de l'horodatage;

d) l'angle d'écoulement ascendant est calculé à partir des vitesses verticales et horizontales du vent mesurées par les anémomètres à ultrasons au niveau de chaque mât météorologique.

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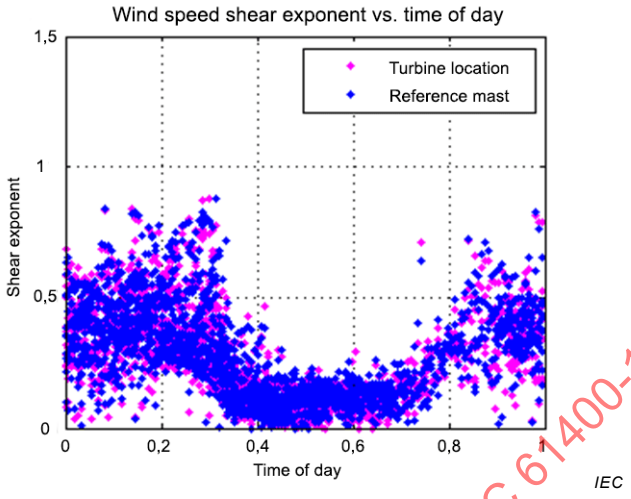
Etape 1: Vérifier l'importance du cisaillement du vent sur le site conformément à C.5.1.2:

Pour les données filtrées, l'exposant de cisaillement du vent au niveau de chaque mât météorologique est tracé par rapport à l'heure du jour.



Anglais	Français
Wind speed shear exponent vs. time of day	Exposant de cisaillement du vent par rapport à l'heure du jour
Turbine location	Emplacement de l'éolienne
Reference mast	Mât de référence
Shear exponent	Exposant de cisaillement
Time of day	Heure du jour

Figure C.4 – Exposant de cisaillement du vent en fonction de l'heure du jour, exemple A

D'après la Figure C.4, il est observé que le cisaillement du vent est élevé la nuit et faible au cours de la journée. Il s'agit d'une situation typique pour un site présentant un cycle diurne de stabilité atmosphérique. La nuit, l'atmosphère forme des couches thermiques (atmosphère stable). Ces couches inhibent les turbulences et entraînent un cisaillement du vent élevé et instable. Au cours de la journée, le soleil réchauffe le sol, ce qui entraîne le brassage des turbulences. Par conséquent, le profil de vitesse du vent est plus uniforme (faible cisaillement du vent) et les turbulences sont plus élevées.

Il apparaît également que les valeurs de cisaillement du vent sont similaires aux emplacements de l'éolienne et du mât météorologique de référence.

Etape 2: Vérifier la corrélation entre le cisaillement du vent à l'emplacement de l'éolienne et à emplacement du mât météorologique de référence – Exemple A

L'objectif est de vérifier que les valeurs d'exposant de cisaillement du vent sont corrélées entre les emplacements de l'éolienne et du mât météorologique de référence. Pour cela, un tracé des exposants de cisaillement du vent à l'emplacement de l'éolienne par rapport aux exposants de cisaillement du vent à l'emplacement du mât météorologique de référence est effectué (voir Figure C.5):

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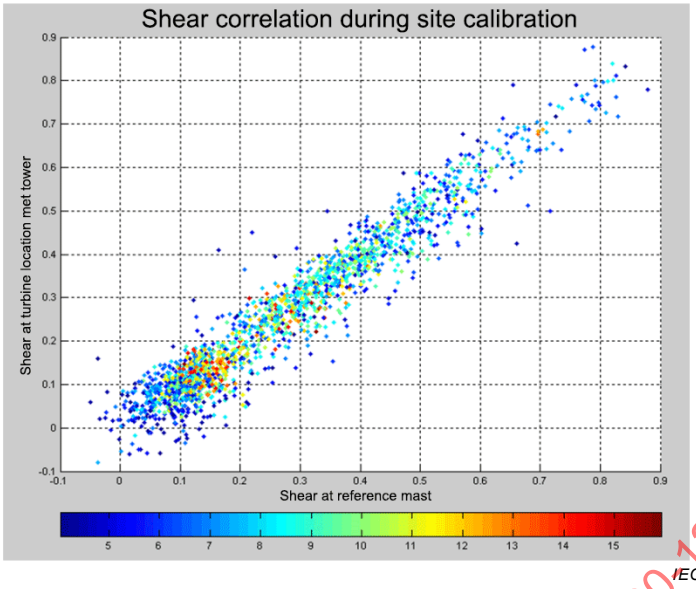

Anglais	Français
Shear correlation during site calibration	Corrélation du cisaillement lors de l'étalonnage du site
Shear at turbine location met tower	Cisaillement à l'emplacement du mât météorologique de référence
Shear at reference mast	Cisaillement au mât de référence

Figure C.5 – Exposants de cisaillement du vent à l'emplacement de l'éolienne par rapport à l'emplacement du mât météorologique de référence, exemple A où l'axe de couleur = vitesse du vent (en m/s)

Les exposants de cisaillement du vent à l'emplacement du mât météorologique de référence fournissent une indication relativement bonne des exposants de cisaillement du vent à l'emplacement de l'éolienne.

Etape 3: Calculer les résultats conformément à C.5.1.3

Les calculs suivants sont effectués pour chaque ensemble de données de 10 min, d'après les mesures réalisées au niveau du mât de référence:

- tranches de cisaillement du vent centrées sur des multiples entiers de valeurs de 0,05 de l'exposant de cisaillement du vent –0,025 à 0,025, 0,025 à 0,075, 0,075 à 0,125, etc.).

A partir de ces calculs, une matrice de l'exposant de cisaillement du vent et de la direction du vent peut être créée. Pour chaque point de ladite matrice, les calculs suivants sont effectués:

- la correction est calculée comme la moyenne des rapports de vitesses du vent dans cette tranche de la matrice;
- le nombre total de points de données valides est calculé au sein de cette tranche de la matrice.

Le Tableau C.1 et le Tableau C.2 donnent respectivement les corrections de l'écoulement dictées par l'étalonnage du site et le nombre de tranches. La Figure C.6 donne une représentation graphique de ces résultats.

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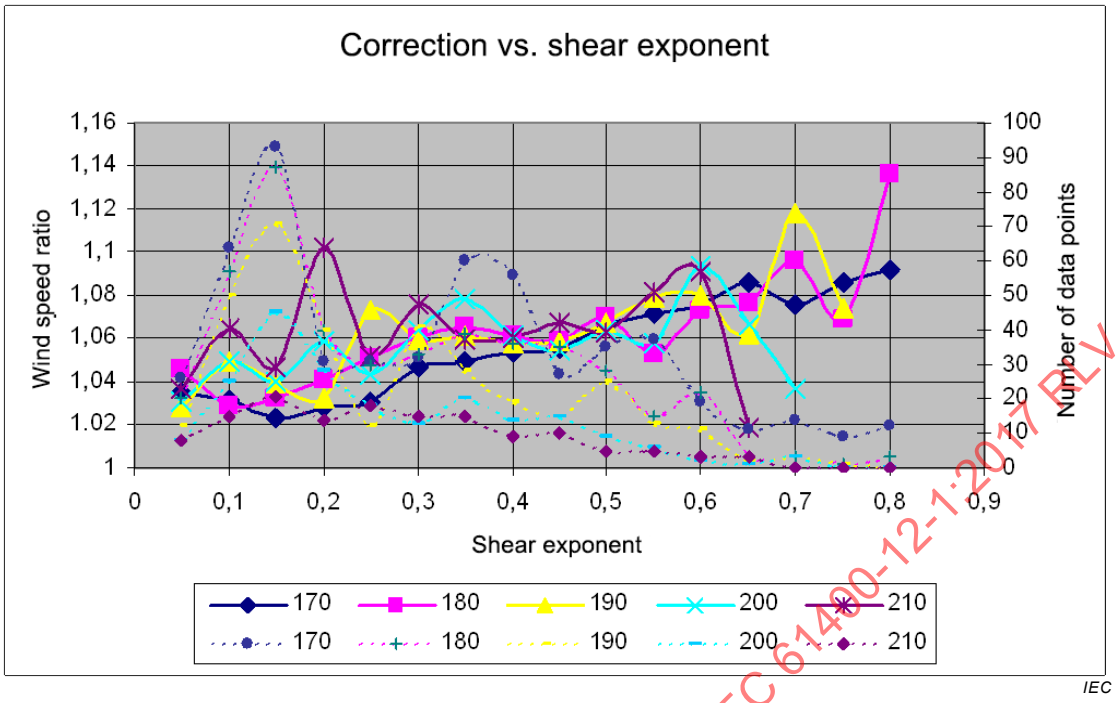

Anglais	Français
Correction vs. shear exponent	Correction en fonction de l'exposant de cisaillement
Wind speed ratio	Rapport de vitesses du vent
Number of data points	Nombre de points de données
Shear exponent	Exposant de cisaillement

Figure C.6 – Rapports de vitesse du vent et nombre de points de données en fonction de l'exposant de cisaillement du vent et de la tranche de direction du vent – rapports de vitesse du vent (lignes pleines), nombre de points de données (lignes en pointillés)

Etape 4: Contrôles de la qualité et incertitudes supplémentaires

Incertitude liée aux caractéristiques d'exploitation de l'anémomètre:

L'angle d'écoulement ascendant a été enregistré, ce qui permet d'estimer l'incertitude liée aux caractéristiques d'exploitation de l'anémomètre en fonction des conditions du site conformément à C.3.2. L'angle maximal d'écoulement ascendant pour tous les points de données de toutes les tranches de direction du vent était de 3° au niveau du mât météorologique de référence et de 1° à l'emplacement du mât de l'éolienne. Tous les autres paramètres se trouvent dans la plage des caractéristiques d'exploitation de l'anémomètre de classe A. Par conséquent, l'incertitude liée aux caractéristiques d'exploitation de l'anémomètre de classe A peut être utilisée pour les deux emplacements. Il s'agit de la classe 1,4A.

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Tableau C.1 – Corrections de l'écoulement dictées par l'étalonnage du site (rapport de vitesses du vent)

	Tranche de direction du vent				
Tranche de cisaillement du vent	**170**	**180**	**190**	**200**	**210**
0,05	1,035	1,046	1,028	1,031	1,037
0,10	1,031	1,029	1,05	1,05	1,064
0,15	1,023	1,033	1,039	1,04	1,047
0,20	1,028	1,041	1,032	1,059	1,102
0,25	1,031	1,051	1,073	1,044	1,052
0,30	1,047	1,06	1,06	1,064	1,076
0,35	1,049	1,066	1,062	1,078	1,06
0,40	1,054	1,061	1,058	1,061	1,06
0,45	1,055	1,058	1,059	1,055	1,067
0,50	1,066	1,07	1,067	1,064	1,063
0,55	1,072	1,053	1,079	1,058	1,081
0,60	1,076	1,074	1,08	INC	1,091
0,65	1,086	1,076	INC	INC	1,019
0,70	1,076	1,096	1,118	INC	INC
0,75	1,086	INC	INC	INC	INC
0,80	1,092	1,136	INC	INC	INC

Tableau C.2 – Nombre de données d'étalonnage du site

	Tranche de direction du vent				
Tranche de cisaillement du vent	**170**	**180**	**190**	**200**	**210**
0,05	26	20	12	8	8
0,10	64	57	50	25	15
0,15	93	87	71	45	21
0,20	31	40	40	28	14
0,25	31	30	12	18	18
0,30	32	33	41	13	15
0,35	60	39	28	20	15
0,40	56	36	19	14	9
0,45	27	35	15	15	10
0,50	35	28	25	9	5
0,55	37	15	13	6	5
0,60	19	22	11	2	3
0,65	11	3	2	1	3
0,70	14	3	3	3	0
0,75	9	1	1	0	0
0,80	12	3	0	0	0

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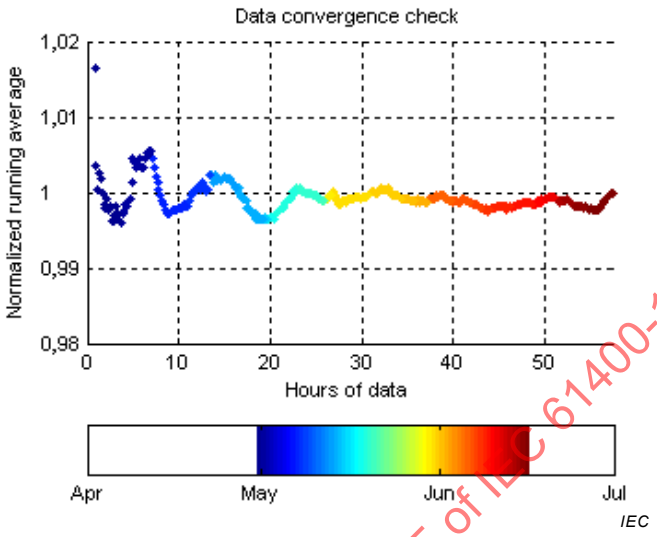
Contrôle de la convergence:

Le contrôle de la convergence a démontré que les données ont convergé dans les 0,5 % de la valeur finale (ou entre 0,995 et 1,005 à la Figure C.7 pour la tranche à 190° utilisant plus de 50 h de données dans la tranche satisfaisant à l'exigence), pour 16 h de données ou pour 25 % du nombre total de points de données dans toutes les tranches (la valeur retenue étant la plus élevée des deux).



Anglais	Français
Data convergence check	Contrôle de la convergence des données
Normalized running average	Moyenne d'exploitation normalisée
Hours of data	Heures de données
Apr	Avril
May	Mai
Jun	Juin
Jul	Juillet

Figure C.7 – Contrôle de la convergence des données pour la tranche à 190°

Variation de correction entre les tranches:

L'amplitude de la variation des corrections de l'écoulement était de 0,02 entre toutes les tranches adjacentes.

Ajustement de la girouette:

La girouette n'a pas été ajustée entre les mesures, donc aucune incertitude supplémentaire n'est exigée.

Incertitude saisonnière:

La mesure de la courbe de puissance a été réalisée pendant la même période saisonnière et une comparaison a révélé qu'aucune des variations des conditions n'excédait les limites données en C.7.5, c'est pourquoi aucune incertitude supplémentaire n'est nécessaire pour tenir compte des variations saisonnières.

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C.9.2 Exemple B

Description du site:

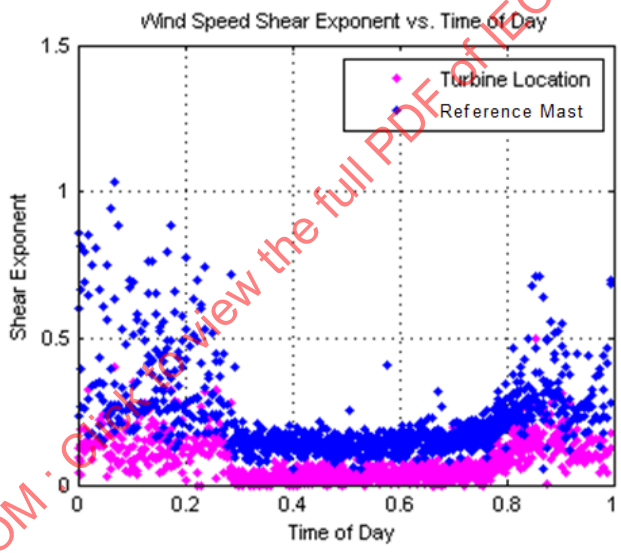
Le site est identique au site de l'exemple A (terrain de type B), à ceci près que le terrain local de l'éolienne est légèrement plus pentu.

Montage d'étalonnage du site:

Contrairement à l'exemple A, le mât météorologique de référence n'a pas pu être localisé sur la crête. Le mât météorologique de référence est situé à la base de la crête (dans la plaine), à 3 diamètres de rotor du côté exposé au vent de l'éolienne à l'essai se trouvant au sommet de la crête. La différence d'altitude entre l'éolienne à l'essai et le mât météorologique de référence est de 45 m.

Etape 1: Vérifier l'importance du cisaillement du vent sur le site

Pour les données filtrées, l'exposant de cisaillement du vent au niveau de chaque mât météorologique est tracé par rapport à l'heure du jour (voir Figure C.8).



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Anglais	Français
Wind speed shear exponent vs. time of day	Exposant de cisaillement de la vitesse du vent en fonction de l'heure du jour
Turbine location	Emplacement de l'éolienne
Reference mast	Mât de référence
Shear exponent	Exposant de cisaillement
Time of day	Heure du jour

Figure C.8 – Exposant de cisaillement du vent par rapport à l'heure du jour, exemple B

Comme pour l'exemple A, le cisaillement du vent est plus élevé la nuit qu'au cours de la journée, ce qui indique un cycle diurne de stabilité atmosphérique. Cependant, le cisaillement du vent à l'emplacement de l'éolienne apparaît comme significativement différent du cisaillement du vent au niveau du mât météorologique de référence. Cette différence sera problématique en raison de la variation de l'altitude entre les deux emplacements. Il est raisonnable de prendre pour hypothèse que la relation entre les vitesses du vent à la hauteur du moyeu sera influencée par les variations du profil de cisaillement du vent.

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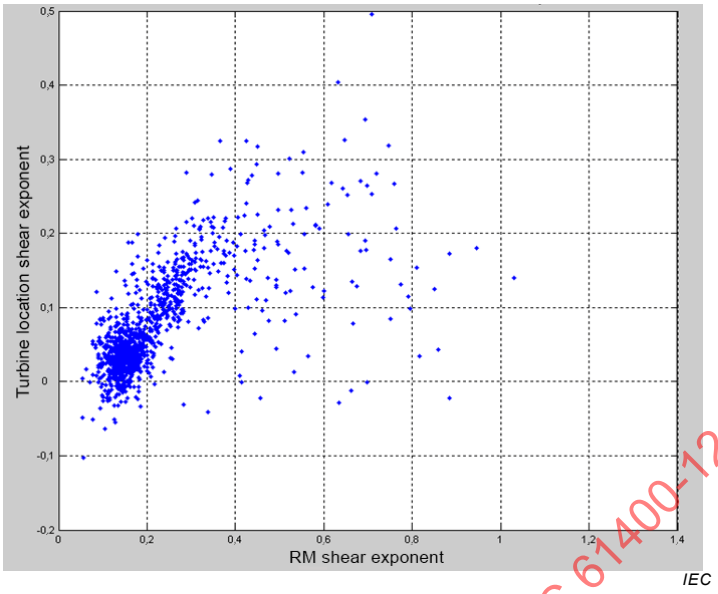
Etape 2: Vérifier la corrélation entre le cisaillement du vent à l'emplacement de l'éolienne et à emplacement du mât météorologique de référence – Exemple B



Anglais	Français
Turbine Location Shear Exponent	Exposant de cisaillement à l'emplacement de l'éolienne
RM Shear Exponent	Exposant de cisaillement au niveau du mât météorologique de référence

Figure C.9 – Exposants de cisaillement du vent à l'emplacement de l'éolienne par rapport à l'emplacement du mât météorologique de référence, exemple B

Il n'existe pas de corrélation pour les valeurs de cisaillement du vent supérieures à 0,25. Cela suggère que la corrélation des corrections de l'écoulement dictées par l'étalonnage du site sera incohérente si les conditions atmosphériques sont stables. Pour démontrer/vérifier la véracité de cette hypothèse, les tracés spécifiés en C.5.3 peuvent être utilisés (voir Figure C.10):

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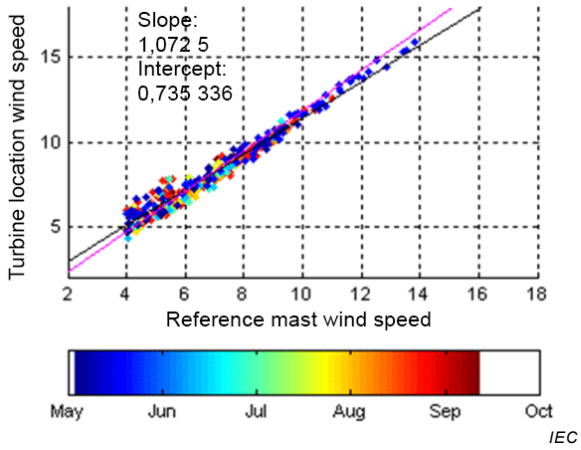

Anglais	Français
Slope: 1,072 5	Pente: 1,072 5
Intercept: 0,735 336	Ordonnée à l'origine: 0,735 336
Turbine location wind speed	Vitesse du vent à l'emplacement de l'éolienne
Reference mast wind speed	Vitesse du vent au niveau du mât de référence
May	Mai
Jun	Juin
Jul	Juillet
Aug	Août
Sep	Septembre
Oct	Octobre

La ligne rouge correspond à la régression linéaire forcée à passer par l'origine (ordonnée à l'origine = 0); la ligne noire correspond à la régression linéaire des deux paramètres (ordonnée à l'origine différente de zéro).

Figure C.10 – Régression linéaire de la vitesse du vent à l'emplacement de l'éolienne par rapport à la vitesse du vent à la hauteur du moyeu du mât météorologique de référence pour la tranche à 330°

La régression linéaire présente une ordonnée à l'origine significative. En outre, les vitesses du vent les plus faibles sont très dispersées.

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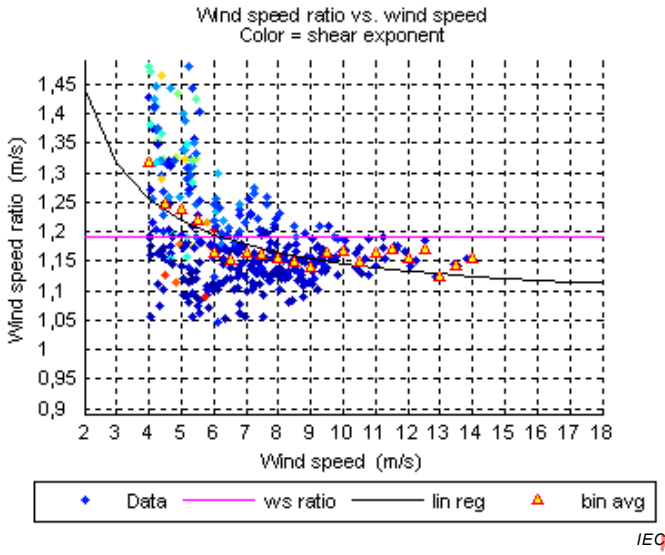

Anglais	Français
Wind speed ratio vs. wind speed Color = shear exponent	Rapport de vitesses du vent en fonction de la vitesse du vent Couleur = Exposant de cisaillement
Wind speed ratio (m/s)	Rapport de vitesses du vent (m/s)
Wind speed (m/s)	Vitesse du vent (m/s)
Data	Données
Ws ratio	Rapport de la vitesse du vent
Lin reg	Régression linéaire
Bin avg	Moyenne de la tranche

Figure C.11 – Rapports de vitesses du vent en fonction de la vitesse du vent pour la tranche à 330°

Le tracé du rapport de vitesses du vent en fonction de la vitesse du vent (voir Figure C.11) montre une dépendance élevée de la correction de l'écoulement par rapport à la vitesse du vent en raison de l'ordonnée à l'origine élevée. Il est également à noter que l'amplitude générale de la correction de l'écoulement est plutôt élevée, à savoir 19 % en moyenne.

A des fins de représentation, un tracé des rapports de vitesses du vent en fonction du cisaillement du vent pour les différentes tranches de vent est donné à la Figure C.12.

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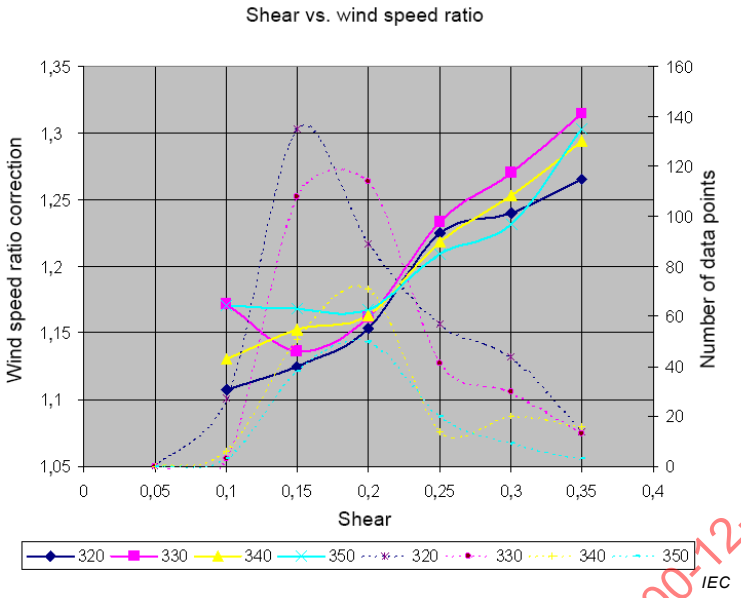

Anglais	Français
Shear vs. Wind Speed Ratio	Cisaillement en fonction du rapport de vitesses du vent
Wind Speed Ratio Correction	Correction du rapport de vitesses du vent
Number of Data Points	Nombre de points de données
Shear	Cisaillement

Figure C.12 – Rapports de vitesses du vent en fonction du cisaillement du vent pour la tranche à 330°

Ces tracés sont des représentations utiles de l'impact des conditions du site et du montage d'essai sur l'étalonnage du site. La Figure C.12 montre que la correction varie de plus de 5 % entre 0,20 et 0,25 et la Figure C.9 montre que le cisaillement du vent au niveau du mât météorologique de référence n'est pas un bon indicateur de prédiction du cisaillement du vent à l'emplacement de l'éolienne pour les valeurs supérieures à 0,25. Les corrections utilisant la méthode de la matrice de la direction du vent et du cisaillement du vent peuvent ne pas être fiables. Il a été démontré que le cisaillement du vent a une influence significative et qu'il n'est pas correctement corrélé entre les deux emplacements; par conséquent, un filtrage supplémentaire est nécessaire pour tenter d'améliorer la corrélation.

Etape 2B: Tentative de suppression des données de cisaillement du vent non corrélées

Les valeurs faibles de cisaillement du vent semblent être corrélées entre les deux emplacements. Les valeurs faibles de cisaillement du vent se produisent au cours de la journée (périodes d'instabilité atmosphérique). Par conséquent, à partir des tracés, un filtre de l'heure du jour est appliqué pour choisir toutes les données de la journée relevées entre 7 h et 19 h.

Les tracés conformes à C.5.2 sont présentés pour le nouvel ensemble de données filtrées (voir Figure C.13, Figure C.14 et Figure C.15).

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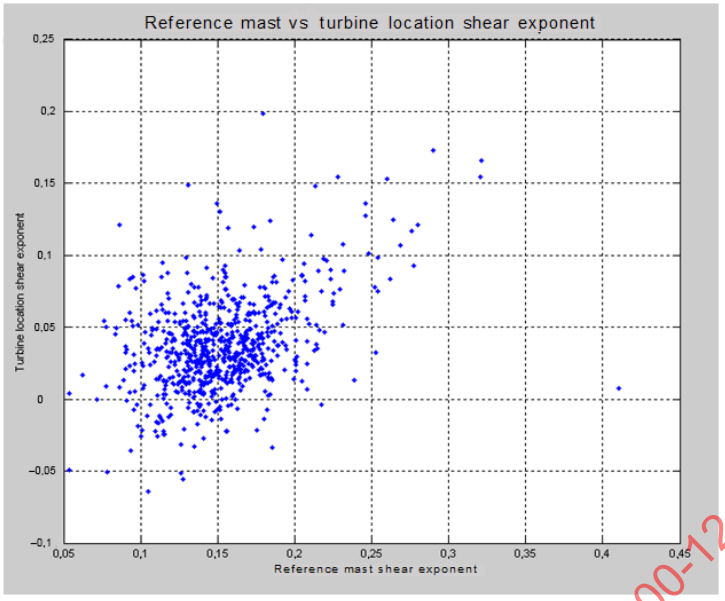

Anglais	Français
Reference mast vs turbine location shear exponent	Exposant de cisaillement au niveau du mât de référence par rapport à l'exposant de cisaillement à l'emplacement de l'éolienne
Turbine location shear exponent	Exposant de cisaillement à l'emplacement de l'éolienne
Reference mast shear exponent	Exposant de cisaillement au niveau du mât de référence

Figure C.13 – Exposants de cisaillement du vent à l'emplacement de l'éolienne par rapport au post-filtrage du mât météorologique de référence

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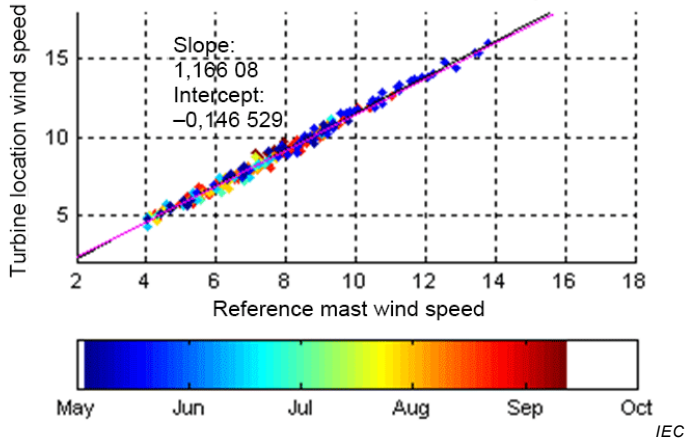

Anglais	Français
Slope: 1,166 08	Pente: 1,166 08
Intercept: -0,146 529	Ordonnée à l'origine: -0,146 529
Turbine location wind speed	Vitesse du vent à l'emplacement de l'éolienne
Reference mast wind speed	Vitesse du vent au niveau du mât de référence
May	Mai
Jun	Juin
Jul	Juillet
Aug	Août
Sep	Septembre
Oct	Octobre

Figure C.14 – Régression linéaire de la vitesse du vent à l'emplacement de l'éolienne par rapport à la vitesse du vent à la hauteur du moyeu du mât météorologique de référence pour la tranche à 330°, post-filtrage

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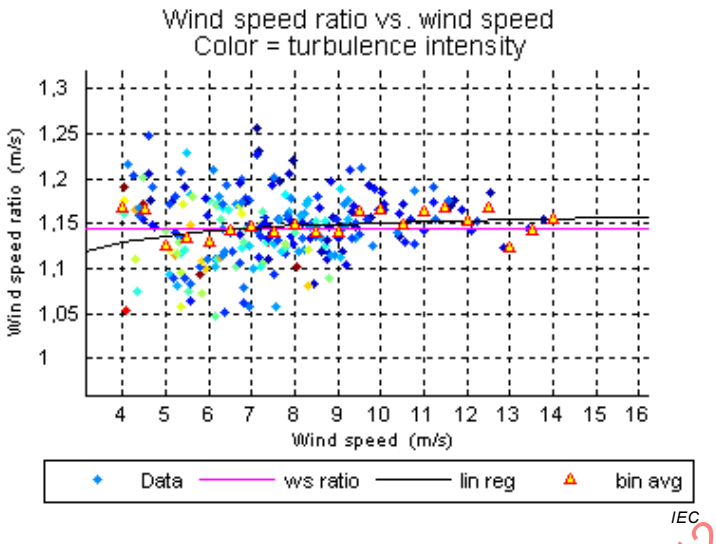

Anglais	Français
Wind speed ratio vs. wind speed Color = Turbulence intensity	Rapport de vitesses du vent en fonction de la vitesse du vent Couleur = Intensité des turbulences
Wind speed ratio (m/s)	Rapport de vitesses du vent (m/s)
Wind speed (m/s)	Vitesse du vent (m/s)
Data	Données
Ws ratio	Rapport de vitesses du vent
Lin reg	Régression linéaire
Bin avg	Moyenne de la tranche

Figure C.15 – Rapports de vitesses du vent en fonction de la vitesse du vent pour la tranche à 330°, post-filtrage

Etape 3: Calculer les résultats

Lors de l'étape précédente, toutes les données relevées en conditions de stabilité atmosphérique élevée ont été supprimées, et seules les données de l'heure du jour relevées en conditions d'instabilité atmosphérique ont été conservées. Les valeurs de cisaillement du vent incluent une plage réduite d'exposants de cisaillement du vent (0,10 à 0,20). Ainsi, les corrections de l'écoulement dictées par l'étalonnage du site ne dépendent plus du cisaillement du vent et la méthode de régression linéaire peut être utilisée en remplacement de la matrice de tranches de la direction du vent et du cisaillement du vent.

Pour chaque tranche de direction du vent, une régression linéaire de la vitesse du vent à l'emplacement de l'éolienne par rapport à la vitesse du vent au mât météorologique de référence est calculée, ainsi que la valeur r^2 de la régression. Le nombre total de points de données valides dans chaque tranche de direction du vent est également enregistré.

Etape 4: Incertitudes supplémentaires

Incertitude opérationnelle de l'anémomètre:

Aucune mesure de la vitesse verticale du vent n'a été incluse, de sorte que l'incertitude liée aux caractéristiques d'exploitation de classe B doit être utilisée. La classification des caractéristiques d'exploitation de l'anémomètre est 5,4B.

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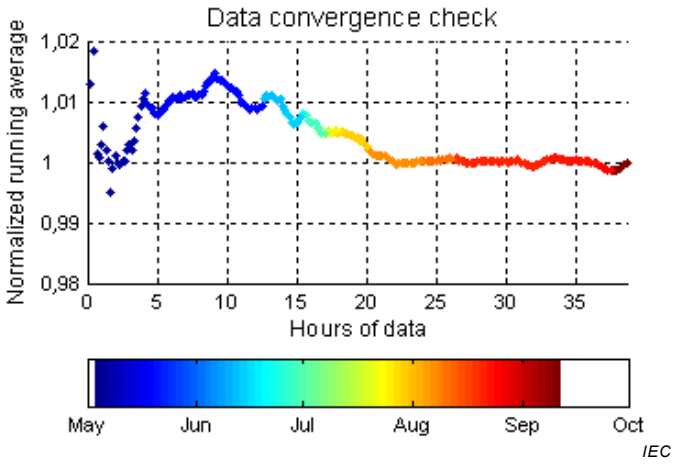
Contrôle de la convergence (voir Figure C.16**):**



Anglais	Français
Data convergence check	Contrôle de la convergence des données
Normalized running average	Moyenne d'exploitation normalisée
Hours of data	Heures de données
May	Mai
Jun	Juin
Jul	Juillet
Aug	Août
Sep	Septembre
Oct	Octobre

Figure C.16 – Contrôle de la convergence des données pour la tranche à 330°

Contrôle de corrélation pour la régression linéaire

Conformément à C.7.2 (voir Tableau C.3).

Tableau C.3 – Valeurs r^2 pour chaque tranche de direction du vent

Centre de la tranche	Valeur r^2	Valeur absolue de la moyenne résiduelle (en m/s)	Ecart-type résiduel (en m/s)
320	0,978	0,00	0,33
330	0,988	0,00	0,26
340	0,979	0,00	0,26
350	0,981	0,00	0,23

Variation de correction entre les tranches:

Conformément à C.7.3 (voir Tableau C.4).

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Tableau C.4 – Incertitude supplémentaire due à des variations dans les tranches

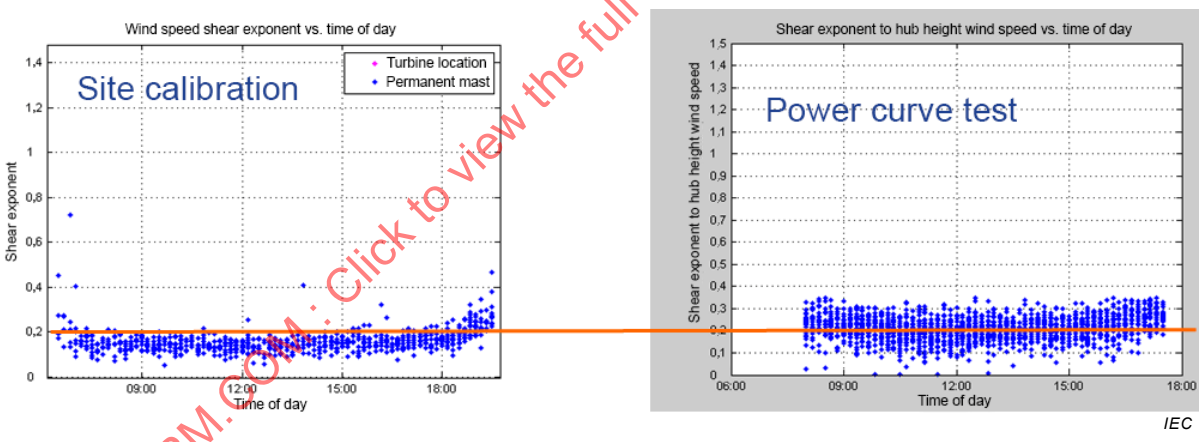
Centre de la tranche	Amplitude de variation entre les tranches (à gauche)	Amplitude de variation entre les tranches (à droite)	Incertitude-type supplémentaire (%)
320	1,019	-	0 % (dans les limites)
330	1,009	0,981	0 % (dans les limites)
340	1,013	0,988	0 % (dans les limites)
350	-	0,992	0 % (dans les limites)

Ajustement de la girouette:

La girouette n'a pas été déplacée, donc aucune incertitude supplémentaire n'est exigée, conformément à C.7.4.

Incertitude saisonnière:

L'étalonnage du site a été réalisé en hiver alors que la mesure de la courbe de puissance a été effectuée au cours de plusieurs saisons, dont l'été. Il est à noter qu'il a été nécessaire d'ajuster le filtre de l'heure du jour en raison des variations des heures de lever et de coucher du soleil. Une comparaison des valeurs des exposants de cisaillement du vent (voir Figure C.17) a révélé une variation de plus de 0,05 (0,15 par rapport à 0,22), c'est-à-dire supérieure aux limites données en C.7.5. Par conséquent, une incertitude supplémentaire due à la réalisation des mesures au cours de différentes saisons est exigée, conformément à C.7.5.



Anglais	Français
Wind speed shear exponent vs. time of day	Exposant de cisaillement de la vitesse du vent en fonction de l'heure du jour
Site calibration	Etalonnage du site
Turbine location	Emplacement de l'éolienne
Permanent mast	Mât permanent
Shear exponent	Exposant de cisaillement
Time of day	Heure du jour
Shear exponent to hub height wind speed vs. time of day	Exposant de cisaillement de la vitesse du vent à la hauteur du moyeu en fonction de l'heure du jour
Power curve test	Essai de courbe de puissance
Shear exponent to hub height wind speed	Exposant de cisaillement de la vitesse du vent à la hauteur du moyeu
Time of day	Heure du jour

Figure C.17 – Cisaillement du vent lors de l'étalonnage du site par rapport au cisaillement du vent lors de l'essai de courbe de puissance

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La composante de correction saisonnière correspond à un tiers de l'amplitude de la correction totale. Elle peut être calculée pour chaque point de données de la manière suivante:

$$U = 1/3 \times \text{abs}(V_{\text{Turb_predicted}} - V_{\text{RM_measured}}) \quad \text{(C.9)}$$

où

U est l'incertitude-type pour un point de données;

$V_{\text{Turb_predicted-}i}$ est la vitesse du vent prédite au niveau de l'éolienne compte tenu des corrections de l'écoulement dictées par l'étalonnage du site;

$V_{\text{RM_measured-}i}$ est la vitesse du vent mesurée à partir du mât météorologique de référence utilisé pour prédire la vitesse du vent au niveau de l'éolienne.

Les incertitudes au cours de l'essai de performance de puissance peuvent alors être moyennées par tranche en fonction de la vitesse et de la direction du vent au niveau du mât météorologique de référence pour calculer l'incertitude totale.

C.9.3 Exemple C

Description du site:

Le site est un terrain très complexe. Il est situé au sommet d'une montagne au sein d'une chaîne de montagnes. Le site se trouve en bord de crête, perpendiculaire à la direction de principe du vent. Le terrain descend en pente raide des deux côtés de la crête. Le vent est principalement unidirectionnel, car presque tous les vents proviennent d'un secteur de 30°. Il y a une autre ligne de crête de 3 km directement face au vent, plus haute de quelques centaines de mètres que le bord de crête sur lequel se trouve le site. Par conséquent, le site est considéré comme un terrain de type C, car il peut être localisé dans une zone de recirculation à partir de la crête face au vent.

Montage d'étalonnage du site:

Le mât météorologique est situé à une distance correspondant à 2,5 diamètres de rotor de l'éolienne à l'essai sur la même crête et à une altitude très similaire (dans les 5 m). Le cisaillement du vent a été mesuré à l'aide d'anémomètres montés à une hauteur inférieure sur des mâts météorologiques. Aucune mesure de la vitesse verticale du vent n'a été incluse.

Etape 1: vérifier l'importance du cisaillement du vent sur le site:

Les valeurs d'exposants de cisaillement du vent sont faibles, voire parfois négatives. Toutes les valeurs d'exposants de cisaillement du vent sont comprises entre –0,05 et 0,20 et ne présentent aucune corrélation évidente avec l'heure du jour ou d'autres conditions mesurées. Les turbulences sont élevées. Ces conditions indiquent une atmosphère neutre à instable. Le cisaillement du vent n'est donc pas considéré comme un facteur significatif pour l'étalonnage du site, et la méthode de régression linéaire peut être utilisée.

Etape 2:

Ignorée car il a déjà été déterminé que le cisaillement du vent est faible. Ce site ne présente pas une atmosphère stable.

Etape 3: calculer les résultats

Pour chaque tranche de direction du vent, une régression linéaire de la vitesse du vent à l'emplacement de l'éolienne par rapport à la vitesse du vent au mât météorologique de référence est calculée, ainsi que la valeur r^2 de la régression. Le nombre total de points de données valides dans chaque tranche de direction du vent est également enregistré. La

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dispersion des données est très élevée, de même que l'amplitude de la variation de correction de l'écoulement entre les tranches.

Etape 4: contrôles de la qualité et incertitude

Les données confirment que le site se trouve dans une zone de recirculation de la crête face au vent. La dispersion des données est très élevée et les résultats ne convergent pas, ce qui indique qu'en dépit de l'installation côte à côte du mât météorologique de référence et de l'éolienne à l'essai sur la crête, à une altitude et sur un terrain local similaires, la corrélation des vitesses du vent entre les deux emplacements est très faible. Cette faible corrélation aura des conséquences négatives sur la précision et l'incertitude d'une mesure de la courbe de puissance pour l'emplacement en question.

Incertitude opérationnelle de l'anémomètre:

Aucune mesure de la vitesse verticale du vent n'a été incluse, de sorte que l'incertitude liée aux caractéristiques d'exploitation de classe B doit être utilisée. La classification des caractéristiques d'exploitation de l'anémomètre est 5,4B.

Contrôle de la convergence:

Le contrôle de la convergence des données pour toutes les tranches de direction du vent échoue. Les données ne convergent pas dans les 0,5 % de la valeur finale tant que 75 % des données recueillies n'ont pas été incluses. Un contrôle sur un échantillon pour l'une des tranches de direction du vent est représenté à la Figure C.18 ci-dessous.

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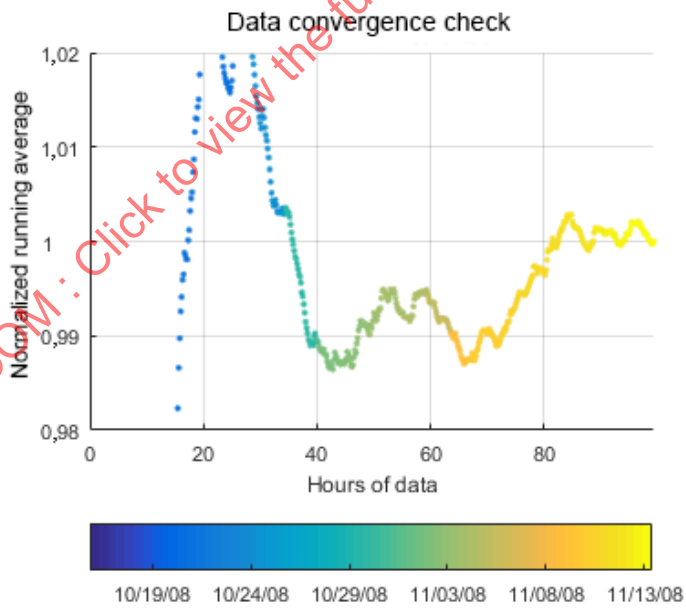

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Anglais	Français
Data convergence check	Contrôle de la convergence des données
Normalized running average	Moyenne d'exploitation normalisée
Hours of data	Heures de données

Figure C.18 – Contrôle de la convergence pour la tranche à 270°

Variation de l'amplitude de correction entre les tranches:

Toutes les tranches adjacentes ont subi des variations d'amplitude de l'ordre de 10 %. L'incertitude supplémentaire est calculée comme suit.

Tableau C.5 – Incertitude supplémentaire due à des variations dans les tranches

Centre de la tranche	Amplitude de variation entre les tranches (à gauche)	Amplitude de variation entre les tranches (à droite)	Incertitude-type supplémentaire (%)
260	1,137	1,176	4,52 %
270	1,093	0,912	2,61 %
280	1,023	0,946	1,11 %

Ajustement de la girouette:

La girouette n'a pas été ajustée, donc aucune incertitude supplémentaire n'est exigée.

Ajustement de l'incertitude saisonnière:

L'étalonnage du site et l'essai de performance de puissance ont été réalisés au cours de différentes saisons (automne et été). Néanmoins, les variations des valeurs de cisaillement du vent et de turbulences n'ont pas dépassé les limites admissibles entre les saisons. Aucune vitesse verticale du vent n'a été enregistrée pour évaluer l'angle d'écoulement ascendant. Cependant, étant donné que le site se trouve dans une zone de recirculation, une large plage d'angles d'écoulement ascendant est prévue. Il n'y a aucune raison de prévoir une dépendance saisonnière. Le site se trouvait dans une zone à climat chaud avec une végétation minimale, donc aucune variation notable de la rugosité de la surface n'est prévue.

Aucune incertitude supplémentaire pour les variations saisonnières n'est nécessaire.

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Annexe D
(normative)

Evaluation de l'incertitude de mesure

L'Annexe D traite des exigences de détermination de l'incertitude de mesure. Les fondements théoriques de la détermination de l'incertitude à l'aide de la méthode des tranches et un exemple élaboré d'estimation des incertitudes peuvent être consultés à l'Annexe E.

La courbe de puissance mesurée doit être complétée par une estimation de l'incertitude de la mesure. L'estimation doit être basée sur l'ISO/IEC Guide 98-3:2008, *Incertitude de mesure – Partie 3: Guide pour l'expression de l'incertitude de mesure* (GUM:1995).

Selon le Guide ISO/IEC Guide 98-3, il existe deux catégories d'incertitudes: les incertitudes de catégorie A dont l'amplitude peut être déduite des mesures et les incertitudes de catégorie B qui sont estimées par d'autres moyens. Dans les deux catégories, les incertitudes sont exprimées sous la forme d'écarts-types et sont appelées incertitudes-types.

a) Mesurandes

Les mesurandes sont la courbe de puissance déterminée par les valeurs de tranches mesurées et normalisées de la puissance électrique et de la vitesse du vent (voir 9.1 et 9.2) et la production annuelle d'énergie estimée (voir 9.3). Les incertitudes de mesure sont converties en incertitude sur le mesurande au moyen de facteurs de sensibilité.

b) Composantes d'incertitude

Le Tableau D.1 donne une liste minimale de paramètres d'incertitude qui doivent être inclus dans l'analyse d'incertitude.

Tableau D.1 – Liste des composantes d'incertitude

Paramètre mesuré	Composante d'incertitude	Catégorie d'incertitude
Puissance électrique	Transformateurs de courant	B
	Transformateurs de tension	B
	Transducteur de puissance ou dispositif de mesure de puissance	B
	Système d'acquisition de données (voir ci-dessous)	B
	Variabilité de la puissance électrique	A
Vitesse du vent (anémomètre à coupelles et à ultrasons)	Etalonnage de la soufflerie	B
	Classification	B
	Distorsion de l'écoulement au niveau du mât	B
	Distorsion de l'écoulement au niveau de la flèche	B
	Système d'acquisition de données (voir ci-dessous)	B
	Essai in situ	B
Vitesse du vent (dispositif de télédétection)	Essai de vérification du RSD	B
	Essai in situ	B
	Classification du RSD	B
	Effets du montage	B
	Variation de l'écoulement sur le volume de sonde à la même hauteur	B
	Essai de surveillance	B
Vitesse du vent équivalente du rotor	Mesure du cisaillement du vent	B
	Mesure de déviation de la trajectoire du vent	B

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Paramètre mesuré	Composante d'incertitude	Catégorie d'incertitude
Direction du vent (girouette ou anémomètre à ultrasons)	Etalonnage	B
	Indicateur du nord	B
	Orientation de la flèche	B
	Caractéristiques opérationnelles (influence du mât)	B
	Angle de déclinaison magnétique	B
	Système d'acquisition de données (voir ci-dessous)	B
Direction du vent (dispositif de télédétection)	Essai de vérification	B
	Classification	B
	Essai de surveillance	B
	Variation de l'écoulement sur le volume de sonde à la même hauteur	B
	Alignement	B
	Angle de déclinaison magnétique	B
	Système d'acquisition de données (voir ci-dessous)	B
Température de l'air	Capteur de température	B
	Protection contre le rayonnement	B
	Effets du montage	B
	Système d'acquisition de données (voir ci-dessous)	B
Pression atmosphérique	Capteur de pression	B
	Effets du montage	B
	Système d'acquisition de données (voir ci-dessous)	B
Humidité relative	Capteur d'humidité	B
	Effets du montage	B
	Système d'acquisition de données (voir ci-dessous)	B
Système d'acquisition de données	Transmission du signal	B
	Précision du système	B
	Conditionnement du signal	B
Terrain (sans étalonnage du site)	Distorsion de l'écoulement due au terrain	B
Terrain (avec étalonnage du site)	Etalonnage de l'anémomètre avant l'essai	B
	Post-étalonnage/Etalonnage in situ	B
	Classification de l'anémomètre	B
	Effets du montage	B
	Montage normal	B
	Autre montage	B
	Montage latéral	B
	Paratonnerre	B
	Système d'acquisition de données (voir ci-dessous)	B
	Variation de correction (tranches adjacentes de direction du vent)	B
	Enlèvement du capteur de direction du vent entre l'étalonnage du site et la mesure de la courbe de puissance	B
	Variations saisonnières	B
	Variabilité statistique de l'étalonnage du site	A
Méthode	Correction de la masse volumique de l'air	B
	Conditions de vent – Informations de cisaillement manquantes	B
	Conditions de vent – Informations de déviation de la trajectoire manquantes	B

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Paramètre mesuré	Composante d'incertitude	Catégorie d'incertitude
	Conditions de vent – Informations d'écoulement ascendant manquantes	B
	Conditions de vent – Informations de turbulences manquantes	B
	Variations saisonnières	B
	Normalisation des turbulences (ou absence de normalisation des turbulences)	B
	Mesures dans un climat froid	B

Il convient de noter que la méthode de la courbe de puissance de la vitesse du vent à la hauteur du moyeu donnée dans la présente norme repose sur l'hypothèse implicite suivante: le rendement de puissance moyen d'une éolienne sur une période de 10 min s'explique entièrement par la vitesse du vent moyenne simultanée sur 10 min mesurée à la hauteur du moyeu et par la masse volumique de l'air.

Cela n'est pas le cas. D'autres variables d'écoulement affectent le rendement de puissance. Des éoliennes identiques donneront donc des rendements de puissance différents sur des sites différents même si la vitesse du vent à la hauteur du moyeu et la masse volumique de l'air sont identiques. Ces autres variables incluent les fluctuations de turbulences de la vitesse du vent (dans les trois directions), l'inclinaison du vecteur d'écoulement par rapport à l'horizontale, l'échelle des turbulences et le cisaillement de la vitesse du vent moyenne sur la surface du rotor. Les outils analytiques offrent actuellement une aide limitée pour identifier l'impact de certaines de ces variables, et les méthodes expérimentales rencontrent également de sérieuses difficultés.

Par conséquent, la courbe de puissance varie d'un site à l'autre, ce qui apparaîtra comme une incertitude.

Cette incertitude provient des différences de rendement de puissance observées dans différentes conditions topographiques et climatiques, c'est-à-dire en comparant une AEP mesurée en terrain homogène à une AEP mesurée sur le site d'un parc éolien non homogène.

Il est difficile de quantifier cette incertitude apparente. Selon les conditions du site et le climat, le pourcentage d'incertitude peut être très élevé. En termes généraux, une augmentation de l'incertitude peut être attendue lorsque la complexité de la topographie s'accroit et lorsque la fréquence des conditions atmosphériques non neutres augmente.

Cependant, cette version de la présente norme décrit des méthodes permettant de rendre compte d'au moins certaines de ces variables d'influence (par exemple, cisaillement du vent et turbulences). L'incertitude de ces méthodes de correction doit également être évaluée. Donc, implicitement, lorsque ces variables sont jugées significatives et lorsqu'aucune correction n'est réalisée, il convient d'augmenter l'incertitude afin de prendre en compte cette absence de correction.

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Annexe E
(informative)

Fondements théoriques de la détermination de l'incertitude de mesure à l'aide de la méthode des tranches

E.1 Généralités

Dans l'Annexe E, toutes les incertitudes énoncées dans l'ensemble de la norme ont été composées et additionnées afin de produire une évaluation cohérente de l'incertitude de mesure de la courbe de puissance, qui couvre à la fois la courbe de puissance et l'AEP calculée.

Pour simplifier la structure dans le but d'introduire ce sujet plutôt complexe, la présente annexe a été organisée de la manière indiquée ci-dessous. La structure principale comporte un article distinct pour chaque catégorie des composantes d'incertitude; comme la vitesse du vent comporte de nombreuses composantes d'incertitude, des articles dédiés leur sont consacrés (voir ci-dessous):

Article E.2 Description mathématique générale et tableau donnant une vue d'ensemble de toutes les composantes d'incertitude et de leurs amplitudes par défaut

Article E.3 Incertitudes de catégorie A

Article E.4 Incertitudes de catégorie B – Introduction et acquisition de données

Article E.5 Catégorie B – Puissance de sortie

Article E.6 Catégorie B – Vitesse du vent – Introduction et capteurs

Article E.7 Catégorie B – Vitesse du vent – RSD

Article E.8 Catégorie B – Vitesse du vent – REWS

Article E.9 Catégorie B – Vitesse du vent – Terrain

Article E.10 Catégorie B – Masse volumique de l'air

Article E.11 Catégorie B – Méthode

Article E.12 Catégorie B – Direction du vent

Article E.13 Composition des incertitudes

Cette annexe donne une méthode de calcul pour le regroupement des incertitudes, ainsi que des tableaux pertinents relatifs aux facteurs de corrélation et un exemple numérique (non exhaustif).

Pour toutes les incertitudes de catégorie B, la présente annexe présente l'objet de chaque composante d'incertitude, le symbole utilisé pour chaque composante, des références à d'autres annexes traitant de la composante ainsi qu'une discussion sur l'amplitude par défaut.

E.2 Composition des incertitudes

E.2.1 Généralités

Dans sa forme la plus générale, l'incertitude-type composée de la puissance dans la tranche i, $u_{c,i}$ peut être exprimée par:

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

où

$c_{k,i}$ est le facteur de sensibilité de la composante k dans la tranche i;

$u_{k,i}$ est l'incertitude-type de la composante k dans la tranche i;

M est le nombre de composantes d'incertitude dans chaque tranche;

$\rho_{k,l,i,j}$ est le coefficient de corrélation entre la composante d'incertitude k dans la tranche i et la composante d'incertitude l dans la tranche j (dans l'expression, les composantes k et l se trouvent toutes les deux dans la tranche i).

La composante d'incertitude est la grandeur d'entrée individuelle correspondant à l'incertitude de chaque paramètre mesuré. L'incertitude-type composée sur la production annuelle d'énergie estimée, u_{AEP}, peut s'exprimer comme suit dans sa forme la plus générale:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{M}\sum_{l=1}^{M} f_i\, c_{k,i}\, u_{k,i}\, f_j\, c_{l,j}\, u_{l,j}\, \rho_{k,l,i,j} \tag{E.2}$$

où

f_i est l'occurrence relative de la vitesse du vent dans la tranche i;

n est le nombre de tranches;

N_h est le nombre d'heures dans une année ≈ 8 760.

Il est rarement possible de déduire toutes les valeurs des coefficients de corrélation $\rho_{k,l,i,j}$ de manière explicite; des simplifications significatives sont normalement nécessaires. Pour pouvoir simplifier à un niveau pratique les expressions ci-dessus des incertitudes composées, les hypothèses suivantes peuvent être retenues:

a) les composantes d'incertitude sont soit entièrement corrélées ($\rho_{k,l,i,j}$ = 1, ce qui implique une sommation linéaire pour obtenir l'incertitude-type composée), soit indépendantes ($\rho_{k,l,i,j}$ = 0, ce qui implique une sommation quadratique, c'est-à-dire que l'incertitude-type composée est la racine carrée de la somme des carrés des composantes d'incertitude);

b) les incertitudes de catégorie A ne sont pas corrélées avec les tranches de vitesse du vent, alors que les incertitudes de catégorie B sont entièrement corrélées avec les tranches de vitesse du vent.

c) valable uniquement pour les incertitudes de l'étalonnage du site: les incertitudes de catégorie A ne sont pas corrélées avec les tranches de direction du vent, alors que les incertitudes de catégorie B sont entièrement corrélées avec les tranches de direction du vent.

La corrélation du même type d'incertitude à différentes hauteurs de mesure du vent lors du calcul de l'incertitude liée à la vitesse du vent équivalente du rotor ou une vitesse du vent normalisée en fonction du cisaillement/de la déviation de la trajectoire du vent doit être évaluée individuellement pour chaque composante et chaque cas. Chaque incertitude peut d'abord être cumulée sur les différentes hauteurs de mesure d'une certaine tranche de vitesse du vent équivalente du rotor ou de la vitesse du vent normalisée en fonction du cisaillement/de la déviation de la trajectoire du vent. Les composantes d'incertitude de la vitesse du vent équivalente du rotor ou de la vitesse du vent normalisée en fonction du cisaillement/de la déviation de la trajectoire du vent peuvent ensuite être traitées comme décrit aux points a) et b).

D'après ces hypothèses, l'incertitude composée de la puissance dans une tranche, $u_{c,i}$ peut être exprimée comme suit:

$$u_{c,i}^2 = \sum_{k=1}^{M_A} c_{k,i}^2\; s_{k,i}^2 + \sum_{k=1}^{M_B} c_{k,i}^2\; u_{k,i}^2 = s_i^2 + u_i^2 \tag{E.3}$$

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où

M_A est le nombre de composantes d'incertitude de catégorie A;

M_B est le nombre de composantes d'incertitude de catégorie B;

$s_{k,i}$ est l'incertitude-type de catégorie A de la composante k dans la tranche i;

s_i est l'incertitude composée de catégorie A dans la tranche i;

u_i est l'incertitude composée de catégorie B dans la tranche i.

Il convient de noter que $u_{c,i}^2$ n'est pas indépendante de la taille de la tranche car $s_{P,i}$ dépend du nombre d'ensembles de données dans la tranche (voir Equation (E.10)).

Ces hypothèses impliquent que l'incertitude-type composée sur la production annuelle d'énergie, u_{AEP}, est:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 \, s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} \left(\sum_{i=1}^{N} f_i \, c_{k,i} \, u_{k,i}\right)^2 \quad \text{(E.4)}$$

Le second terme de cette équation signifie que chaque composante d'incertitude individuelle de catégorie B progresse grâce à l'incertitude de l'AEP correspondante, en appliquant l'hypothèse d'une corrélation complète entre les tranches pour les composantes individuelles. Enfin, les composantes d'incertitude composée entre tranches sont additionnées de manière quadratique pour obtenir l'incertitude de l'AEP.

En outre, certaines composantes de l'incertitude de catégorie A ne peuvent pas toujours être déduites ou estimées aisément en se fondant sur les tranches. Par exemple, les composantes de catégorie A de la méthode d'étalonnage du site peuvent avoir été déduites d'une analyse de la sensibilité sur le calcul de l'AEP. Il convient dans ce cas d'additionner ces composantes de manière quadratique dans l'incertitude sur l'AEP obtenue. Voir Equation (E.8) pour un exemple.

En pratique, il peut être malaisé d'additionner les composantes d'incertitude de catégorie B dans toutes les tranches avant de les composer individuellement. Une approximation, qui permet de composer les composantes d'incertitude de catégorie B au sein des tranches avant de les composer entre des tranches différentes (s_i et u_i peuvent être utilisés), conduit à l'expression plus pratique suivante:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + N_h^2 \left(\sum_{i=1}^{N} f_i \sqrt{\sum_{k=1}^{M_B} c_{k,i}^2 u_{k,i}^2}\right)^2 = N_h^2 \sum_{i=1}^{N} f_i^2 s_i^2 + N_h^2 \left(\sum_{i=1}^{N} f_i u_i\right)^2 \quad \text{(E.5)}$$

La valeur u_{AEP} obtenue par cette expression est toujours supérieure ou égale à celle obtenue à l'aide de l'Equation (E.4).

E.2.2 Incertitude élargie

Les incertitudes-types composées de la courbe de puissance et de l'AEP peuvent, de plus, être exprimées en termes d'incertitudes élargies. En se référant au Guide ISO/IEC 98-3 et en prenant l'hypothèse de distributions normales, des intervalles présentant les niveaux de confiance donnés dans le Tableau E.1 peuvent être obtenus en multipliant ces incertitudes-types composées par un facteur de couverture également donné dans le tableau.

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Tableau E.1 – Incertitudes élargies

Niveau de confiance %	Facteur de couverture
68,27	1
90	1,645
95	1,960
95,45	2
99	2,576
99,73	3

E.2.3 Fondements de l'évaluation de l'incertitude

La méthodologie de calcul passe par une estimation des incertitudes de catégorie A et de catégorie B pour chaque tranche d'une courbe de puissance mesurée. L'incertitude sur la courbe de puissance est déduite, puis l'incertitude sur la production annuelle d'énergie (AEP) est estimée. Etant donné les différences de calculs dans les différentes approches de mesure, il n'a pas été fourni d'exemple très élaboré. Lorsque cela est possible, un exemple élaboré pour une partie du calcul a été fourni afin de montrer comment ont été appliquées les équations et les estimations des valeurs par défaut pour les composantes d'incertitude.

La méthodologie de calcul s'appuie sur le Guide ISO, ainsi que sur les hypothèses ci-dessus. En utilisant la composition des composantes d'incertitude de catégorie B selon l'Equation (E.5), toutes les composantes d'incertitude de chaque tranche peuvent dans un premier temps être combinées afin d'exprimer l'incertitude composée de catégorie B de chaque paramètre mesuré, par exemple la vitesse du vent:

$$u_{\mathrm{V},i}^2 = u_{\mathrm{V1},i}^2 + u_{\mathrm{V2},i}^2 + \ldots \tag{E.6}$$

où les composantes d'incertitude se réfèrent aux composantes d'incertitude du Tableau E., selon les mêmes symboles et indices que dans ce tableau.

Dans un deuxième temps, les incertitudes-types des mesurandes peuvent être exprimées par les incertitudes des paramètres de mesure dans la tranche i:

$$u_{\mathrm{c},i}^2 = s_{\mathrm{P},i}^2 + c_{\mathrm{V},i}^2 s_{\mathrm{SC},i}^2 + u_{\mathrm{P},i}^2 + c_{\mathrm{V},i}^2 u_{\mathrm{V},i}^2 + c_{\mathrm{T},i}^2 u_{\mathrm{T},i}^2 + c_{\mathrm{B},i}^2 u_{\mathrm{B},i}^2 + c_{\mathrm{RH},i}^2 u_{\mathrm{RH},i}^2 + c_{\mathrm{V},i}^2 u_{\mathrm{M},i}^2 \tag{E.7}$$

où

$s_{\mathrm{P},i}$ est l'incertitude-type de catégorie A sur la puissance dans la tranche i;

$s_{\mathrm{SC},i}$ est l'incertitude-type de catégorie A sur l'étalonnage du site dans la tranche i;

$u_{\mathrm{P},i}$ est l'incertitude-type de catégorie B sur la puissance dans la tranche i;

$u_{\mathrm{V},i}$ est l'incertitude-type de catégorie B sur la vitesse du vent dans la tranche i;

$u_{\mathrm{T},i}$ est l'incertitude-type de catégorie B sur la température dans la tranche i;

$u_{\mathrm{B},i}$ est l'incertitude-type de catégorie B sur la pression dans la tranche i;

$u_{\mathrm{RH},i}$ est l'incertitude-type de catégorie B sur l'humidité relative dans la tranche i;

$u_{\mathrm{M},i}$ est l'incertitude-type de catégorie B sur la méthode dans la tranche i;

$c_{\mathrm{V},i}$ est le facteur de sensibilité de la vitesse du vent dans la tranche i;

$c_{\mathrm{T},i}$ est le facteur de sensibilité de la température dans la tranche i;

$c_{\mathrm{B},i}$ est le facteur de sensibilité de la pression dans la tranche i;

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$c_{RH,i}$ est le facteur de sensibilité de l'humidité relative dans la tranche i.

Cela donne également:

$$u_{AEP}^2 = N_h^2\left(\sum_{i=1}^{N} f_i^2 (s_{P,i}^2 + c_{V,i}^2 s_{SC,i}^2) + \left(\sum_{i=1}^{N} f_i \sqrt{u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{RH,i}^2 u_{RH,i}^2 + c_{V,i}^2 u_{M,i}^2}\right)^2\right) \quad \text{(E.8)}$$

Dans l'équation ci-dessus, les incertitudes dues au système d'acquisition de données font partie de l'incertitude pour chaque paramètre de mesure.

La courbe de puissance mesurée, représentée à la Figure 6 et au Tableau 4, est utilisée dans le calcul d'incertitude de la présente annexe. Les résultats de l'analyse d'incertitude de l'exemple sont également représentés à la Figure 6, au Tableau 4 et au Tableau 5. Tous les facteurs de sensibilité sont répertoriés au Tableau E.10; les incertitudes de catégorie B sont répertoriées au Tableau E.11.

Tableau E.2 – Liste des incertitudes de catégories A et B

Catégorie B: Instruments	Note	Incertitude	Sensibilité	Amplitude
Puissance de sortie		$u_{P,i}$	$c_{P,i} = 1$	
Transformateurs de courant	a	$u_{P,CT,i}$		0,75 %
Transformateurs de tension	a	$u_{P,VT,i}$		0,5 %
Transducteur de puissance ou dispositif de mesure de puissance	a	$u_{P,PT,i}$		0,5 %
Acquisition de données (voir E.4.2)	d	$u_{dP,i}$		0,1 % à 0,2 %
Vitesse du vent		$u_{V,i}$		
Mesure de la vitesse du vent		$u_{VHW,i}$		
Vitesse du vent (anémomètre à coupelles ou à ultrasons)		$u_{VS,i}$		
Etalonnage	b	$u_{VS,precal,i}$	Pour l'incertitude sur l'*AEP* (et pour la dernière tranche de l'incertitude sur la courbe de puissance), utiliser: $c_{V,i} \approx \frac{P_i - P_{i-1}}{V_i - V_{i-1}}$	D'après l'étalonnage
Post-étalonnage/Etalonnage in situ	b	$u_{VS,postcal,i}$		0,2 m/s
Classification	c	$u_{VS,class,i}$		1,0 %
Effets du montage				
Montage unique en tête de mât	d	$u_{VS,mnt,i}$	Pour l'incertitude sur la courbe de puissance, utiliser: $c_{V,i} \approx \frac{1}{2}\cdot\left(\frac{(P_{i+1}-P_i)}{(V_{i+1}-V_i)} + \frac{(P_i-P_{i-1})}{(V_i-V_{i-1})}\right)$	0,5 %
Montage côte à côte	d	(identique)		1,0 %
Montage latéral	d	(identique)		1,5 %
Paratonnerre	d	$u_{VS,lgt,i}$		0,1 % à 0,2 %
Acquisition de données (voir E.4.2)	d	$u_{dVS,i}$		0,1 % à 0,2 %
Vitesse du vent (RSD)		$u_{VR,i}$	$c_{V,i}$ (voir ci-dessus)	
Etalonnage	bc	$u_{VR,ver,i}$		2 % à 3 %
Contrôle in situ	c	$u_{VR,isc,i}$		Voir E.7.3
Classification	c	$u_{VR,class,i}$		1,0 % à 1,5 %
Montage	c	$u_{VR,mnt,i}$		0,1 %
Variation de l'écoulement sur différents volumes de sonde à la même hauteur	d	$u_{VR,flow,i}$		2 % à 3 %, voir E.7.6
Essai de surveillance	c	$u_{VR,mon,i}$		0,5 %

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Catégorie B: Instruments	Note	Incertitude	Sensibilité	Amplitude
Vitesse du vent équivalente du rotor		$u_{REWS,\ i}$	$c_{V,i}$ (voir ci-dessus)	
Cisaillement du vent	c	$u_{REWS,shear,\ i}$		Voir E.8.2
Déviation de la trajectoire du vent	c	$u_{REWS,veer,\ i}$		Voir E.8.3
Vitesse du vent – Effets du terrain		$u_{VT,i}$	$c_{V,i}$ (voir ci-dessus)	
Sans étalonnage du site				
Distorsion de l'écoulement due au terrain	d	$u_{VT,i}$	$c_{V,i}$ (voir ci-dessus)	2 % ou 3 % (en mer 1 % ou 2 %)
Avec l'étalonnage du site				
Etalonnage de l'anémomètre	b	$u_{VT,precal,i}$		D'après l'étalonnage
Post-étalonnage/Etalonnage in situ	b	$u_{VT,postcal,i}$		0,2 m/s
Classification de l'anémomètre	c	$u_{VT,class}$		1,0 %
Effets du montage				
Montage unique en tête de mât	d	$u_{VT,mnt,i}$		0,5 %
Montage côte à côte	d	(identique)		1,0 %
Montage lateral	d	(identique)		1,5 %
Paratonnerre	d	$u_{VT,lgt,i}$		0,1 % à 0,2 %
Acquisition de données (voir E.4.2)	d	$u_{dVT,i}$		0,1 % à 0,2 %
Variation de correction (tranches adjacentes de **direction** du vent)	c	$u_{VT,coc,i}$		Voir E.9.8
Enlèvement du capteur de direction du vent entre l'étalonnage du site et la mesure de la courbe de puissance	c	$u_{VT,rmv,i}$		Voir E.9.9
Variations saisonnières	c	$u_{VT,sv,i}$		Voir E.10.10
Masse volumique de l'air		$u_{AD,i}$		
Température		$u_{T,i}$	$c_{T,i}$ (voir E.10.2)	
Capteur de temperature	ab	$u_{T,cal,i}$		0,4 K à 0,6 K
Protection contre le rayonnement	cd	$u_{T,shield,i}$		1,5 K à 2,5 K
Effets du montage	cd	$u_{T,mnt,i}$		0,25 K à 0,4 K
Acquisition de données (voir E.4.2)	c	$u_{dT,i}$		0,1 % à 0,2 %
Pression atmosphérique		$u_{B,i}$	$c_{B,i}$ (voir E.10.7)	
Capteur de pression	ab	$u_{B,cal,i}$		2 hPa à 4 hPa
Effets du montage	a	$u_{B,mnt,i}$		10 % de correction
Acquisition de données (voir E.4.2)	c	$u_{dB,i}$		0,1 % à 0,2 %
Humidité relative		$u_{RH,i}$	$c_{RH,i}$ (voir E.10.11)	
Capteur d'humidité	ab	$u_{RH,cal,i}$		1 % à 2 % (HR)
Effets du montage	cd	$u_{RH,mnt,i}$		0,1 % à 0,2 %
Acquisition de données (voir E.4.2)	c	$u_{dRH,i}$		0,1 % à 0,2 %
Méthode	cd	$u_{AD,method,i}$	$c_{AD,method,I} = c_{V.,i}$ (pour les éoliennes avec contrôle actif)	0,2 % à 0,3 % de la vitesse du vent
Normalisation de la masse volumique de l'air			$c_{AD,method,I} = c_{V.,i} = I$ (pour les éoliennes à régulation par décrochage)	

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Catégorie B: Instruments	Note	Incertitude	Sensibilité	Amplitude
Méthode		$u_{M,\,i}$	$c_{V,i}$ (voir ci-dessus)	
Conditions de vent	d	$u_{M,wc,\,i}$		Voir E.11.2.1, point a) ou b).
Conditions de vent – cisaillement du vent	d	$u_{M,shear,\,i}$		Voir E.11.2.2
Conditions de vent – déviation de la trajectoire du vent	d	$u_{M,veer,\,i}$		Voir E.11.2.3
Conditions de vent – écoulement ascendant	d	$u_{M,upflow,\,i}$		Voir E.11.2.4
Conditions de vent – turbulences	d	$u_{M,ti,\,i}$		0,3 % à 0,5 % (uniquement pour un RSD avec mât météorologique plus bas). Voir E.11.2.5
Variations saisonnières	d	$u_{M,sfx,\,i}$		0,7 %. Voir E.11.3
Normalisation des turbulences	d	$u_{M,tinorm,\,i}$		Voir E.11.4
Climat froid	d	$u_{M,cc,\,i}$		0,5 % à 1 %
Direction du vent				
Girouette de direction du vent		$u_{WV,\,i}$	Aucune (voir E.12.2.1)	
Etalonnage	b	$u_{WV,cal,\,i}$		Voir E.12.2.1
Indicateur du nord	c	$u_{WV,nm,\,i}$		Voir E.12.2.2
Orientation de la flèche	d	$u_{WV,bo,\,i}$		Voir E.12.2.3
Caractéristiques opérationnelles (influence du mât)	c	$u_{WV,oe,\,i}$		Voir E.12.2.4
Angle de déclinaison magnétique	c	$u_{WV,mda,\,i}$		Voir E.12.2.5
Acquisition de données (voir E.4.2)	c	$u_{dWV,\,i}$		Voir E.12.2.6
Direction du vent (RSD)		$u_{WR,\,i}$	Aucune (voir E.12.3)	
Vérification	ab	$u_{WR,ver,\,i}$		Voir E.12.3.1
Classification	c	$u_{WR,class,\,i}$		Voir L.4.4
Essai de surveillance	c	$u_{WR,mon,\,i}$		Voir E.12.3.2
Variation de l'écoulement sur différents volumes de sonde à la même hauteur	c	$u_{WR,fv,\,i}$		Voir E.12.3.3
Alignement	d	$u_{WR,align,\,i}$		Voir E.12.3.4
Angle de déclinaison magnétique	c	$u_{WR,mda,\,i}$		Voir E.12.3.5
Acquisition de données (voir E.4.2)	c	$u_{dWR,\,i}$		Voir E.12.3.6
Catégorie A: Statistiques				
Puissance électrique	e	$s_{P,I}$	$c_{P,i}$ = 1	
Etalonnage du site	e	s_{sc}	$c_{V,i}$ (voir ci-dessus)	

NOTE Identification des incertitudes:

a = référence à la norme;

b = étalonnage;

c = autre "méthode objective";

d = "estimation";

e = statistique.

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Il convient de tenir compte des plages des composantes d'incertitude données dans le Tableau E.2. Il convient d'utiliser les valeurs réelles des mesures spécifiques lorsqu'elles sont disponibles. Il convient de noter qu'il est recommandé de ne pas estimer les composantes d'incertitude à une valeur nulle, comme indiqué dans les lignes directrices du *Guide pour l'expression de l'incertitude de mesure*, sauf si les composantes d'incertitude spécifiques ne conviennent pas à la méthodologie d'essai spécifique appliquée (voir Article E.14).

Il est également important de noter que l'incertitude de direction du vent n'a aucune influence directe sur l'incertitude relative à la courbe de puissance ou à l'AEP (sauf si une normalisation de la déviation de la trajectoire du vent est appliquée). L'incertitude de direction du vent est toutefois incluse ici. Il est en effet important de comprendre avec quel niveau de précision est mis en œuvre le filtrage du secteur de mesure, mais aussi avec quel niveau de précision les facteurs d'étalonnage du site sont appliqués aux données des secteurs appropriés. Etant donné que l'incertitude de direction du vent doit être consignée, ce tableau donne les composantes d'incertitude minimales qui doivent être prises en compte pour l'incertitude de direction du vent. Aucune estimation de l'amplitude de ces composantes n'est donnée, mais il convient de les inclure dans une courbe de puissance consignée.

Il est à noter que certains rapports d'étalonnage donnent une incertitude pour un facteur de couverture de 2 au lieu de 1. Afin de composer correctement les incertitudes, il convient de les convertir à un facteur de couverture cohérent avec toutes les entrées d'incertitude (par défaut, utiliser un facteur de couverture de 1).

E.3 Incertitudes de catégorie A

E.3.1 Généralités

Les incertitudes de catégorie A relatives à la puissance électrique mesurée et normalisée, ainsi que celles dues aux variations climatiques et à l'étalonnage du site (s'il a été réalisé) doivent être prises en compte.

E.3.2 Incertitude de catégorie A sur la puissance électrique

L'écart-type de la distribution des données de puissance normalisées dans chaque tranche est calculé à l'aide de l'équation suivante:

$$\sigma_{\mathrm{P},i} = \sqrt{\frac{1}{N_i - 1} \sum_{j=1}^{N_i} \left(P_i - P_{\mathrm{n},i,j}\right)^2} \tag{E.9}$$

où

$\sigma_{\mathrm{P},I}$ est l'écart-type des données de puissance normalisées dans la tranche i;

N_i est le nombre d'ensembles de données de 10 min dans la tranche i;

P_i est la puissance de sortie normalisée et moyennée dans la tranche i;

$P_{\mathrm{n},i,}$ est la puissance de sortie normalisée de l'ensemble de données j dans la tranche i.

L'incertitude-type sur la puissance normalisée et moyennée dans la tranche est estimée à l'aide de l'équation suivante:

$$s_i = s_{\mathrm{P},i} = \frac{\sigma_{\mathrm{P},i}}{\sqrt{N_i}} \tag{E.10}$$

où

$s_{\mathrm{P},i}$ est l'incertitude-type de catégorie A sur la puissance dans la tranche i;

$\sigma_{\mathrm{P},i}$ est l'écart-type des données de puissance normalisées dans la tranche i;

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N_i est le nombre d'ensembles de données de 10 min dans la tranche i.

E.3.3 Incertitudes de catégorie A sur l'étalonnage du site

Les résidus entre la vitesse du vent corrigée après l'étalonnage du site et mesurée au niveau du mât météorologique représentant l'éolienne sont utilisés pour déterminer l'incertitude de catégorie A de l'étalonnage du site, s_{sc}. Pour la méthode de dérivation, se reporter à C.6.1.

E.4 Incertitudes de catégorie B: Introduction et système d'acquisition de données

E.4.1 Incertitudes de catégorie B: Introduction

Par hypothèse, les incertitudes de catégorie B se rapportent aux instruments, au système d'acquisition de données, au terrain qui entoure le site d'essai de performance de puissance, ainsi qu'à l'incertitude relative à la méthode appliquée. Si les incertitudes sont exprimées comme des limites d'incertitude ou qu'elles comportent des facteurs implicites de couverture non unitaires, l'incertitude-type doit être estimée ou les incertitudes doivent être converties convenablement en incertitudes-types.

Soit une incertitude exprimée sous la forme d'une limite d'incertitude ± U. Si l'hypothèse d'une distribution de probabilité rectangulaire est retenue, l'incertitude-type est:

$$\sigma = \frac{U}{\sqrt{3}} \tag{E.11}$$

Si l'hypothèse d'une distribution de probabilité triangulaire est retenue, l'incertitude-type est:

$$\sigma = \frac{U}{\sqrt{6}} \tag{E.12}$$

E.4.2 Incertitudes de catégorie B: Système d'acquisition de données

Les incertitudes relatives à l'acquisition de données ont été incluses dans le traitement des signaux spécifiques. L'incertitude de la puissance électrique inclut une composante concernant l'acquisition de données; il en va de même pour la vitesse du vent et les autres signaux mesurés.

La présente annexe prend l'hypothèse que le système d'acquisition de données dispose d'une incertitude-type $u_{d,i}$ égale à 0,1 % de la plage complète de chaque canal de mesure. Toutefois, lors de la consignation d'un essai de performance de puissance spécifique, l'incertitude relative à l'acquisition de données doit être estimée pour la configuration d'essai spécifique, y compris au minimum les contributions à l'incertitude relative à l'acquisition de données mentionnées en E.4.2.

Il peut exister des incertitudes dues à la transmission, au conditionnement des signaux, à la conversion analogique-numérique, ainsi qu'au traitement de données dans le système d'acquisition de données. Les incertitudes peuvent être différentes selon le canal de mesure. L'incertitude-type du système d'acquisition de données concernant la plage complète d'un canal de mesure donné, $u_{d,i}$, peut être exprimée comme suit:

$$u_{d,i} = \sqrt{u_{d,ST,i}^2 + u_{d,SA,i}^2 + u_{d,SC,i}^2} \tag{E.13}$$

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où

$u_{d,ST,i}$ est l'incertitude due à la transmission du signal dans la tranche i;

$u_{d,SA,i}$ est l'incertitude due à la précision du système dans la tranche i;

$u_{d,SC,i}$ est l'incertitude due au conditionnement des signaux dans la tranche i.

Bien que l'hypothèse d'une incertitude-type égale à 0,1 % de la plage complète du canal de mesure se révèle raisonnable dans la plupart des cas, des conditions et des matériels spécifiques peuvent faire augmenter considérablement cette valeur. Pour s'assurer que l'incertitude du système d'acquisition de données est effectivement négligeable par rapport à l'incertitude des capteurs (qu'il convient, selon les lignes directrices, d'interpréter comme un facteur 10 d'amplitude par rapport aux incertitudes-types), une évaluation de l'incertitude réelle du système d'acquisition de données utilisé doit être réalisée.

E.5 Incertitudes de catégorie B: Puissance de sortie

E.5.1 Généralités

Les incertitudes de catégorie B relatives à la puissance de sortie sont fondées sur quatre composantes d'incertitude, présentées ci-après.

Le symbole de cette composante d'incertitude est $u_{P,i}$.

L'incertitude de la mesure de puissance comporte des contributions d'incertitude dues aux transformateurs de courant et de tension, ainsi qu'au transducteur de puissance (ou tout autre dispositif de mesure de puissance). Les incertitudes de ces sous-composantes sont normalement mentionnées dans leurs classifications.

Enfin, l'incertitude relative à l'acquisition de données du signal de puissance doit être ajoutée.

E.5.2 Incertitudes de catégorie B: Puissance de sortie – Transformateurs de courant

Cette composante d'incertitude couvre l'incertitude due au transformateur de courant, déterminée par la classification du capteur.

Le symbole de cette composante d'incertitude est $u_{P,CT,i}$.

Dans la présente annexe, l'hypothèse retenue est que les transformateurs de courant et le transducteur de puissance sont tous de classe 0,5, qui constitue la classe acceptable minimale pour une mesure de la courbe de puissance selon les exigences de la présente norme.

Les transformateurs de courant sont de classe 0,5 (les charges nominales des transformateurs de courant sont ici prévues pour correspondre à la puissance nominale de 2 000 kW, et non à 125 % de la puissance nominale). Ils ont des limites d'incertitude égales à ± 0,5 % du courant pour une charge de 100 % (voir l'IEC 61689-2). Cependant, pour des charges de 20 % et 5 %, les limites d'incertitude augmentent respectivement jusqu'à ± 0,75 % et ± 1,5 % du courant. Pour les mesures de performance de puissance sur des éoliennes, la production d'énergie la plus importante s'effectue à puissance réduite. Il est ainsi prévu que les limites d'incertitude de ± 0,75 % du courant à une charge de 20 % soient une bonne moyenne.

L'hypothèse d'une distribution d'incertitude rectangulaire du transformateur de courant est retenue. Si les transformateurs de courant ne sont pas exploités dans leurs limites de charges opérationnelles sur la boucle secondaire, des incertitudes supplémentaires doivent être ajoutées.

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L'hypothèse retenue est que les incertitudes des trois transformateurs de courant sont causées par des facteurs d'influence externes, par exemple la température de l'air, la fréquence du réseau électrique, etc. Il est donc pris pour hypothèse qu'elles sont entièrement corrélées (par exception à l'hypothèse générale) et sont additionnées de manière linéaire. Puisque chaque transformateur de courant contribue à 1/3 de la mesure de puissance, il en résulte que l'incertitude de tous les transformateurs de courant est proportionnelle à la puissance comme suit:

$$u_{\mathrm{P,CT},i} = \frac{0{,}75\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}43\ \% \cdot P_i\ [\mathrm{kW}] \tag{E.14}$$

E.5.3 Incertitudes de catégorie B: Puissance de sortie – Transformateurs de tension

Cette composante d'incertitude couvre l'incertitude due au transformateur de tension, déterminée par la classification du capteur.

Le symbole de cette composante d'incertitude est $u_{\mathrm{P,VT},i}$.

Dans la présente annexe, l'hypothèse retenue est que les transformateurs de tension et le transducteur de puissance sont tous de classe 0,5, qui constitue la classe acceptable minimale pour une mesure de la courbe de puissance selon les exigences de la présente norme.

Les transformateurs de tension de classe 0,5 ont des limites d'incertitude égales à ± 0,5 % de la tension pour toutes les charges (voir l'IEC 61869-3). L'hypothèse d'une distribution d'incertitude rectangulaire est retenue.

Les transformateurs de tension ne sont pas utilisés pour toutes les mesures, et la valeur de ces composantes d'incertitude peut être définie à zéro lorsqu'ils ne sont pas utilisés.

Si les transformateurs de tension ne sont pas exploités dans leurs limites de charges opérationnelles sur la boucle secondaire, des incertitudes supplémentaires doivent être ajoutées.

La tension du réseau électrique est normalement relativement constante et indépendante de la puissance de l'éolienne. L'hypothèse retenue est que les incertitudes des trois transformateurs de tension sont, comme pour les transformateurs de courant, causées par des facteurs d'influence externes, par exemple la température de l'air, la fréquence du réseau électrique, etc. Il est donc pris pour hypothèse qu'elles sont entièrement corrélées (par exception à l'hypothèse générale) et sont additionnées de manière linéaire. Puisque chaque transformateur de tension contribue à 1/3 de la mesure de puissance, il en résulte que l'incertitude de tous les transformateurs de courant est proportionnelle à la puissance comme suit:

$$u_{\mathrm{P,VT},i} = \frac{0{,}5\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}29\ \% \cdot P_i\ [\mathrm{kW}] \tag{E.15}$$

E.5.4 Incertitudes de catégorie B: Puissance de sortie – Transducteur de puissance ou autre dispositif de mesure de puissance

Cette composante d'incertitude couvre l'incertitude due au transducteur de puissance (ou tout autre dispositif de mesure de puissance) déterminée par la classification du capteur.

Le symbole de cette composante d'incertitude est $u_{\mathrm{P,PT},i}$.

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Le transducteur de puissance de classe 0,5 (voir l'IEC 60688) d'une puissance nominale de 2 500 kW (125 % de la puissance nominale, soit 2 000 kW, de l'éolienne) a une limite d'incertitude de 12,5 kW. L'hypothèse d'une distribution d'incertitude rectangulaire est retenue.

L'incertitude du transducteur de puissance est ainsi:

$$u_{\mathrm{P,PT},i} = \frac{12{,}5\ \mathrm{kW}}{\sqrt{3}} = 7{,}2\ \mathrm{kW} \tag{E.16}$$

E.5.5 Incertitudes de catégorie B: Puissance de sortie – Acquisition de données

Cette composante d'incertitude couvre l'incertitude relative à l'acquisition de données du signal de puissance.

Le symbole de cette composante d'incertitude est $u_{\mathrm{dP},i}$.

Par hypothèse, la valeur par défaut de l'amplitude de cette composante est comprise entre 0,1 % et 0,2 % de la plage complète du système d'acquisition de données.

En prenant pour hypothèse que la plage de puissance électrique du canal de mesure d'une éolienne de 2 MW est égale à 3 000 kW et que l'incertitude du système d'acquisition de données est égale à 0,1 % de cette plage, l'incertitude obtenue est de 3 kW.

E.6 Incertitudes de catégorie B: Vitesse du vent – Introduction et capteurs

E.6.1 Incertitudes de catégorie B: Vitesse du vent – Introduction

L'incertitude de la vitesse du vent compte trois composantes, chacune comportant elle-même plusieurs sous-composantes. Ces trois composantes sont:

a) l'incertitude relative à l'utilisation de matériel de détection (anémomètres à coupelles, à ultrasons et dispositifs de télédétection (RSD);
b) l'incertitude relative à la distorsion de l'écoulement due au terrain;
c) l'incertitude relative aux méthodes appliquées.

Le symbole de cette composante d'incertitude est $u_{\mathrm{V},i}$.

Ces composantes d'incertitude, ainsi que leurs sous-composantes, seront introduites dans les paragraphes qui suivent.

Le facteur de sensibilité, $c_{\mathrm{V},i}$, est défini au Tableau E.2.

E.6.2 Incertitudes de catégorie B: Vitesse du vent – Matériel

L'incertitude de la vitesse du vent relative au matériel compte trois composantes, chacune comportant elle-même plusieurs sous-composantes. Ces trois composantes sont:

a) l'incertitude relative à l'utilisation de capteurs placés sur un mât météorologique (anémomètres à coupelles et à ultrasons);
b) l'incertitude relative au dispositif de télédétection (RSD);
c) l'incertitude relative à la vitesse du vent équivalente du rotor (REWS).

Le symbole de cette composante d'incertitude est $u_{\mathrm{VHW},I}$.

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E.6.3 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique

E.6.3.1 Généralités

Cette composante d'incertitude couvre l'incertitude relative à l'utilisation d'anémomètres à coupelles et à ultrasons sur les mâts météorologiques (montés en tête ou latéralement).

Le symbole de cette composante d'incertitude est $u_{VS,i}$. (où V représente la vitesse du vent et S représente les capteurs).

Cette composante d'incertitude compte six sous-composantes:

a) l'incertitude relative à l'étalonnage du capteur avant le début de l'essai de performance de puissance;

b) l'incertitude relative à l'étalonnage du capteur pendant ou après l'essai de performance de puissance;

c) l'incertitude relative aux caractéristiques opérationnelles, déterminées par la classification du capteur;

d) l'incertitude relative au montage du capteur;

e) l'incertitude relative au montage du paratonnerre;

f) l'incertitude relative à l'acquisition de données du signal du capteur.

E.6.3.2 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Pré-étalonnage

Cette composante d'incertitude couvre l'incertitude relative à l'étalonnage du capteur avant l'essai. Cela inclut la variabilité des essais répétés pour une installation d'essai, ainsi que la variabilité des essais répétés entre différentes installations.

Le symbole de cette composante d'incertitude est $u_{VS,\mathrm{precal},i}$.

Cette incertitude est également décrite à l'Annexe F de la présente norme.

Pour un essai de performance de puissance spécifique, les valeurs indiquées sur l'étalonnage des capteurs utilisés doivent être utilisées pour le calcul de l'incertitude.

E.6.3.3 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Post-étalonnage

Cette composante d'incertitude couvre l'incertitude relative à l'étalonnage in situ et/ou au post-étalonnage du capteur pendant et/ou après l'essai.

Le symbole de cette composante d'incertitude est $u_{\mathrm{VS,postcal},i}$.

Cette incertitude est également décrite en 7.2.2 et à l'Annexe K de la présente norme.

Si un étalonnage in situ a été réalisé lors de l'essai de performance de puissance et si un post-étalonnage a été réalisé après l'essai de performance de puissance, l'amplitude de cette composante d'incertitude doit être issue du post-étalonnage.

Si un post-étalonnage est réalisé, l'amplitude de cette composante d'incertitude doit être égale à la différence maximale entre le pré-étalonnage et le post-étalonnage dans la plage de vitesses du vent comprise entre 4 m/s et 12 m/s, jusqu'à un maximum de 0,2 m/s.

Il est à noter que, étant donné l'incertitude inhérente de l'étalonnage, des différences mineures apparaîtront entre le pré-étalonnage et le post-étalonnage. La meilleure estimation

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de la valeur d'étalonnage pour un capteur spécifique correspondra à la moyenne des étalonnages réalisés; dans la limite d'un très grand nombre d'étalonnages, la moyenne convergera vers le centre de la distribution.

Comme seul le pré-étalonnage est utilisé pour déterminer la vitesse du vent au niveau du capteur, la différence maximale peut donc être utilisée comme une contribution d'incertitude supplémentaire.

Si seul un étalonnage in situ est réalisé conformément à l'Annexe K, l'amplitude de cette composante d'incertitude doit être égale à la valeur maximale de δ dans la plage de vitesses du vent comprise entre 4 m/s et 12 m/s, jusqu'à un maximum de 0,2 m/s.

E.6.3.4 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Classification

Cette composante d'incertitude couvre l'incertitude relative aux caractéristiques opérationnelles du capteur, déterminées par la classification du capteur.

Le symbole de cette composante d'incertitude est $u_{V\mathrm{S,class},i}$.

Cette incertitude est également décrite à l'Annexe I de la présente norme.

L'amplitude de cette incertitude doit être issue du rapport de classification. Le type de terrain sur lequel est utilisé le capteur doit correspondre au type de terrain adapté à la classification du capteur (classe A, B ou S).

Le rapport de performance de puissance doit faire référence au rapport de classification.

La plage mesurée des paramètres d'influence utilisés pour la classification, conformément à l'Annexe I, doit être consignée pour l'ensemble de données utilisé aux fins du rapport de performance de puissance. Si l'écoulement ascendant n'est pas mesuré, la conformité à la classe de précision doit être justifiée à partir des pentes du terrain local pour les directions du vent rencontrées, en adaptant un plan au terrain à une distance inférieure à 5 fois la mesure de hauteur relative à la position du WME conformément à l'IEC 61400-1:2005, 11.9.

L'incertitude opérationnelle de l'anémomètre de référence (dictée par un éventuel étalonnage du site) doit être incluse dans cette composante d'incertitude. Elle peut englober toutes les incertitudes de l'anémomètre de référence de l'étalonnage du site, certaines d'entre elles ou aucune d'entre elles, selon que la plage mesurée des paramètres d'influence rencontrés par le capteur de référence sur le mât météorologique permanent pendant l'étalonnage du site est ou non significativement différente de la plage des paramètres d'influence rencontrés par le capteur de référence sur le mât météorologique permanent pendant l'essai de courbe de puissance.

Par défaut, la moitié des incertitudes opérationnelles de l'anémomètre de référence et toutes les incertitudes opérationnelles de l'anémomètre monté sur l'éolienne pendant l'étalonnage du site, ainsi que la moitié des incertitudes opérationnelles de l'anémomètre pendant l'essai de courbe de puissance, doivent être incluses. Elles doivent être additionnées selon la méthode quadratique.

E.6.3.5 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Montage

Cette composante d'incertitude couvre l'incertitude relative au montage du capteur.

Le symbole de cette composante d'incertitude est $u_{V\mathrm{S,mnt},i}$.

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Cette incertitude est également décrite en 7.2.4 et en 9.1.2, mais aussi à l'Annexe G de la présente norme.

Cette composante d'incertitude a trois valeurs par défaut qui correspondent aux trois configurations de montage admises par l'Annexe G (un seul anémomètre monté en tête de mât, anémomètres montés en tête de mât côte à côte ou anémomètre monté latéralement).

Pour un seul anémomètre monté en tête de mât, l'amplitude par défaut de cette composante d'incertitude est égale à 0,5 % de la vitesse du vent mesurée.

Pour des anémomètres montés côte à côte en tête de mât, l'amplitude par défaut de cette composante d'incertitude est égale à 1,0 %.

Pour un anémomètre monté latéralement, l'amplitude par défaut de cette composante d'incertitude est égale à l'une des valeurs suivantes:

- pour les signaux n'ayant pas subi de correction de l'écoulement, l'amplitude par défaut pour cette composante d'incertitude est égale à 1,5 % du signal mesuré;
- pour les signaux ayant subi une correction de l'écoulement conformément à 7.2.4 et à 9.1.2 (correction de la distorsion de l'écoulement au niveau du mât), l'amplitude par défaut de cette composante d'incertitude est égale à la résultante quadratique de la moitié de la correction moyenne appliquée au signal de vitesse du vent et à 0,5 % du signal mesuré. Les effets du sillage doivent être exclus pour appliquer la correction.

Le même principe de correction peut également être appliqué à deux anémomètres montés en tête de mât dans une configuration en poteaux de but, avec la même amplitude par défaut pour le signal ayant subi une correction de l'écoulement.

E.6.3.6 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Paratonnerre

Cette composante d'incertitude couvre l'incertitude relative à un éventuel paratonnerre monté en tête de mât et à son influence sur un anémomètre monté en tête de mât lorsque les exigences de l'Article G.5 pour le montage du paratonnerre ne peuvent pas être respectées.

Le symbole de cette composante d'incertitude est $u_{V\mathrm{S,lgt},i}$.

L'amplitude par défaut pour cette composante d'incertitude est comprise entre 0,1 % et 0,2 % du signal de vitesse du vent.

E.6.3.7 Incertitudes de catégorie B: Vitesse du vent – Capteurs montés sur mât météorologique – Acquisition de données

Cette composante d'incertitude couvre l'incertitude relative à l'acquisition de données du signal de vitesse du vent.

Le symbole de cette composante d'incertitude est $u_{\mathrm{d}V\mathrm{S},i}$.

Cette incertitude est également décrite en E.4.2 de la présente norme.

L'amplitude par défaut pour cette composante d'incertitude est comprise entre 0,1 % et 0,2 % de la plage complète du signal de vitesse du vent mesuré.

En prenant pour hypothèse que la plage de vitesses du vent est égale à 30 m/s du canal de mesure et que l'incertitude du système d'acquisition de données est égale à 0,1 % de cette plage, l'incertitude-type de l'acquisition de données est de 0,03 m/s.

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E.7 Incertitudes de catégorie B: Vitesse du vent – RSD

E.7.1 Généralités

Cette composante d'incertitude couvre l'incertitude relative à l'utilisation de dispositifs de télédétection pour les mesures de vitesse du vent, comme les dispositifs de détection et télémétrie par ondes lumineuses (LIDAR, *Light Detection And Ranging*) et par ondes sonores (SODAR, *Sonic Detection And Ranging*).

Le symbole de cette composante d'incertitude est $u_{V\mathrm{R},i}$ (V représente la vitesse du vent et R représente le dispositif de télédétection).

Cette composante d'incertitude compte six sous-composantes:

a) l'incertitude relative à la vérification du dispositif;

b) l'incertitude relative au contrôle in situ du dispositif;

c) l'incertitude relative aux caractéristiques opérationnelles du dispositif, déterminées par la classification du dispositif;

d) l'incertitude relative au montage du dispositif;

e) l'incertitude relative à la variation d'écoulement sur différents volumes de sonde à la même hauteur;

f) l'incertitude relative à l'essai de surveillance.

g)

E.7.2 Incertitudes de catégorie B: Vitesse du vent – RSD – Etalonnage

Cette composante d'incertitude couvre l'incertitude relative à l'étalonnage du dispositif de télédétection.

Le symbole de cette composante d'incertitude est $u_{V\mathrm{R,ver},i}$.

Cette incertitude est également décrite à l'Annexe L.

Avant de procéder à la mesure, un étalonnage selon l'Annexe L doit être effectué et ses incertitudes doivent être évaluées ($u_{V\mathrm{R,vrf},i}$) (pour plus d'informations, voir L.4.3). Si les incertitudes relatives à la hauteur de mesure exacte ne sont pas disponibles, il est recommandé d'interpoler les incertitudes. L'amplitude par défaut de cette composante d'incertitude est comprise entre 1,0 % et 3,0 % de la vitesse du vent mesurée.

E.7.3 Incertitudes de catégorie B: Vitesse du vent – RSD – Contrôle in situ

Cette composante d'incertitude couvre l'incertitude relative à la vérification du dispositif de télédétection, appliquée uniquement aux RSD équipant un mât météorologique d'une hauteur inférieure à celle du moyeu.

Le symbole de cette composante d'incertitude est $u_{\mathrm{VR,isc},i}$ ("isc" représente le contrôle in situ, "*in-situ check*").

Cette incertitude est également décrite à l'Annexe L de la présente norme.

L'essai in situ doit être évalué conformément à la description de l'Annexe K, où le RSD est le principal matériel de mesure et l'anémomètre monté sur le mât de surveillance est l'anémomètre de commande disposant des mêmes limites d'incertitude.

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E.7.4 Incertitudes de catégorie B: Vitesse du vent – RSD – Classification

Cette composante d'incertitude couvre l'incertitude relative à la classification du dispositif de télédétection.

Le symbole de cette composante d'incertitude est $u_{\mathrm{VR,class},i}$.

Cette incertitude est également décrite à l'Annexe L de la présente norme.

L'incertitude due aux caractéristiques opérationnelles est issue du rapport de classification du RSD, qui donne les pentes et les plages des variables environnementales. Il existe trois façons de calculer l'incertitude due à ces variables:

1. La variable environnementale est mesurée lors de la mesure:

(selon l'Equation (L.6) de l'Annexe L)

$$u_{\mathrm{VR,class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \left| \bar{x}_{\mathrm{PC},j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)^2} \tag{E.17}$$

où

v_i est la vitesse du vent mesurée à la hauteur i;

M est le nombre de variables environnementales réputées avoir une influence significative sur la précision du dispositif de télédétection selon l'essai de classification;

m_j est la pente décrivant la sensibilité de la mesure de la vitesse du vent par le dispositif de télédétection sur la variable environnementale j obtenue par combinaison des résultats d'au moins 3 essais de classification;

$\bar{x}_{\mathrm{PC},j,i}$ est la valeur moyenne de la variable environnementale j dans la tranche de vitesse du vent i présente lors de l'essai de courbe de puissance;

$\bar{x}_{\mathrm{ver},j,i}$ est la valeur moyenne de la variable environnementale j dans la tranche de vitesse du vent i présente lors de l'essai de vérification de performance sur le dispositif de télédétection.

2. La variable environnementale N'EST PAS mesurée lors de la mesure:

$$u_{\mathrm{VR,class},i} = v_i \sqrt{\sum_{j=1}^{M} \left(\frac{m_j}{100} \cdot \frac{\max\left(\left| x_{\mathrm{min},j,i} - \bar{x}_{\mathrm{ver},j,i} \right|, \left| x_{\mathrm{max},j,i} - \bar{x}_{\mathrm{ver},j,i} \right| \right)}{\sqrt{3}} \right)^2} \tag{E.18}$$

où

v_i est la vitesse du vent mesurée à la hauteur i;

M est le nombre de variables environnementales réputées avoir une influence significative sur la précision du dispositif de télédétection selon l'essai de classification;

m_j est la pente décrivant la sensibilité de la mesure de la vitesse du vent par le dispositif de télédétection sur la variable environnementale j obtenue par combinaison des résultats d'au moins 3 essais de classification;

$x_{\mathrm{min},j,i}$ est la limite inférieure de la plage attendue pour la variable environnementale non mesurée j dans la tranche de vitesse du vent i;

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