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Functions concerned
Fonctions concernées

☐ Safety / Sécurité ☐ EMC / CEM ☐ Environment / Environnement ☐ Quality assurance / Assurance de la qualité

INTERNATIONAL ELECTROTECHNICAL COMMISSION **COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE**

Title

IEC 61400-12-1 Ed.1: Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines

ATTENTION
VOTE PARALLÈLE
CEI – CENELEC

L'attention des Comités nationaux de la CEI, membres du CENELEC, est attirée sur le fait que ce projet final de Norme internationale est soumis au vote parallèle. Un bulletin de vote séparé pour le vote CENELEC leur sera envoyé par le Secrétariat Central du CENELEC.

ATTENTION
IEC – CENELEC
PARALLEL VOTING

The attention of IEC National Committees, members of CENELEC, is drawn to the fact that this final Draft International Standard (DIS) is submitted for parallel voting. A separate form for CENELEC voting will be sent to them by the CENELEC Central Secretariat.

1906-2006 The electric century

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINES –

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61400-12-1 has been prepared by IEC technical committee 88: Wind turbines.

This standard cancels and replaces IEC 61400-12 published in 1998. This first edition of IEC 61400-12-1 constitutes a technical revision. IEC 61400-12-2 and IEC 61400-12-3 are additions to IEC 61400-12-1.

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

FDIS	Report on voting
88/XX/FDIS	88/XX/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.

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

IEC 61400-12 consists of the following parts, under the general title *Wind turbines:*

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

Part 12-2: Verification of power performance of individual wind turbines (under consideration)

Part 12-3: Wind farm power performance testing (under consideration)

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date[1] indicated on the IEC web site 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.

A bilingual version of this standard may be issued at a later date.

[1] The National Committees are requested to note that for this publication the maintenance result date is 2008.

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

– a wind turbine purchaser in specifying such performance requirements;

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

– a wind turbine planner or regulator who must 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 standard provides guidance in the measurement, analysis, and reporting of power performance testing for wind turbines. The standard 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. This standard 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 standard prescribes the use of cup anemometers to measure the wind speed. This instrument is robust and has long been regarded as suitable for this kind of test. Even though suitable wind tunnel calibration procedures are adhered to, the field flow conditions associated with the fluctuating wind vector, both in magnitude and direction, will cause different instruments to potentially perform differently.

Tools and procedures to classify cup 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. Special care should therefore be taken in the selection of the instruments chosen to measure the wind speed.

WIND TURBINES –

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 turbines at specific locations, but equally the methodology can be used to make generic comparisons between different turbine models or different turbine settings.

The wind turbine power performance characteristics are determined by the measured power curve and the estimated annual energy production (AEP). The measured power curve is determined by collecting simultaneous measurements of wind speed and 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.

The standard 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 referenced documents are indispensable for the application 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)[2]

IEC 60688: 1992, *Electrical measuring transducers for converting a.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*

ISO 2533:1975, *Standard atmosphere*

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

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

3 Terms and definitions

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

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
complex terrain
terrain surrounding the test site that features significant variations in topography and terrain obstacles that may cause flow distortion

3.4
data set
collection of data that was sampled over a continuous period

3.5
distance constant
indication of the response time of an anemometer, defined as the length of air that must pass the instrument for it to indicate 63 % of the final value for a step input in wind speed

3.6
extrapolated power curve
extension of the measured power curve by estimating power output from the maximum measured wind speed to cut-out wind speed

3.7
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

3.8
hub height (wind turbines)
height of the centre of the swept area of the wind turbine rotor above the ground at the tower

NOTE For a vertical axis wind turbine the hub height is the height of the equator plane.

3.9
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

3.10
measurement period
period during which a statistically significant database has been collected for the power performance test

3.11
measurement sector
a sector of wind directions from which data are selected for the measured power curve

3.12
method of bins
data reduction procedure that groups test data for a certain parameter into wind speed intervals (bins)

NOTE 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.

3.13
net active electric power
measure of the wind turbine electric power output that is delivered to the electrical power network

3.14
obstacles
things that blocks the wind and creates distortion of the flow, such as buildings and trees

3.15
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

3.16
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

3.17
power performance
measure of the capability of a wind turbine to produce electric power and energy

3.18
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.

3.19
standard uncertainty
uncertainty of the result of a measurement expressed as a standard deviation

3.20
swept area
for a horizontal axis turbine, the projected area of the moving rotor upon a plane normal to axis of rotation. For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft. For a vertical axis turbine, the projected area of the moving rotor upon a vertical plane.

3.21
test site
location of the wind turbine under test and its surroundings

3.22
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

4 Symbols and units

A	swept area of the wind turbine rotor	[m^2]
AEP	annual energy production	[Wh]
B	barometric pressure	[Pa]
$B_{10\text{min}}$	measured air pressure averaged over 10 min	[Pa]
C_h	pitot tube head coefficient	
$C_{\text{P},i}$	power coefficient in bin i	
C_QA	generalized aerodynamic torque coefficient	
C_T	thrust coefficient	
c	sensitivity factor on a parameter (the partial differential)	
$c_{\text{B},i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{\text{d},i}$	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	
$c_{\text{m},i}$	sensitivity factor of air density correction in bin i	[Wm^3/kg]
$c_{\text{T},i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{\text{V},i}$	sensitivity factor of wind speed in bin i	[Ws/m]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
D_n	rotor diameter of neighbouring and operating wind turbine	[m]
d	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	
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_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	
$K_\text{B,t}$	barometer	
$K_\text{B,s}$	barometer gain	
$K_\text{B,d}$	barometer sampling	
$K_\text{T,t}$	temperature transducer	
$K_\text{T,s}$	temperature transducer gain	
$K_\text{T,d}$	temperature transducer sampling	
$K_\text{p,t}$	pressure transducer sensitivity	
$K_\text{p,s}$	pressure transducer gain	
$K_\text{p,d}$	pressure transducer sampling conversion	

L	leg distance of three legged mast	[m]
L	distance between the wind turbine and the meteorological mast	[m]
L_e	distance between the wind turbine or the meteorological mast and an obstacle [m]	
L_n	distance between the wind turbine or the meteorological mast 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 ≈ 8760	[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)	
P_0	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	[m]
R_0	gas constant of dry air (287,05)	[J/(kgK)]
R_w	gas constant of water vapour (461,5)	[J/kgK]
r	correlation coefficient	
s	uncertainty component of category A	
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]
$s_{w,i}$	category A standard uncertainty of climatic variations in bin i	
$s_{\alpha,j}$	category A standard uncertainty of wind speed ratios in bin j	
T	absolute temperature	[K]
TI	turbulence intensity	
T_{10min}	measured absolute air temperature averaged over 10 min	[K]
t	mast solidity	
t	time	[s]
U	wind speed	[m/s]
U_d	centre-line 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]
$\vec{U}$	wind speed vector	
u	longitudinal wind speed component	[m/s]
u	uncertainty component of category B	
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	
$u_{m,i}$	category B standard uncertainty of air density correction in bin i	[kg/m³]
$u_{P,i}$	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]
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]
w	vertical wind speed component	[m/s]
w_i	weighing function to define deviation envelope	
X_k	parameter averaged over pre-processing time period	
X_{10min}	parameter averaged over 10 min	
x	distance downstream obstacle to met mast or wind turbine	[m]
z	height above ground	[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]
$\varepsilon_{max,i}$	maximum deviation for any wind speed bin i in the wind speed range	[m/s]
κ	von Karman constant 0,4	
λ	speed ratio	
ρ	correlation coefficient	
ρ	air density	
ρ_0	reference air density	[kg/m³]
ρ_{10min}	derived air density averaged over 10 min	[kg/m³]

$\sigma_{P,i}$	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 1)	
ω	angular speed	[s^{-1}]

5 Preparation for performance test

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 9.

5.1 Wind turbine and electrical connection

As detailed in Clause 6, the wind turbine and electrical connection shall be described and documented to identify uniquely the specific machine configuration that is tested.

5.2 Test site

At the test site a meteorological mast shall be set up in the neighbourhood of the wind turbine to determine the wind speed that drives the wind turbine. The test site may have significant influence on the measured power performance of the wind turbine. In particular, flow distortion effects may cause the wind speed at the meteorological mast and at the wind turbine to be different, though correlated.

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

– choose the position of the meteorological mast;
– define a suitable measurement sector;
– estimate appropriate flow correction factors;
– evaluate the uncertainty due to wind flow distortion.

The following factors shall be considered, in particular:

– topographical variations;
– other wind turbines;
– obstacles (buildings, trees, etc.).

The test site shall be documented as detailed in Clause 9.

5.2.1 Location of the meteorological mast

Care shall be taken in locating the meteorological mast. It 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 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 defined as L+0,5D, where L is the distance between the centre of the turbine tower and the mast.

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

In most cases, the best location for the meteorological mast will be upwind of the 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 alongside the turbine, for example for a wind turbine that is sited on a ridge.

5.2.2 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.

For all neighbouring wind turbines and 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 being in the wake of the wind turbine under test are shown in Figure 1 for distances of 2, 2,5 and 4 times the rotor diameter of the wind turbine. Reasons to reduce the sector 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.

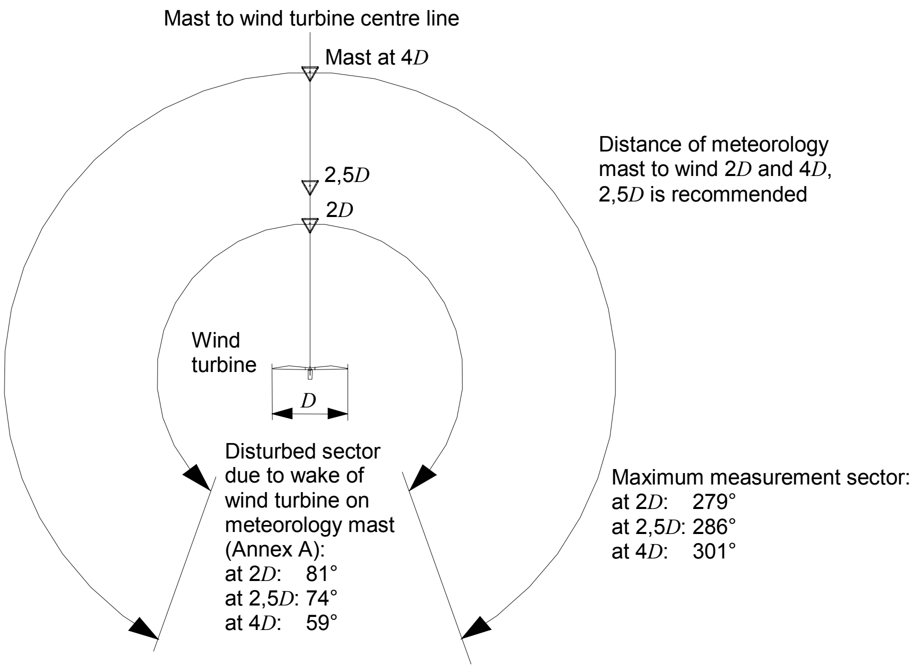

Figure 1 – Requirements as to distance of the meteorological mast and maximum allowed measurement sectors

5.2.3 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 shall identify whether the power curve can be 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 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 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 3 to 4 times the rotor diameter, 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 test site calibration shall be undertaken. If an experimental test site calibration is undertaken Annex C shall be used. The measured flow correction factors for each sector shall be used.

6 Test equipment

6.1 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 and the class of the voltage transformers, if used, shall meet the requirements of IEC 60186. They shall be 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, the full-scale range of the power measurement device should be set to –50 % to +200 % of the wind turbine rated power. 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 turbine side or the network side of the transformer.

6.2 Wind speed

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[3], including only the 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.

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[3] 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.

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.

6.3 Wind direction

Wind direction should be measured with a wind vane. 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.

6.4 Air density

Air density shall be derived from the measurement of air temperature and air pressure using equation (1). 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).

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 centre.

The air pressure sensor should be mounted on the meteorological mast close to hub height to represent the air pressure at the wind turbine rotor centre. If the air pressure sensor is not mounted close to the hub height, air pressure measurements shall be corrected to the hub height according to ISO 2533.

6.5 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 9.

6.6 Blade condition

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

6.7 Wind turbine control system

Sufficient status signals shall be identified, verified and monitored to allow the rejection criteria of 7.4 to be applied. Obtaining these parameters from the turbine controller's data system, if available, is adequate[4]. The definition of each status signal shall be reported.

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

6.8 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.

The calibration and accuracy of the data system chain (transmission, signal conditioning and data recording) shall be verified by injecting known signals 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.

7 Measurement procedure

7.1 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 9, 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 measurement uncertainty, as described in Annex D. During the measurement period, data should be periodically checked 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.

7.2 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 not be changed. The operational status of the wind turbine shall be reported by the status signals as described in Clause 6. Normal maintenance of the 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.

7.3 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or higher. Air temperature, air pressure, wind turbine status and 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:

– mean value;
– standard deviation;
– maximum value;
– 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 7.6 are satisfied.

7.4 Data rejection

To ensure that only data obtained during normal operation of the 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:

- external conditions other than wind speed are out of the operating range of the wind turbine;
- turbine cannot operate because of a turbine fault condition;
- turbine is manually shut down or in a test or maintenance operating mode;
- failure or degradation (e.g. due to icing) of test equipment;
- wind direction outside the measurement sector(s) as defined in 5.2.2;
- wind directions outside valid (complete) site calibration sectors.

Any other rejection criteria shall be clearly reported.

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. The effect on the power curve of a large hysteresis loop in the cut-out control algorithm may be considerable. 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 shall exclude all data sets where the turbine has stopped generating power due to cut-out at high wind speed (database B)[5].

Subsets of the database collected under special operational conditions (e.g. high blade roughness due to dust, salt, insects, ice) 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.

7.5 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).

7.6 Database

After data normalization (see 8.1) the selected data sets shall be sorted using the “method of bins” procedure (see 8.2). 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 1m/s below cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated" (see 8.3). 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:

- each bin includes a minimum of 30 min of sampled data;
- the database includes a minimum of 180 h of sampled data;

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5 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.

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 9.

8 Derived results

8.1 Data normalization

The selected data sets shall be normalized to two reference air densities. One shall be the sea level air density, referring to ISO standard atmosphere (1,225 kg/m^3). The other shall be the average of the measured air density data at the test site during periods of valid data collection, rounded to the nearest 0,05 kg/m^3. 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:

$$\rho_{10\,\mathrm{min}} = \frac{B_{10\,\mathrm{min}}}{\mathrm{R}_0 \cdot T_{10\,\mathrm{min}}} \qquad (1)$$

where

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

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

$B_{10\mathrm{min}}$ 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 normalization shall be applied to the measured power output according to the equation:

$$P_\mathrm{n} = P_{10\mathrm{min}} \cdot \frac{\rho_0}{\rho_{10\mathrm{min}}} \qquad (2)$$

where

P_n is the normalized power output;

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

ρ_0 is the reference air density.

For a wind turbine with active power control, the normalization shall be applied to the wind speed according to the equation:

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

where

V_n is the normalized wind speed;

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

8.2 Determination of the measured power curve

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

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j} \quad (4)$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{n,i,j} \quad (5)$$

where

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

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

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

$P_{n,i,j}$ 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 9. 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.

8.3 Annual energy production (*AEP*)

Generic *AEP* is estimated by applying the measured power curve to different reference wind speed frequency distributions. 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, 5, 6, 7, 8, 9, 10 and 11 m/s according to the equation:

$$AEP = N_h \sum_{i=1}^{N} \left[F(V_i) - F(V_{i-1}) \right] \left(\frac{P_{i-1} + P_i}{2} \right) \quad (6)$$

where

AEP is the annual energy production;

N_h is the number of hours in one year ≈ 8760;

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.

and
$$F(V) = 1 - \exp\left(-\frac{\pi}{4}\left(\frac{V}{V_{\mathrm{ave}}}\right)^2\right) \tag{7}$$

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, 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.

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.

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 9. 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 wind speeds.

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.

8.4 Power coefficient

The power coefficient, C_{P}, of the wind turbine shall be added to the test results and presented as detailed in Clause 9. C_{P} shall be determined from the measured power curve according to the following equation:

$$C_{\mathrm{P},i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \tag{8}$$

where

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

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

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.

9 Reporting format

The test report shall contain the following information:

a) An identification and description of the specific wind turbine configuration under test (see 5.1), including:
   1) 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 5.2), 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, 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.

c) A description of the test equipment (see Clause 6):
   1) identification of the sensors and data acquisition system, including documentation of calibrations for the sensors, 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;
   3) sketch of the arrangement of the meteorological mast showing principle dimensions of the tower and instrument mounting fixtures;
   4) description of method how to maintain the anemometer calibration 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 5.1 and Clause 7):
   1) documentation of the procedural steps, test conditions, sampling rate, averaging time, measurement period;
   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 and 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.

e) Presentation of measured data (see 7.3 to 7.6):

   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:
   - scatter plots of mean, standard deviation, maximum, and minimum power output as a function of wind speed (plots must include information on sample frequency). An example is shown in Figure 2;
   - scatter plots of mean wind speed and turbulence intensity as a function of wind direction;
   - 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;
   - special databases consisting of data collected under special operational or atmospheric conditions should also be presented as described above;
   - 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;
   - definition of status signals, and plots of status signals during the measurement period.

f) Presentation of measured power curve for air density at sea level (see 8.1 and 8.2):
   1) the power curve shall be presented in a table similar to Table 1. 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 Annexes D and E);
      - standard uncertainties of category B (see Annexes D and E);
      - combined standard uncertainty (see Annexes D and E);
   2) the power curve shall be presented in a graph similar to Figure 3. The graph shall show 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 4;
   4) both the graph and the table shall state the sea level air density 1,225 kg/m^3, used for the normalization;
   5) in case 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 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.

h) Presentation of measured power curves collected under special operational and atmospheric conditions (see 7.5):

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.

i) Presentation of estimated annual energy production for air density at sea level (see 8.3):

1) a table that for each annual average hub height wind speed shall include:
   – *AEP*-measured;
   – standard uncertainty of *AEP*-measured (see Annexes D and 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.

k) Presentation of measured power coefficient (see 8.4):

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.

l) Presentation of results of site calibration (see Annex C):

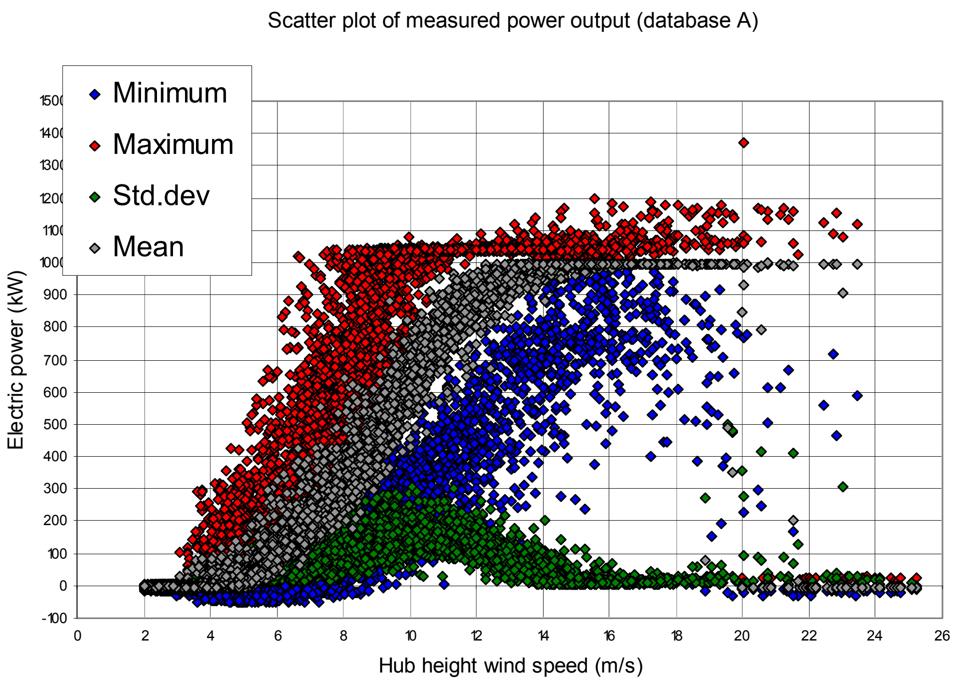
1) if a site calibration is undertaken, it shall be presented in the report as a table and a graph;
2) the table shall for each wind direction bin present:
   – minimum and maximum wind direction limits;
   – the bin-averaged wind direction;
   – the bin-averaged ratio of wind speeds;
   – number of hours of data;
   – combined standard uncertainty of the wind speed ratio for 6, 10 and 14 m/s;
3) the graph (see Figure 5) shall present:
   – the bin-averaged ratio of wind speeds with standard deviation $S_{\alpha,j}$ versus wind direction.

m) Uncertainty of measurement (see Annex D):

uncertainty assumptions on all uncertainty components shall be provided.

n) Deviations from the procedure:

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.



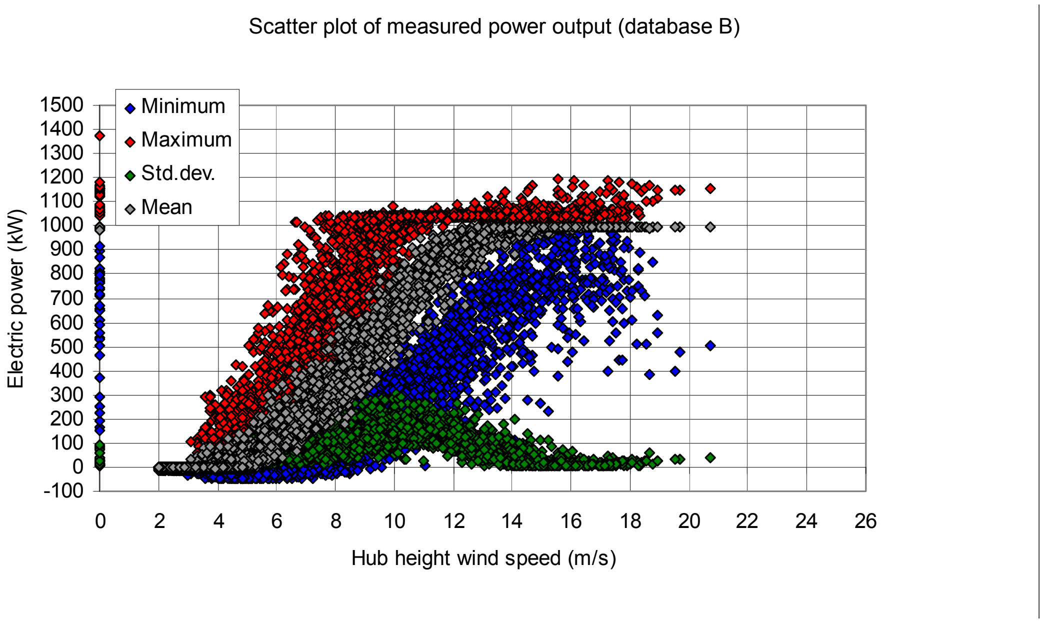
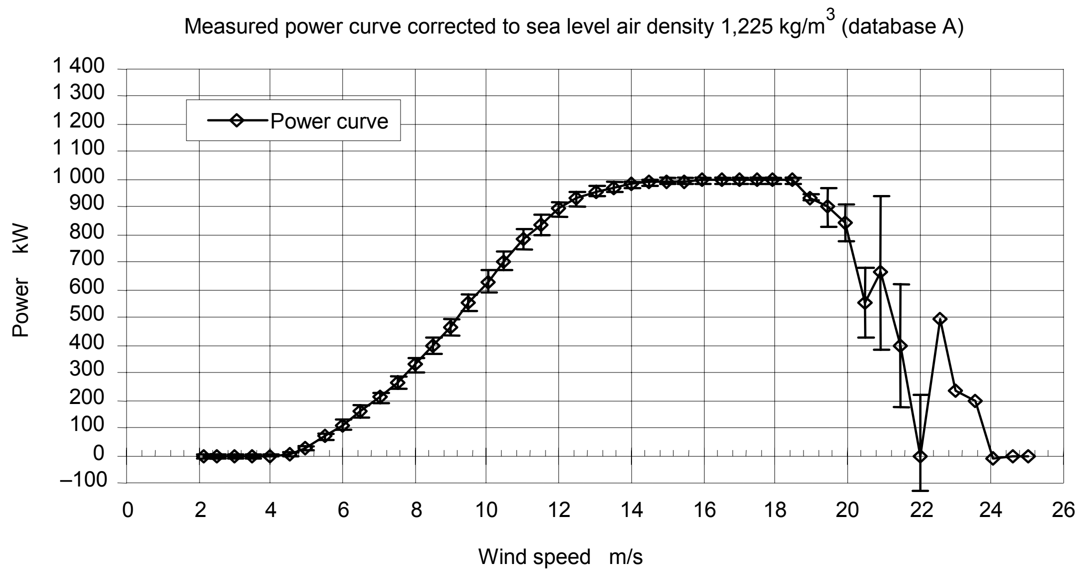


Figure 2 – Presentation of example database A and B: power performance test scatter plots sampled at 1 Hz (mean values averaged over 10 min)



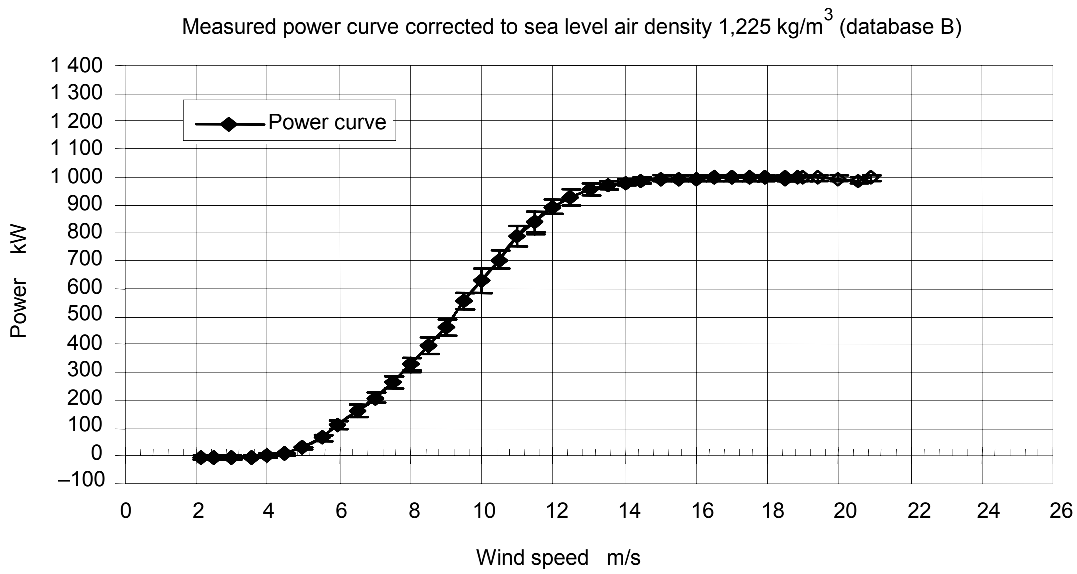
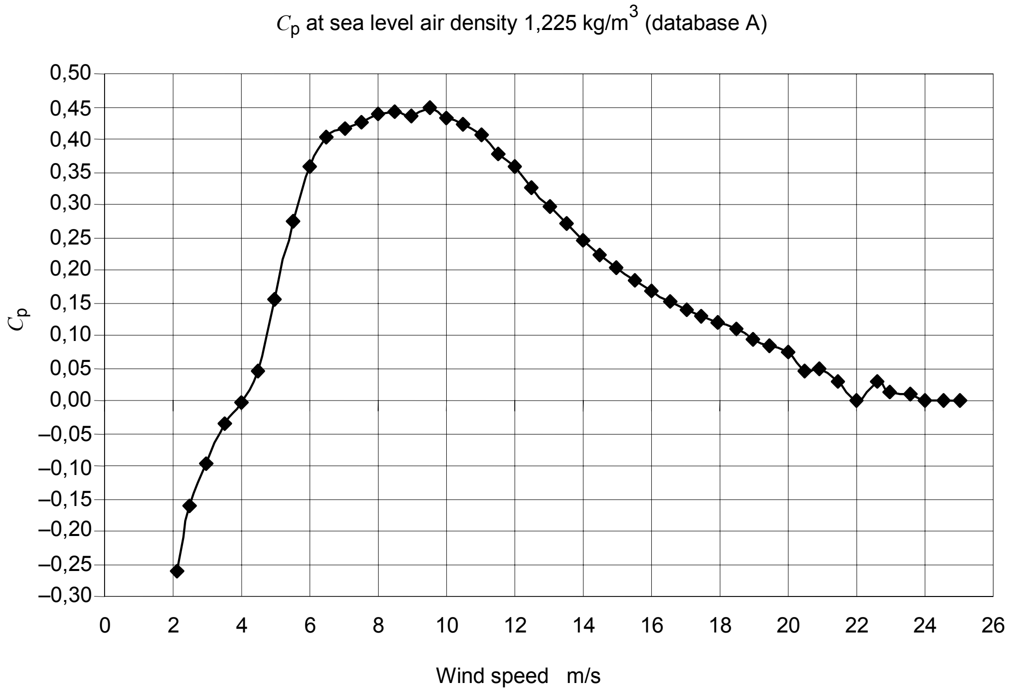


Figure 3 – Presentation of example measured power curve for databases A and B



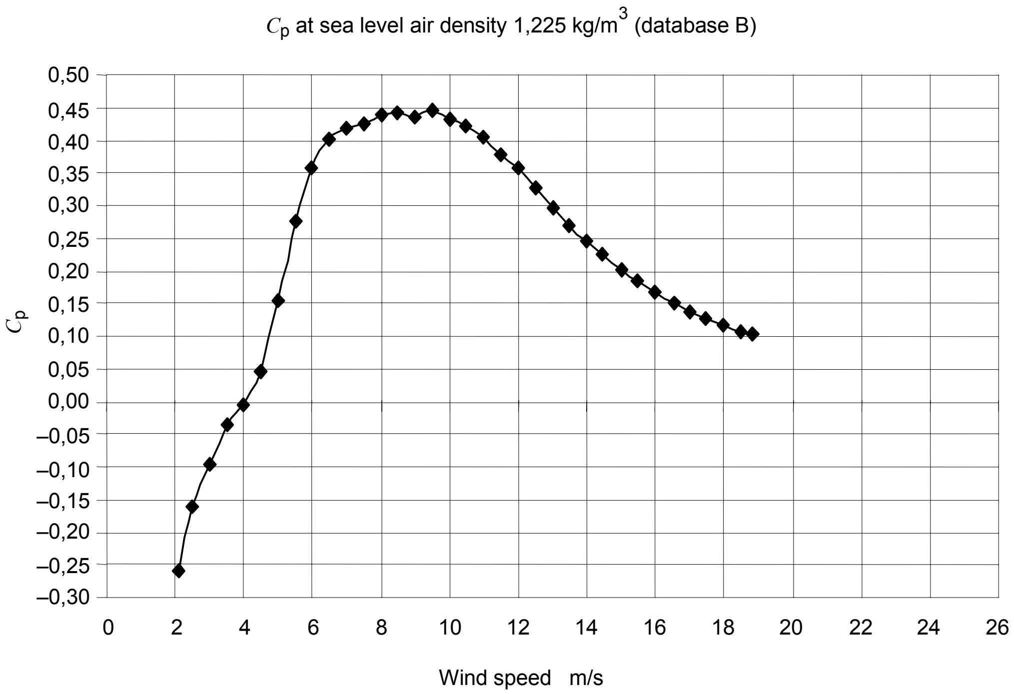


Figure 4 – Presentation of example C_p curve for databases A and B

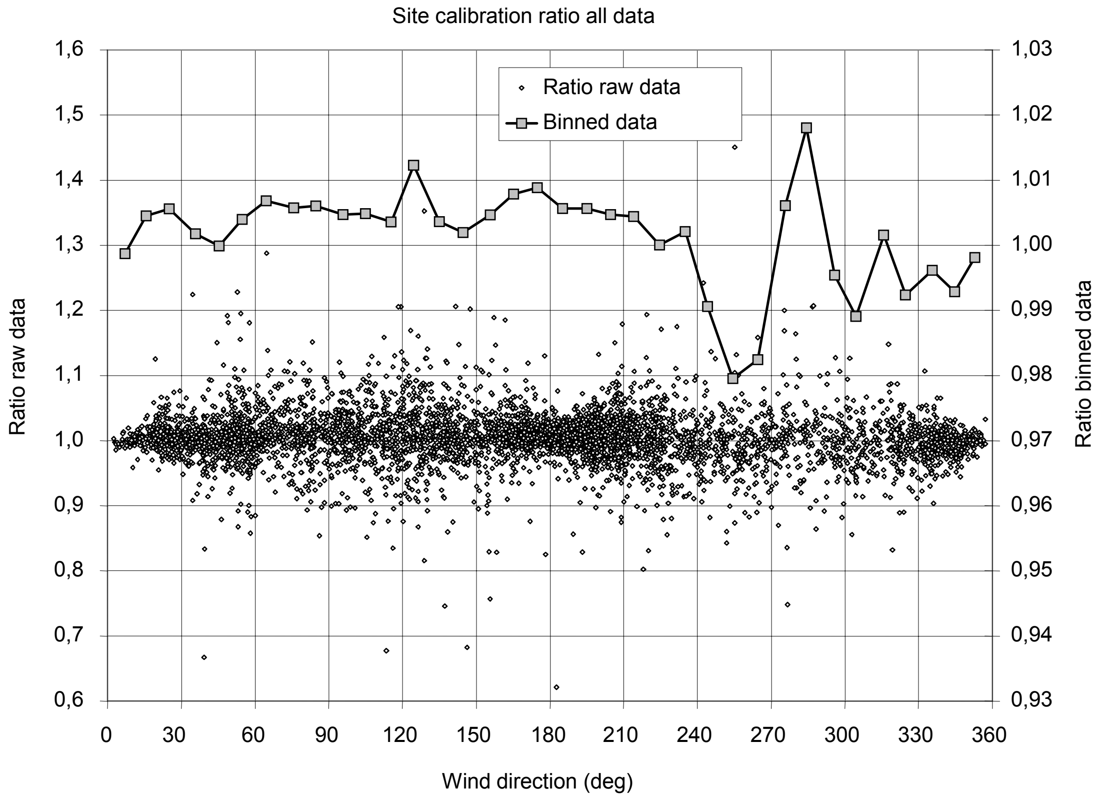


Figure 5 – Presentation of example site calibration (only the sectors 20° to 30°, 40° to 60°, 160° to 210° and 330° to 350° are valid sectors)

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 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	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

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 [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
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

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

Estimated annual energy production (database A) Reference air density: 1,225 kg/m³ 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	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/m³ 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	481	99	21	495	
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

Annex A
(normative)

Assessment of obstacles at the test site

NOTE The 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.

A.1 Requirements regarding neighbouring and operating wind turbines

The wind turbine under test and the meteorological mast shall not be influenced by neighbouring wind turbines. If a neighbouring turbine is operated at any time during the power performance test, its wake shall be determined and accounted for as described in this annex. If the 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.2.

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

A.2 Requirements regarding obstacles

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. Only small buildings, connected to the wind turbine operation or the measurement equipment, are acceptable.

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.

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

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

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

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

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

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. The equivalent rotor diameter of the obstacle shall be defined as:

$$D_e = \frac{2 l_h l_w}{l_h + l_w} \tag{A.4}$$

where

D_e is the equivalent rotor diameter;

l_h is the height of obstacle;

l_w is the width of obstacle.

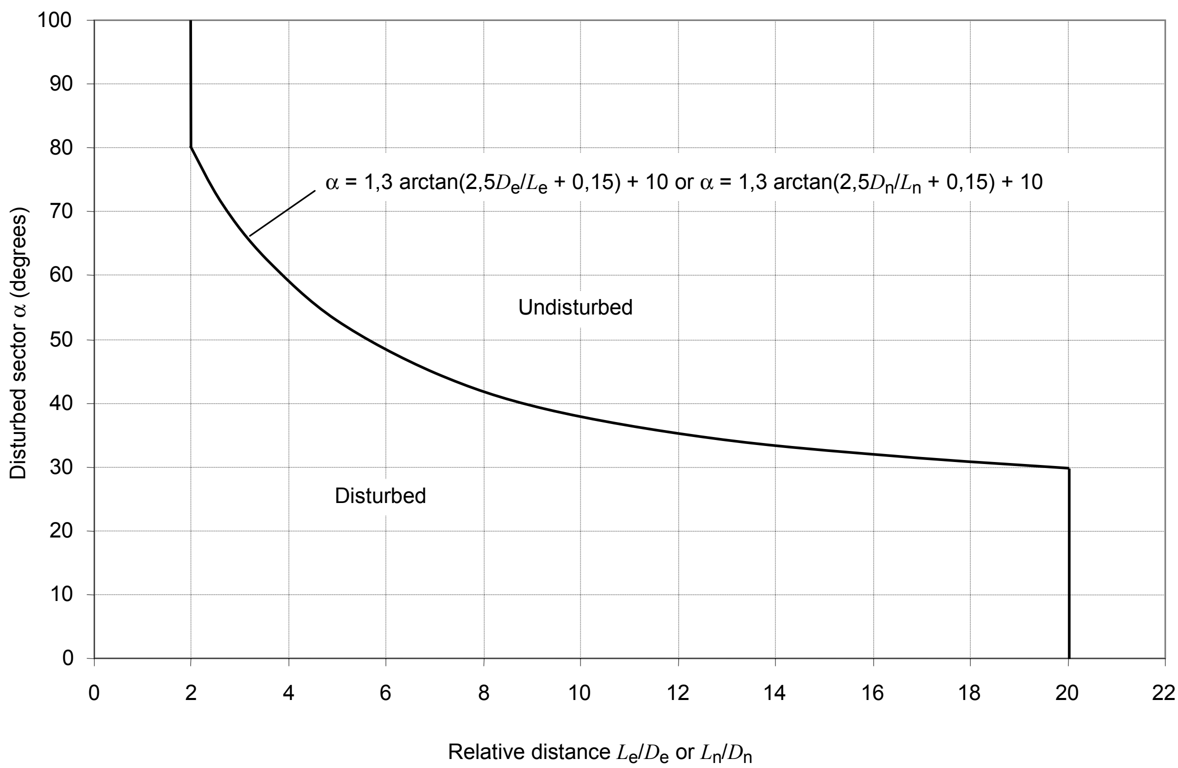


Figure A.1 – Sectors to exclude due to wakes of neighbouring and operating wind turbines and significant obstacles

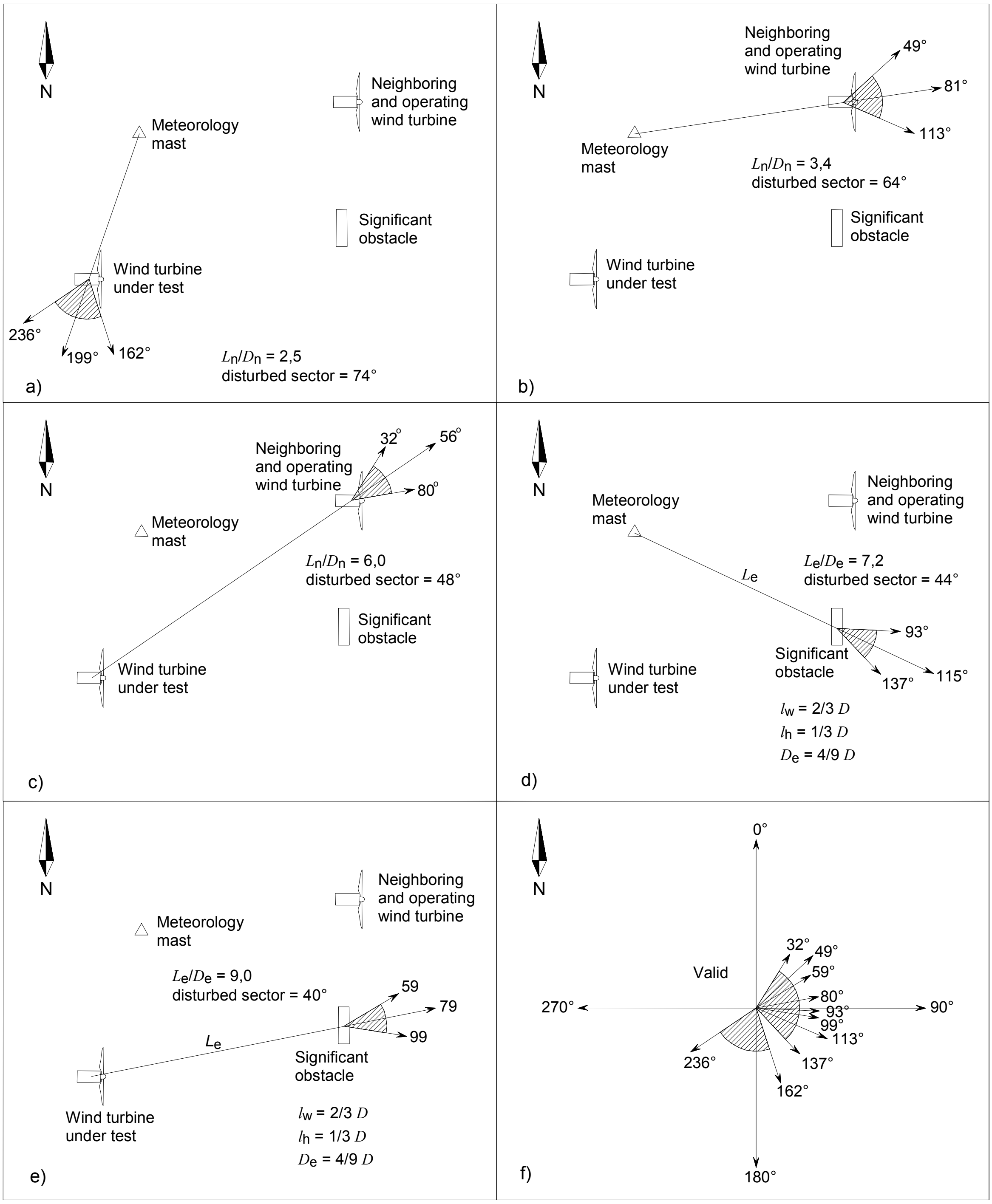


Figure A.2 – An example of sectors to exclude due to wakes of the wind turbine under test, a neighbouring and operating wind turbine and a significant obstacle

The figures show the sectors to exclude when:

a) the meteorological mast is in the wake of the wind turbine under test;

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

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

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

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

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

Annex B
(normative)

Assessment of terrain at the test site

For testing without a site calibration, 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.

If the terrain complies with the requirements of Table B.1, then no site calibration 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 10m/s for the measurement sectors, then no site calibration measurement is required.

Otherwise a site calibration measurement is required.

Table B.1 – Test site requirements: topographical variations

Distance	Sector	Maximum slope %	Maximum terrain variation from plane
<2 *L*	360°	<3*	<0,04 *(H+D)*
≥2 *L* and < 4 *L*	Measurement sector	<5*	<0,08 *(H+D)*
≥2 *L* and <4 *L*	Outside measurement sector	<10**	Not applicable
≥4 *L* and <8 *L*	Measurement sector	<10*	<0,13*(H+D)*

* The maximum slope of the plane, which provides the best fit to the sectoral terrain and passes through the tower base.

** The line of steepest slope that connects the tower base to individual terrain points within the sector.

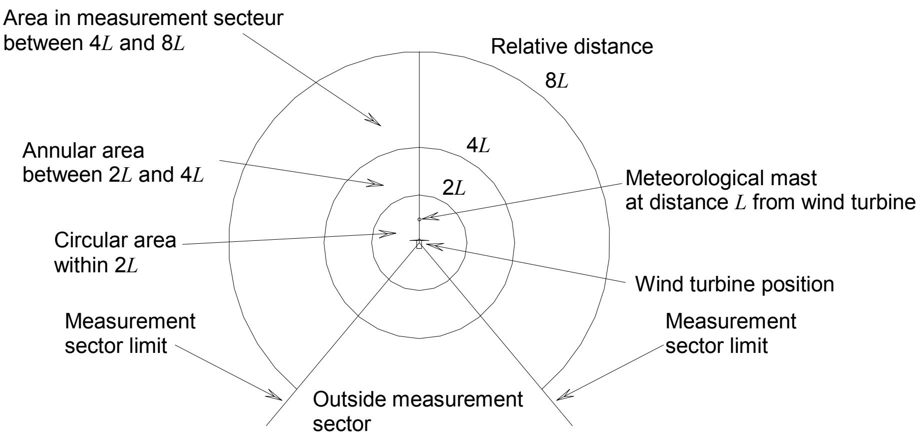


Figure B.1 – Illustration of area to be assessed, top view

Annex C
(normative)

Site calibration procedure

C.1 General

A site calibration quantifies and potentially reduces the effects of terrain and obstacle effects 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 centre of the turbine rotor.

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.

C.2 Test set-up

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.

C.3 Data acquisition and analysis

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.

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

1) failure or degradation (e.g. due to icing) of test equipment;
2) wind direction outside the measurement sector(s) as defined in 5.2.2;
3) mean wind speed less than 4 m/s or greater than 16 m/s
4) any other special atmospheric conditions that will also be used as rejection criteria during the power performance test.

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[6].

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.

C.4 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.

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 sector be eliminated when flow correction factors change by more than 0,02.

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.6 Report requirements

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

C.7 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.

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

Annex D
(normative)

Evaluation of uncertainty in measurement

This annex 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 information publication "Guide to the expression of uncertainty in measurement".

Following the ISO Guide, there are two types 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 8.1 and 8.2), and the estimated annual energy production (see clause 8.3). 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)	B
	Variability of electric power	A
Wind speed	Anemometer calibration	B
	Operational characteristics	B
	Mounting effects	B
	Data acquisition system (see note)	B
	Flow distortion due to terrain	B
Air temperature	Temperature sensor	B
	Radiation shielding	B
	Mounting effects	B
	Data acquisition system (see note)	B
Air pressure	Pressure sensor	B
	Mounting effects	B
	Data acquisition system (see note)	B
Data acquisition system	Signal transmission	B
	System accuracy	B
	Signal conditioning	B

NOTE The implicit assumption of the 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 shear of mean wind speed over the rotor. Presently, analytical tools offer little help in identification of the impact 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 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.

Annex E
(informative)

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

E.1 General

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

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

where

$c_{k,i}$ is the 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

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

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 ≈ 8760.

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:

– uncertainty components are either fully correlated ($\rho = 1$, implying linear summation to obtain the combined standard uncertainty) or independent ($\rho = 0$, implying quadratic summation, i.e. the combined standard uncertainty is the square root of summed squares of the uncertainty components);

– 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).

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

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

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 are the combined category A uncertainties in bin i;

u_i are 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:

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

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.

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:

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + N_h^2 \left(\sum_{i=1}^{N} f_i \sqrt{\sum_{k=1}^{M_B} c_{k,i}^2 u_{k,i}^2} \right)^2 = N_h^2 \sum_{i=1}^{N} f_i^2 \, s_i^2 + N_h^2 \left(\sum_{i=1}^{N} f_i \, u_i\right)^2 \qquad \text{(E.5)}$$

The u_{AEP}, obtained by this expression is always equal to or larger than that obtained using equation (E.4).

E.2 Expanded uncertainty

The combined standard uncertainties of the power curve and the *AEP* may additionally be expressed by expanded uncertainties. Referring to the ISO guide 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

E.3 Example

The following example 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 AEP is estimated.

The example 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:

$$u_{\mathrm{V},i}^2 = u_{\mathrm{V1},i}^2 + u_{\mathrm{V2},i}^2 + \ldots \tag{E.6}$$

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:

$$u_{\mathrm{c},i}^2 = s_{\mathrm{P},i}^2 + u_{\mathrm{P},i}^2 + c_{\mathrm{V},i}^2 u_{\mathrm{V},i}^2 + c_{\mathrm{T},i}^2 u_{\mathrm{T},i}^2 + c_{\mathrm{B},i}^2 u_{\mathrm{B},i}^2 \tag{E.7}$$

$$u_{\mathrm{AEP}}^2 = N_{\mathrm{h}}^2 \left(\sum_{i=1}^{N} f_i^2 s_{\mathrm{P},i}^2 + s_{\mathrm{w}}^2 + \left(\sum_{i=1}^{N} f_i \sqrt{u_{\mathrm{P},i}^2 + c_{\mathrm{V},i}^2 u_{\mathrm{V},i}^2 + c_{\mathrm{T},i}^2 u_{\mathrm{T},i}^2 + c_{\mathrm{B},i}^2 u_{\mathrm{B},i}^2 + c_{\mathrm{m},i}^2 u_{\mathrm{m},i}^2} \right)^2 \right) \tag{E.8}$$

where 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 Figures 2 and 3 and Table 1, is used in the example. 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 3 and Tables 1 and 2. All sensitivity factors are listed in Tables E.4 and E.5, and category B uncertainties are listed in Tables E.6 and E.7.

E.4 Category A uncertainties

The only category A uncertainty that needs to be considered is the uncertainty of the measured and normalized electric power data in each bin.

E.4.1 Category A uncertainty in electric power

The standard deviation of the distribution of normalized power data in each bin is calculated by the equation:

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1} \sum_{j=1}^{N_i} \left(P_i - P_{n,i,j}\right)^2} \tag{E.9}$$

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.

Table E.2 – List of categories B and A uncertainties

Category B: Instruments	Note	Standard	Uncertainty	Sensitivity
Power output			$u_{P,i}$	$c_{P,i} = 1$
Current transformers *	a	IEC 60044-1	$u_{P1,i}$	
Voltage transformers *	a	IEC 60044-2	$u_{P2,i}$	
Power transducer or *	a	IEC 60688	$u_{P3,i}$	
Power measurement device *	c		$u_{P4,i}$	
Wind speed			$u_{V,i}$	
Anemometer *	b		$u_{V1,i}$	$c_{V,i} \approx \left\| \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right\|$
Operational characteristics *	cd		$u_{V2,i}$	
Mounting effects *	c		$u_{V3,i}$	
Air density				
<u>Temperature</u>			$u_{T,i}$	$c_{T,i} \approx \frac{P_i}{288{,}15\,\mathrm{K}}$
Temperature sensor *	a		$u_{T1,i}$	
Radiation shielding *	cd		$u_{T2,i}$	$c_{B,i} \approx \frac{P_i}{1013\,\mathrm{hPa}}$
Mounting effects *			$u_{T3,i}$	
<u>Air pressure</u>		ISO 2533	$u_{B,i}$	
Pressure sensor *	a		$u_{B1,i}$	
Mounting effects *	c		$u_{B2,i}$	
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 *			$u_{d3,i}$	
Category B: Terrain				
Flow distortion due to terrain *	bc		$u_{V4,i}$	$c_{V,i}$ (see above)
Category B: Method				
Method			$u_{m,i}$	
Air density correction	cd		$u_{m1,i}$	$c_{T,i}$ and $c_{B,i}$
Category A: Statistical				
Electric power *	e		$s_{P,i}$	$c_{P,i} = 1$
Climatic variations	e		s_W	---
* parameter required for the uncertainty analysis				

NOTE Identification of uncertainties:
a = reference to standard;
b = calibration;
c = other "objective" method;
d = "guestimate";
e = statistics.

The standard uncertainty of the normalized and averaged power in the bin is estimated by the equation:

$$s_i = s_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \tag{E.10}$$

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.4.2 Category A uncertainties in climatic variations

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.

E.5 Category B uncertainties

The category B uncertainties are assumed to be related to the instruments, the data acquisition system, and the terrain surrounding the power performance test site. If the uncertainties are expressed as uncertainty limits, or have implicit, non-unity coverage factors, the standard uncertainty must be estimated or they must be properly converted into standard uncertainties.

NOTE Consider an uncertainty expressed as an uncertainty limit $\pm U$. 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.5.1 Category B uncertainties in the data acquisition system

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, $u_{d,i}$, can be expressed as:

$$u_{d,i} = \sqrt{u_{d1,i}^2 + u_{d2,i}^2 + u_{d3,i}^2} \tag{E.13}$$

where

$u_{d1,i}$ is the uncertainty in signal transmission and signal conditioning in bin i;

$u_{d2,i}$ is the uncertainty in digitization in bin i, for example from quantization resolution;

$u_{d3,i}$ is the uncertainty in other parts of the integrated data acquisition system (software, storage system) in bin i.

We assume in this example the data acquisition system to have a standard uncertainty $u_{d,i}$ of 0,1 % of full range of each measurement channel.

E.5.2 Category B uncertainties in electric power

The uncertainty of the power sensor has uncertainty contributions from current and voltage transformers and from the power transducer. Uncertainties of these subcomponents are normally stated by their classification.

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:

$$u_{P,i} = \sqrt{u_{P1,i}^2 + u_{P2,i}^2 + u_{P3,i}^2 + u_{dP,i}^2} \tag{E.14}$$

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.

In the example, the current and voltage transformers and the power transducer are all assumed to be of class 0,5.

The current transformers of class 0,5 (nominal loads of the current transformers are here designed to match the nominal power, 1 000 kW, and not 200 % of nominal power). They have uncertainty limits, referring to IEC 60044-1, 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 is assumed to be rectangular. 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:

$$u_{P1,i} = \frac{0{,}75\ \% \cdot P_i\ [\text{kW}]}{\sqrt{3}} \frac{1}{3} 3 = 0{,}43\ \% \cdot P_i\ [\text{kW}] \tag{E.15}$$

The voltage transformers of class 0,5, have uncertainty limits, referring to IEC 60044-2, of ±0,5 % of the voltage at all loads. The uncertainty distribution is assumed to be rectangular. 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:

$$u_{P\,2,i} = \frac{0{,}5\ \% \cdot P_i\ [\mathrm{kW}]}{\sqrt{3}}\ \frac{1}{3}3 = 0{,}29\ \% \cdot P_i\ [\mathrm{kW}] \qquad \text{(E.16)}$$

If current and voltage transformers are not operated within their secondary loop operational load limits, additional uncertainties shall be added.

The power transducer of class 0,5, referring to IEC 60688, with a nominal power of 2 000 kW (200 % of the nominal power, 1 000 kW, of the wind turbine) has an uncertainty limit of 10 kW. The uncertainty distribution is assumed to be rectangular. The uncertainty of the power transducer is thus:

$$u_{P\,3,i} = \frac{10\ \mathrm{kW}}{\sqrt{3}} = 5{,}8\ \mathrm{kW} \qquad \text{(E.17)}$$

Considering the electric power range of the measurement channel to be 2 500 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:

$$\begin{aligned} u_{P,i} &= \sqrt{(0{,}43\ \% \cdot P_i\ [\mathrm{kW}]\ )^2 + (0{,}29\ \% \cdot P_i\ [\mathrm{kW}]\ )^2 + (5{,}8\ \mathrm{kW}\ )^2 + (0{,}1\,\% \cdot 2\ 500\ \mathrm{kW}\ )^2} \\ &= \sqrt{(0{,}52\ \% \cdot P_i\ [\mathrm{kW}]\ )^2 + (6{,}3\ \mathrm{kW}\ )^2} \end{aligned} \qquad \text{(E.18)}$$

E.5.3 Category B uncertainties in wind speed

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:

$$u_{V,i} = \sqrt{u_{V\,1,i}^2 + u_{V\,2,i}^2 + u_{V\,3,i}^2 + u_{V\,4,i}^2 + u_{dV,i}^2} \qquad \text{(E.19)}$$

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:

$$c_{V,i} = \left| \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right| \tag{E.20}$$

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:

$$\begin{aligned} u_{V,i} &= \sqrt{\begin{aligned}&(0{,}1\,\text{m/s})^2 + (0{,}034\,\text{m/s} + 0{,}0034 \cdot V_i[\text{m/s}])^2 + \\ &(0{,}01 \cdot V_i[\text{m/s}])^2 + (0{,}03 \cdot V_i[\text{m/s}])^2 + (0{,}001 \cdot 30\,\text{m/s})^2\end{aligned}} \\ &= \sqrt{(0{,}104\,\text{m/s})^2 + (0{,}032 \cdot V_i[\text{m/s}])^2 + (0{,}034\,\text{m/s} + 0{,}0034 \cdot V_i[\text{m/s}])^2} \end{aligned} \tag{E.21}$$

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:

$$u_{\alpha,i,j} = \sqrt{2u_{V1,i}^2 / V_i^2 + 2u_{dV,i}^2 / V_i^2 + s_{\alpha,j}^2 / N_j} \tag{E.22}$$

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:

$$u_{V4,i,j} = \sqrt{2u_{V1,i}^2 + 2u_{dV,i}^2 + s_{\alpha,j}^2 V_i^2 / N_j} \quad \text{(E.23)}$$

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 $N_{i,\mathrm{j}}$ is number of power curve data sets for wind speed bin i and wind direction bin j.

E.5.4 Category B uncertainties in air density

The air density is derived from measurements of the air temperature and the air pressure.

The measurement of the air temperature might include the following uncertainty components:

- uncertainty of the temperature sensor calibration;
- 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 standard uncertainty in measured air temperature for each bin, $u_{T,i}$, can be expressed as:

$$u_{T,i} = \sqrt{u_{T1,i}^2 + u_{T2,i}^2 + u_{T3,i}^2 + u_{dT,i}^2} \quad \text{(E.26)}$$

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

$$c_{T,i} \approx \frac{P_i}{288{,}15} \text{ [kW/K]} \quad \text{(E.27)}$$

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:

$$u_{B,i} = \sqrt{u_{B1,i}^2 + u_{B2,i}^2 + u_{dB,i}^2} \quad \text{(E.28)}$$

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

$$c_{B,\mathrm{i}} \approx \frac{P_\mathrm{i}}{1013}\,[\mathrm{kW/hPa}] \tag{E.29}$$

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:

$$u_{T,\mathrm{i}} = \sqrt{(0{,}5\,\mathrm{K})^2 + (2{,}0\,\mathrm{K})^2 + (0{,}3\,\mathrm{K})^2 + (0{,}1\,\% \cdot 40\,\mathrm{K})^2} = 2{,}1\,\mathrm{K} \tag{E.30}$$

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:

$$u_{\mathrm{B},i} = \sqrt{(3{,}0\ \mathrm{hPa})^2 + (0{,}34\ \mathrm{hPa})^2 + (0{,}1\,\% \cdot 100\ \mathrm{hPa})^2} = 3{,}0\ \mathrm{hPa} \tag{E.31}$$

E.5.5 Combined category B uncertainties

The category B uncertainties in each bin are combined as:

$$\begin{aligned} u_\mathrm{i} &= \sqrt{u_{P,\mathrm{i}}^2 + c_{V,\mathrm{i}}^2\,u_{V,\mathrm{i}}^2 + c_{T,\mathrm{i}}^2\,u_{T,\mathrm{i}}^2 + c_{B,\mathrm{i}}^2\,u_{B,\mathrm{i}}^2} \\ &= \sqrt{\begin{array}{l}(0{,}52\,\% \cdot P_\mathrm{i}\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{V,\mathrm{i}}^2\left((0{,}104\mathrm{m/s})^2 + (0{,}032 \cdot V_\mathrm{i}\,[\mathrm{m/s}])^2 + (0{,}034\,\mathrm{m/s} + 0{,}0034 \cdot V_\mathrm{i}\,[\mathrm{m/s}])^2\right) + \\ c_{T,i}^2((2{,}1\mathrm{K})^2 + c_{B,i}^2(3{,}0\mathrm{hPa})^2)\end{array}} \end{aligned} \tag{E.32}$$

E.5.6 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.

$$u_{c,i} = \sqrt{s_i^2 + u_i^2} = \sqrt{s_{P,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2}$$

$$= \sqrt{\begin{matrix} s_{P,i}^2 + (0{,}52\,\% \cdot P_i\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{V,i}^2\left((0{,}104\,\mathrm{m/s})^2 + (0{,}032 \cdot V_i\,[\mathrm{m/s}])^2 + (0{,}034\,\mathrm{m/s} + 0{,}0034 \cdot V_i\,[\mathrm{m/s}])^2\right) + \\ c_{T,i}^2((2{,}1\,\mathrm{K})^2 + c_{B,i}^2(3{,}0\,\mathrm{hPa})^2) \end{matrix}} \tag{E.33}$$

E.5.7 Combined standard uncertainty – Energy production

The combined standard uncertainty of AEP is found by combining individually the category A and B uncertainties bin-wise:

$$u_{AEP} = N_h \sqrt{\sum_{i=1}^{N} f_i^2\, s_i^2 + \left(\sum_{i=1}^{N} f_i\, u_i\right)^2}$$

$$= N_h \sqrt{\sum_{i=1}^{N} f_i^2\, s_{P,i}^2 + \left(\sum_{i=1}^{N} f_i \sqrt{\begin{matrix} (0{,}52\,\% \cdot P_i\,[\mathrm{kW}])^2 + (6{,}3\,\mathrm{kW})^2 + \\ c_{V,i}^2((0{,}104\,\mathrm{m/s})^2 + (0{,}032 \cdot V_i\,[\mathrm{m/s}])^2) + \\ c_{V,i}^2((0{,}034\,\mathrm{m/s} + 0{,}0034 \cdot V_i\,[\mathrm{m/s}])^2) + \\ c_{T,i}^2((2{,}1\,\mathrm{K})^2 + c_{B,i}^2(3{,}0\,\mathrm{hPa})^2) \end{matrix}} \right)^2} \tag{E.34}$$

where

$f_i = ((F_{i+1} - F_i) + (F_i - F_{i-1}))/2$ is the average probability of wind speed in bin i

Table E.3 – Uncertainties from site calibration

Bin No. i	**Wind speed** V_i m/s	**Site calibration** 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

Table E.4 – Sensitivity factors (database A)

	Power curve (database A)		Sensitivity factors		
Bin No. i	Wind speed V_i m/s	Electric power P_i kW	Wind speed $c_{V,i}$ kW/ms	Air temperature $c_{T,i}$ kW/K	Air pressure $c_{B,i}$ 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
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. i	**Wind speed** V_i m/s	**Electric power** P_i kW	**Wind speed** $c_{V,i}$ kW/ms	**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

Table E.6 – Category B uncertainties (database A)

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/K	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	8,86	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

Table E.7 – Category B uncertainties (database B)

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/K	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

Annex F
(normative)

Cup anemometer calibration procedure

F.1 General requirements

The general requirements for anemometer calibration are summarised 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;
- flow quality measurement shall be carried out;
- the repeatability of the calibration shall be verified;
- anemometer calibration shall be supported by a thorough assessment of calibration uncertainty, carried out in accordance with ISO guidelines.

F.2 Requirements of 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 or boundary effects. The blockage ratio – defined as the ratio of the anemometer frontal area (including its mounting system) to the total test section area – shall not exceed 0,1 for open test section and 0,05 for closed test section.

The flow across the area covered by the anemometer 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.

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 shall be less than 0,2 %. The axial turbulence intensity at the anemometer’s position shall be below 2 %.

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.

The facility shall undergo a detailed examination of the repeatability of anemometer calibrations. The facility shall designate a reference anemometer 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 0,5 % at 10 m/s wind speed. This process shall be repeated after any modification or recalibration of the facility.

The facility shall prove, through round robin testing, that its results are comparable with other anemometer calibration facilities. 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, particularly if the ratio of tube diameter to rotor diameter is high.

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 instrument changes. To remove uncertainty caused by uncontrolled drift of the tunnel, it is suggested that this procedure is repeated several times.

The pitot tubes shall be positioned at the test section perpendicular to the flow field of the wind tunnel as accurate as possible. The maximum declination allowed is 1°.

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

The anemometer shall run in for about 5 min 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 1m/s or less. 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.

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 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. This will typically 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.

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].

$$P_w = 0{,}0000205 \exp(0{,}0631846 \cdot T) \quad \text{(F.2)}$$

where vapour pressure P_w depends on mean air temperature.

The mean flow speed at anemometer position is calculated from mean differential pressure Δp_{ref} at reference position using the equation:

$$\bar{v} = k_b \frac{1}{n} \sum_{i=1}^{n} \sqrt{\frac{2k_c}{C_h} \frac{\Delta p_{ref,i_i}}{\rho}} \quad \text{(F.3)}$$

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.

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 0,99995 then the calibration shall be repeated. 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.

F.6 Uncertainty analysis

It is important to identify the uncertainty with which the horizontal wind speed incident upon the anemometer is known. It is required that an uncertainty analysis is carried out in accordance with the ISO guide to the expression of uncertainty comprising both type A and type B uncertainty. The magnitude of the net uncertainty shall be assessed statistically and shall take account of:

- flow speed measurement uncertainty (pitot tubes, transducers, air density evaluation, etc.);
- frequency measurements;
- wind tunnel calibration including blockage effect;
- flow variability in the vicinity of the anemometer.

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) and on the individual anemometer calibration (anemometer calibration report).

The test report on the calibration campaign shall contain the following information as a minimum:

- description of the wind tunnel;
- sketch of the wind tunnel showing the exact positions of anemometer and pitot tube(s) in the test section;
- flow quality measurements;
- blockage correction factor;
- instrumentation certificates;
- measurement procedure;
- data evaluation procedure;
- repeatability documentation of the anemometer calibration;
- uncertainty analysis;
- deviations from these requirements.

The calibration report of an anemometer shall as a minimum contain the following information:

- make, type and serial number of the tested anemometer and cup serial number if transported separately;
- tube diameter of the mounting system;
- make, type and serial number of external converters, if taken (i.e. frequency-to-voltage converters);
- name and address of the customer;
- signatures from the persons who carried out the calibration, checked the results and approved their issue;
- name of the wind tunnel;
- environmental conditions during calibration (air temperature, air pressure and humidity);
- 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);
- tabular and graphical presentation (deviations from linear regression line amplified) of all calibration points and regression results;
- uncertainty associated to each measuring point;
- reference to the corresponding calibration campaign report, date of the calibration;
- photo showing the anemometer and the mounting in the wind tunnel;

F.8 Example uncertainty calculation

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 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, k_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	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 type 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 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 × 10/1,02 = 4,90 m/s	0,049

Error source, u_i	**Discussion**	**Value, u_i**	**Sensitivity value, c_i**	$U_i c_i$ m/s
$u_{p,t}$ pressure transducer sensitivity, $K_{p,t}$	Assume the pressure transducer is rated at 500 N/m^2. At 10 m/s wind speed, the pressure will be about 60 N/m^2. Assuming the 'limits' on error are quoted by the manufacturer to be 0,2 % of full scale (1 N/m^2), 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/m^2. Assuming also that the transducer sensitivity, $K_{p,t}$ is 5000 N/m^2 per V (100 mV max output), then the standard uncertainty at 60 N/m^2 $u_{p,t}$ equates to 33 N/m^2 per V	33	$c_{p,t}$ = 0,5 $v/K_{p,t}$ = 0,5 × 10/5000 = 0,001	0,033
$u_{p,s}$ pressure transducer signal conditioning gain, $K_{p,s}$	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	0,00002	$c_{p,s}$ = 0,5 $v/K_{p,s}$ = 0,5 × 10/0,01 = 500	0,010
$u_{p,d}$ pressure transducer data sampling conversion $K_{p,d}$	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	0,000704	$c_{p,d}$ =0,5 $v/K_{p,d}$ = 0,5 × 10/ 0,00244 = 2049	0,004
$u_{T,t}$ ambient temperature transducer, $K_{T,t}$	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	n/a	$c_{T,t}$ = 0,5 $v/K_{T,t}$ n/a	0,001
$u_{T,s}$ temperature signal conditioning gain, $K_{T,s}$	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 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	0,0008	$c_{T,t}$ = 0,5 $v/K_{T,s}$ = 0,5 × 10/2 = 2,5	0,002

Error source, u_i	Discussion	Value, u_i	Sensitivity value, c_i	$u_i c_i$ m/s
$u_{T,d}$ temperature signal digital conversion, $K_{T,d}$	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	0,0000023	$c_{T,d}$ = 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.	0,000997	C_h = –0,5 v/C_h = –0,5 × 10/0,997 = –5,015	0,005
$u_{B,t}$ sensitivity of barometer, $K_{B,t}$	The barometer can be treated in much the same way as the temperature probe, since it to will have a large physical offset.		$c_{B,t}$ = –0,5 $v/k_{B,t}$	
$u_{B,s}$ signal conditioning gain on barometer, $K_{B,s}$	Similar approach as for other signal processing parameters		$c_{B,s}$ = 0,5 $v/K_{B,s}$	
$u_{B,d}$ digital conversion of barometer signal, $K_{B,d}$	Similar approach as for other data acquisition channels		$c_{B,d}$ = 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_ρ, humidity correction to density, k_ρ 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 $$c_\varphi = \frac{\partial \bar{v}}{\partial k_\rho}.\frac{\partial k_\rho}{\partial \varphi} = \frac{1}{2}\frac{\bar{v}}{k_\rho}0{,}378\frac{P_w}{B}$$ At 15 °C, P_w = 1700 Pa and assuming B = 1013 mbar = 101 300 Pa, k_ρ is evaluated as 0,997 and c_φ (at 10 m/s) is 0,032	u_φ = 0,025	c_ρ = 0,032	0,001

The combined 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 m/s.

The example shows that type B error is liable to dominate. Extending the calibration period can help reduce the type A uncertainty, but will have no effect on type B. Furthermore, type 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. 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 along the 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.

G.2 Preferred method of top mounting of 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.

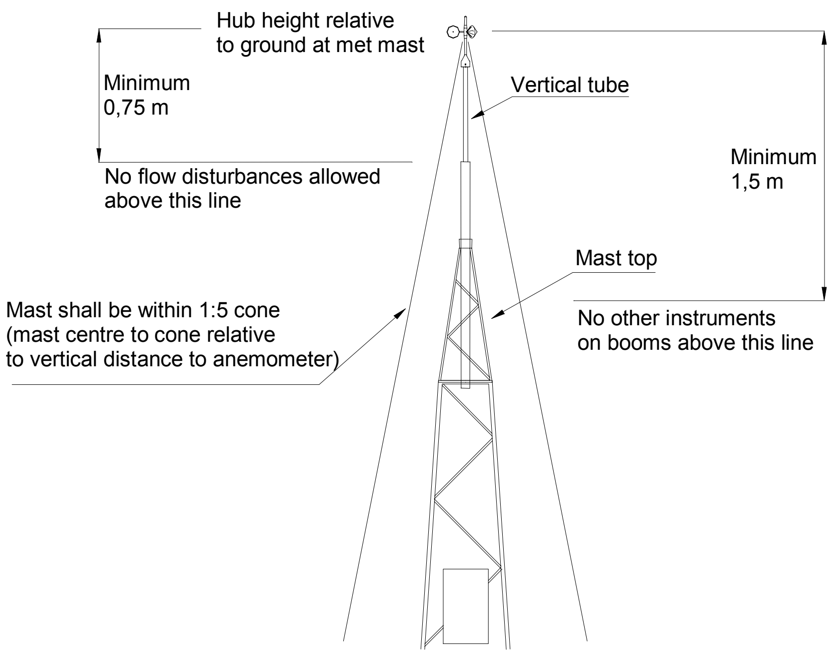


Figure G.1 – Example of a top-mounted anemometer and requirements for mounting

G.3 Alternative method of top mounting of anemometer

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.

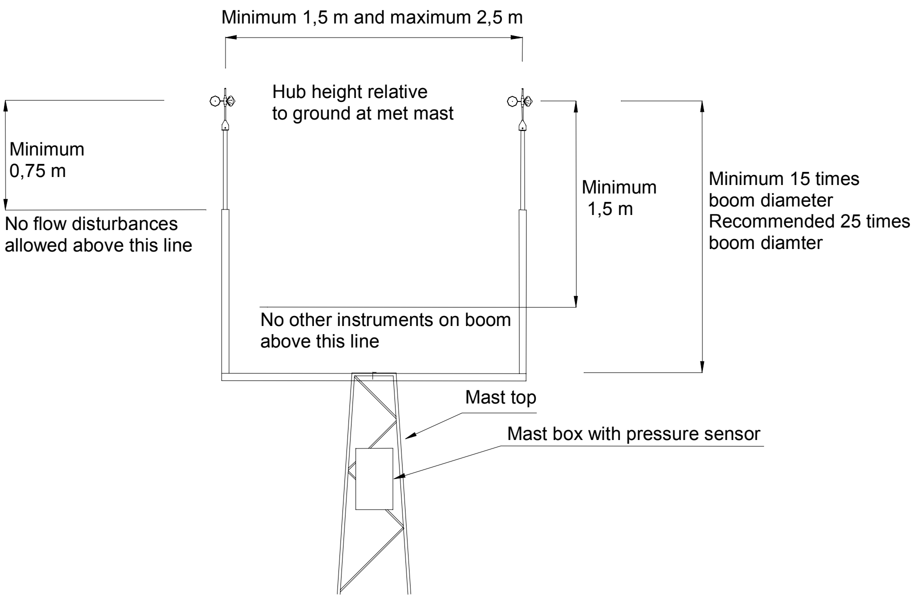


Figure G.2 – Example of alternative top-mounted primary and control anemometers positioned side-by-side and wind vane and other instruments on the boom

G.4 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 mast in such a way that it affords the top mounted anemometers with a 60º protection umbrella and in such a way that the anemometer never is in the wake of the finial when the wind is in the measurement sector;

– an adequately sized earth connection should be strapped to the tower base;

– the flow distortion on the anemometer shall be assessed, and an additional uncertainty shall be added.

G.5 Mounting of other meteorological instruments

If a control anemometer is used it should be located close to the primary anemometer 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 not interfere with the primary anemometer.

The wind vane shall be mounted at a minimum of 1,5 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.

Temperature and pressure sensors should be located close to the hub height on the meteorological mast at a minimum of 1,5 m below the primary anemometer. 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.

Examples of suitable arrangements for other boom-mounted instruments and top-mounted anemometers are shown in Figures G.3 and G.4.

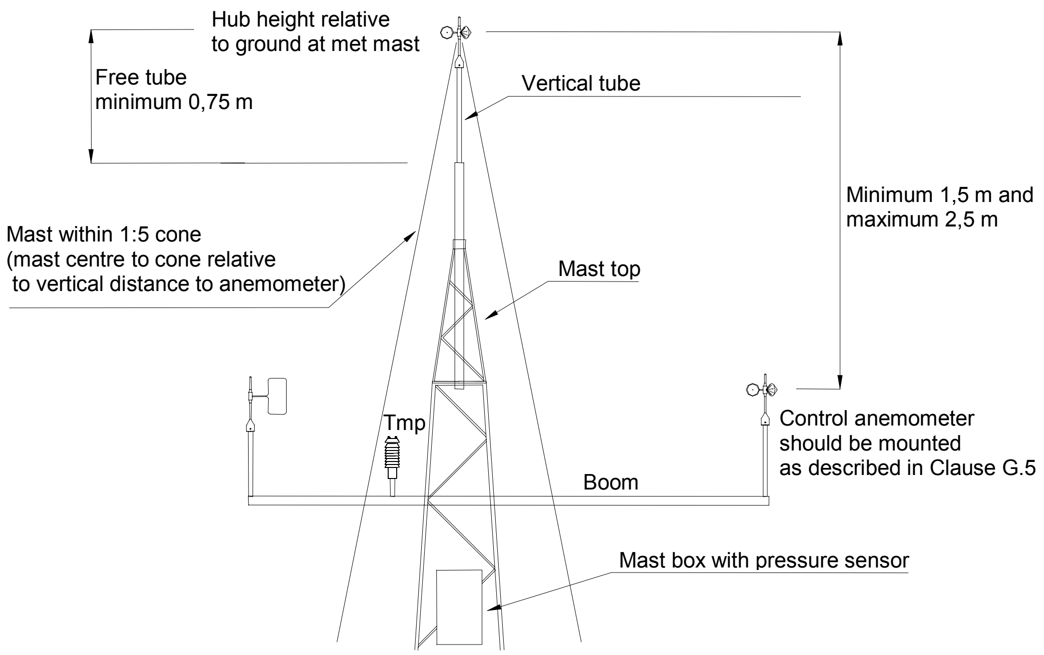


Figure G.3 – Example of a top-mounted anemometer and mounting of control anemometer, wind vane and other sensors on a boom

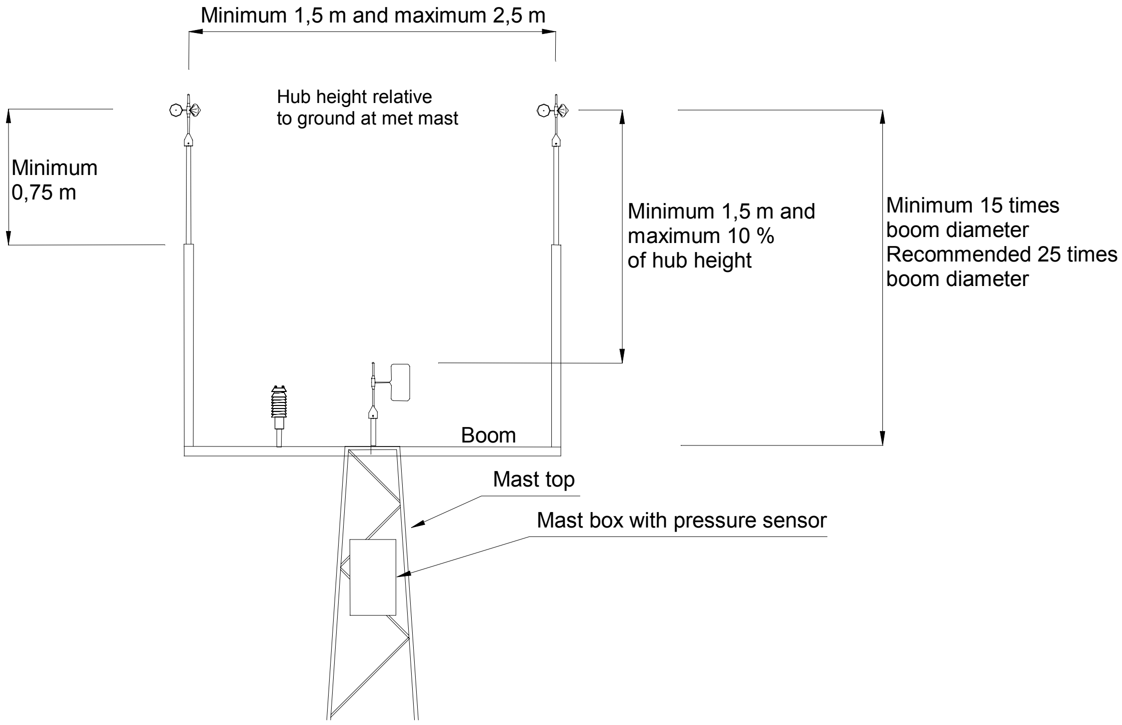


Figure G.4 – Example of top-mounted primary and control anemometers positioned side-by-side, wind vane and other instruments on the boom

G.6 Boom mounting of cup anemometers

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 %.

An anemometer operating in the wake of the meteorological mast is highly disturbed. Such measurements may not be used in power performance measurements. Flow distortion upstream of the mast can be significant. Adequate separation must be allowed between the cup anemometer and the mast to keep flow distortion effects to an acceptably low level. Guidance for appropriate anemometer – tower separation is given in G.6.1 and G.6.2.

Wakes from tower guys can have a strong influence on cup anemometers over surprisingly long distances. Location of cup anemometers in the vicinity of upstream 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 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 depends upon the type of mast and solidity.

G.6.1 Tubular meteorological masts

An approximation to the flow disturbance in the vicinity of a tubular mast can be obtained from Figure G.5. This figure shows an iso-speed plot of the flow around a tubular 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 mast, acceleration round it, and a wake behind it.

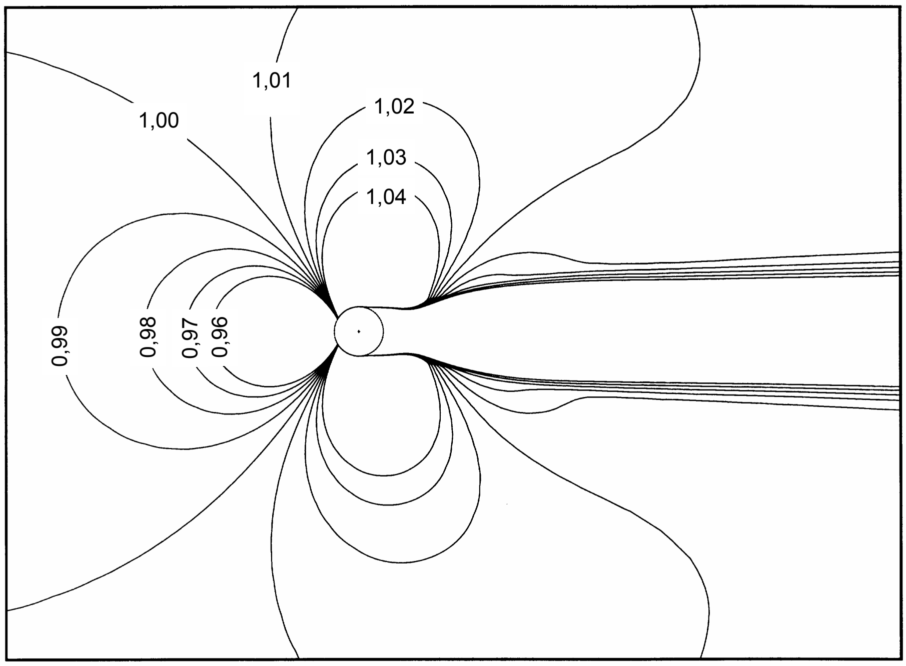


Figure G.5 – Iso-speed plot of local flow speed around a cylindrical mast, normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computations

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.6 shows this 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.

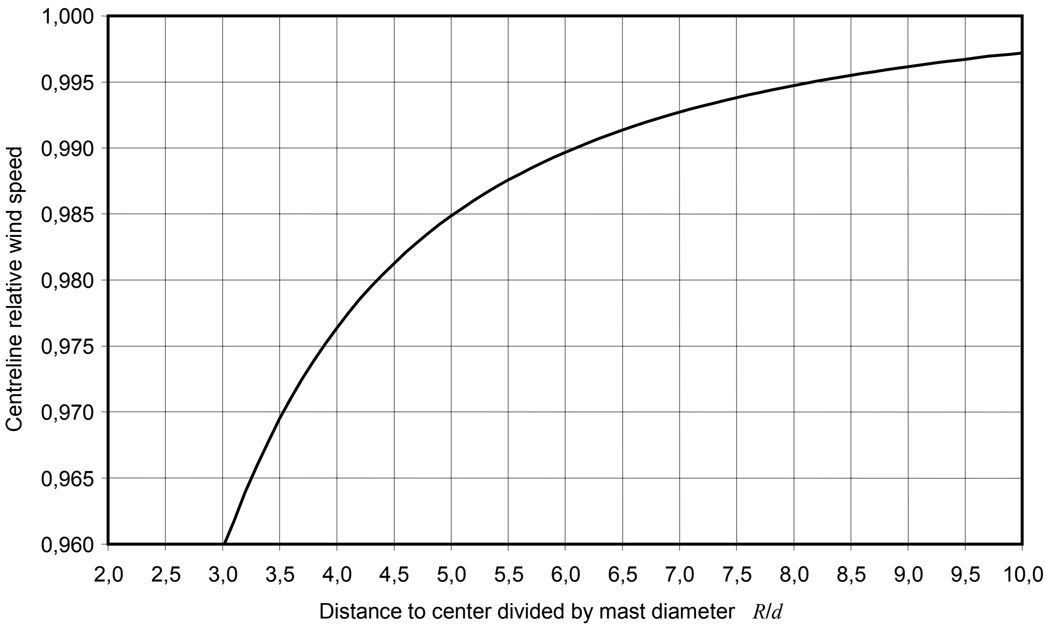


Figure G.6 – Centre-line relative wind speed as a function of distance *R* from the centre of a tubular mast and mast diameter *d*

A 99,5 % relative wind speed is seen to occur at R/d of 8,2. The corresponding figure for a 99 % relative wind speed is 6,1.

G.6.2 Lattice meteorological masts

Analysis of the flow round 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 mast is a function of the solidity of the mast, the drag of the individual members, the orientation of the wind and the separation of the measurement point from the mast. Figure G.7 shows the dimensions of interest on a top-view of a triangular lattice mast.

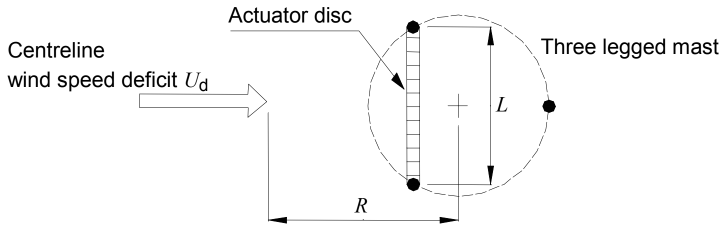


Figure G.7 – Representation of a three-legged lattice mast showing the centre-line wind speed deficit, the actuator disc representation of the mast with the leg distance L and distance R from the centre of the mast to the point of observation

The flow distortion is a function of the assumed thrust coefficient, C_T, which in turn depends upon the porosity of the mast and the drag on the individual members. C_T can be regarded as the total drag force per unit length of the tower, divided by the dynamic pressure and the face width, L.

Figure G.8 shows the computed flow around a lattice tower having a C_T of 0,5. At typical distances of the anemometer R above 2, this flow disturbance is very little affected by tower orientation (whether the face or a corner is oriented into the wind), and it can therefore be assumed to be the same.

If the measurement sector is 90° or less, minimum distortion is obtained when the anemometer is placed at an angle of 90° to the centre of the measurement sector. Otherwise, the flow distortion may be determined by considering the upwind deficit as a function of distance. Figure G.9 shows the computed centre-line 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.9 if winds approach from angles greater than 100° from the anemometer-mast alignment.

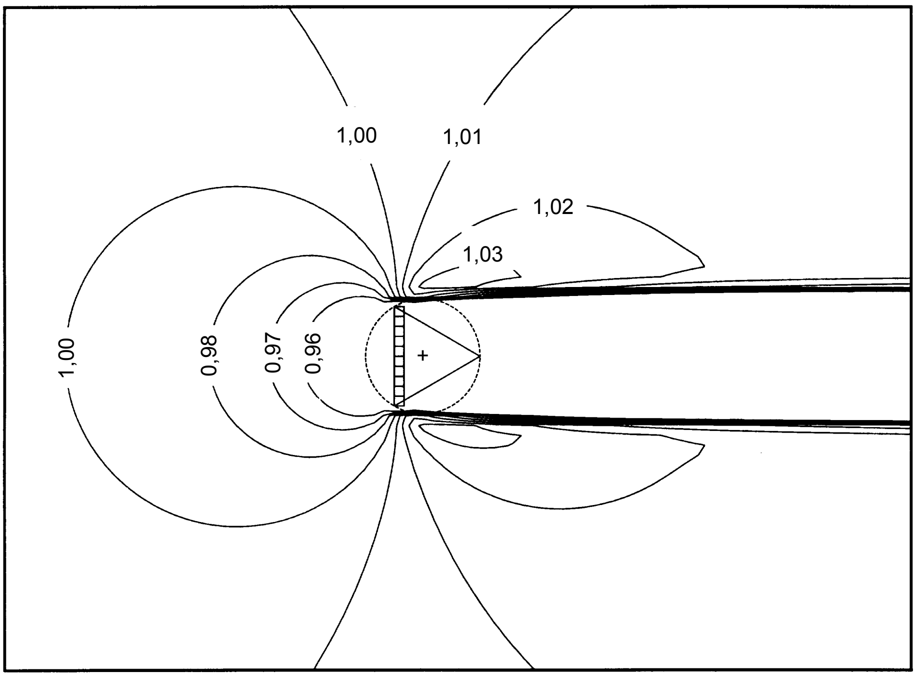


Figure G.8 – Iso-speed plot of local flow speed around a triangular lattice mast with a C_T of 0,5 normalised by free-field wind speed (from the left); analysis by 2 dimensional Navier-Stokes computation and actuator disc theory

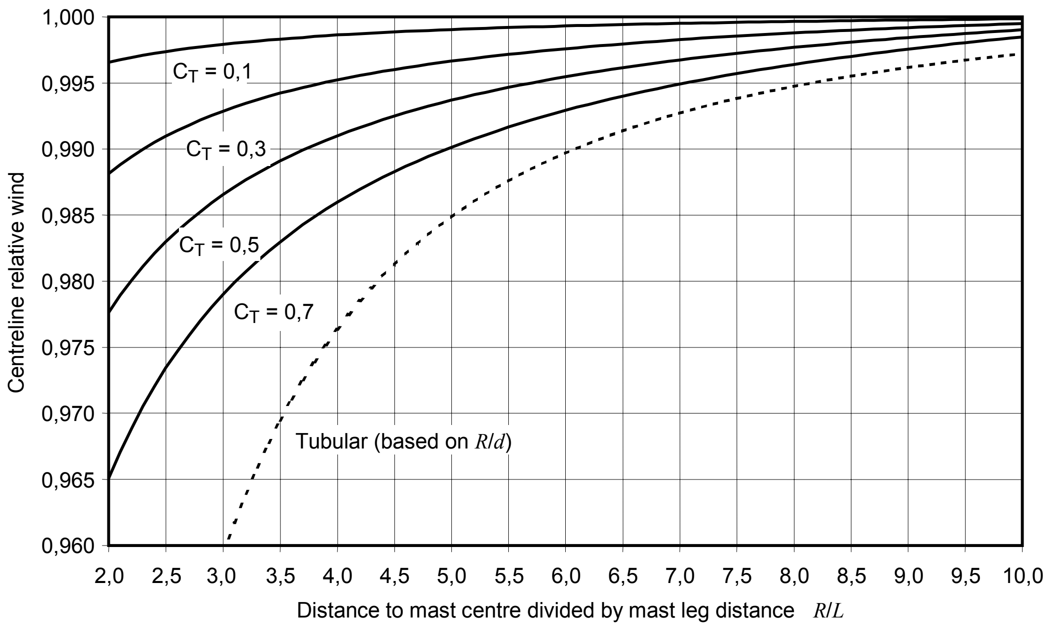


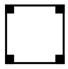
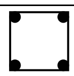
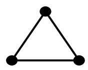
Figure G.9 – Centre-line relative wind speed as a function of distance R from the centre of a triangular lattice mast of face width L for various C_T values

The equation below may be used to estimate the centre-line wind speed deficit U_d as a function of C_T and R/L:

$$U_d = 1 - \left(0,062C_T^2 + 0,076C_T\right).\left(\frac{L}{R} - 0,082\right) \quad \text{(G.1)}$$

C_T can be estimated from local building codes or, within the ranges specified, from Table G.1. In this table, the solidity t is defined as the ratio of the projected area of all structural members on the side of the tower to the total exposed area.

Table G.1 – Estimation method for C_T for various types of lattice tower

Type of tower	Plan section	Expression for C_T	Valid range
Square cross-section, members with sharp edges		4,4(1 – t)t	0,1 < t < 0,5
Square cross-section, round members		2,6(1 – t)t	0,1 < t< 0,3
Triangular cross-section, round members		2,1(1 – t)t	0,1 < t < 0,3

Alternatively, if the desired maximum centre-line wind speed deficit is specified, the distance R may be obtained from the following equation:

$$R = \frac{L}{\dfrac{1-U_d}{\left(0,062C_T^2+0,076C_T\right)}+0,082} \tag{G.2}$$

For a lattice tower with a C_T of 0,5 and a 99,5 % centre-line wind speed deficit R shall be 5,7 times the mast leg distance L. A wind speed deficit of 99 % will reduce the distance R to 3,7 times the mast leg distance.

Annex H
(normative)

Power performance testing of small wind turbines

Small wind turbines (as defined by the most recent edition of IEC 61400-2) require special provisions for power performance testing. In particular, 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. When testing a small wind turbine, all requirements described in this standard shall be met with the following additions and changes:

a) in 5.1: when characterizing battery charging performance, the wind turbine generator system shall include the turbine, turbine tower, turbine controller, and wiring between the turbine and the load. The wind turbine generator system includes the 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 turbine when the batteries are fully charged. The wind turbine generator system does not include a battery bank because it is considered as part of the load;

b) in 5.1: when characterizing system output to a grid, the wind turbine generator system shall include the turbine, turbine tower, turbine controller, wiring between the turbine and the load, charge controller and dump load (if used) as noted above. 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;

c) also in 5.1: the wind turbine shall be connected to an electrical load that is representative of the load for which the 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. In the ideal test set-up, the battery bank does not store energy produced by the turbine. Rather all turbine output is routed through the voltage regulator. Therefore, the battery bank may be smaller than typically recommended for the turbine as long as voltage at the connection of the 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 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 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. Wiring between the small wind turbine and the load shall be in accordance with the manufacturer’s specifications. 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 turbine to load within 10 % of the settings given in Table G.1 over the full range of power output of the turbine. The 1-min average of the load voltage must be within 5 % of the settings given in Table G.1 to be included in the usable data set;

g) in 5.2.1: if it is more practical to mount the anemometer on a long boom that is connected to the turbine tower, a separate meteorological mast is not required. To minimize the potential for 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 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;

h) in 6.1: turbine output power shall be measured at the connection to the load;

i) in 6.1: in addition to electric power, voltage at the connection to the load shall be measured to ensure compliance with the requirements listed below;

j) in 6.4: the air temperature sensor and the air pressure sensor shall be mounted so that they are at least 1,5 rotor diameters below hub height even if such mounting results in a location less than 10 m above ground level;

k) in 6.6: monitoring of small wind turbine status is required only when the turbine controller provides an indication of turbine faults;

l) in 7.2: if the wind turbine’s charge controller reduces turbine output at the optional, high voltage setting, the device may be adjusted to a higher voltage. If the device is adjusted, the test report shall document the settings before and after adjustment. Any other adjustments to the turbine's controls must be clearly reported;

m) in 7.3: 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;

n) in 7.6: 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 hours of data with the small wind turbine within the wind speed range,

   3) in the case of furling turbines, the database should include completed wind speed bins characterizing performance when the turbine is furled;

o) in 8.1: for turbines with passive power control such as furling or blade fluttering, wind speed be normalized using equation (5) (wind speed adjustment), equation (6) (power adjustment), or an alternative method. Documentation must be provided to justify the use of an alternative method;

p) in 8.3: in cases where the small wind turbine does not shut down in high winds, AEP measured and AEP projected shall be calculated as though cut-out wind speed were the highest, filled wind speed bin or 25 m/s, whichever is greater;

q) in Clause 9: in addition to the information listed in Clause 6, the description of the wind turbine and the test set-up shall include:

   1) wiring sizes, conductor material, types, lengths and connectors used to connect the wind turbine to the load,

   2) measured resistance of wiring between the inverter and the load or between the turbine and the load if no inverter is used,

   3) voltage setting(s) for any over or under-voltage protection devices that are part of the small wind turbine generator system,

   4) nominal battery bank voltage (e.g. 12 V, 24 V, 48 V),

   5) battery bank size (i.e. amp-hour capacity), battery type and age,

   6) description including make, model, and specifications of the voltage regulation device used to maintain the battery bank voltage within specified limits;

r) it is recommended that additional performance data be obtained to quantify the effect that changes of battery bank voltage have on 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	Required setting	Optional low setting	Optional high setting
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

Annex I
(normative)

Classification of 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[7] 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.

I.2 Influence parameter ranges and classes

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. The class number k shall be determined as the maximum anemometer response deviation (from the horizontal wind speed input) in the wind speed range corresponding to the formula:[8]:

$$\begin{aligned} w_i &= 5m/s + 0,5 \cdot U_i \\ k &= 100 \cdot \max\left|\varepsilon_i / w_i\right| \end{aligned} \qquad \text{(I.1)}$$

where

w_i is a weighting function that defines the deviation envelope;

$\varepsilon_{\max,i}$ is the maximum deviation for any wind speed bin i in the wind speed range in m/s;

k is the class number;

U_i wind speed in bin 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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7 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.

8 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 (based on 10 min averages) of Classes A and B

	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 $\sigma_u/\sigma_v/\sigma_w$[9]	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

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.

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[10].

The classification of an anemometer is specified by the class number k and the class type by kA and kB or kS, for example 1,7A and 2,5S. The operational standard uncertainty (see Tables D.1 and E.2) of a cup 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:

$$u_{V2,i} = (0,05m/s + 0,005 \cdot U_i) \cdot k / \sqrt{3} \tag{I.2}$$

9 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.

10 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)

Assessment of cup anemometry

J.1 General

Assessment of anemometry for classification may be derived from wind tunnel tests, other laboratory tests, field tests, and associated modelling and extrapolation. A thorough assessment method should include both wind tunnel tests and field tests, and the tests should be mutually verified.

An assessment of a type of cup anemometer should include verified procedures to incorporate influence of the following basic characteristics on the cup anemometer operation:

- angular response characteristics;
- dynamic effects due to different rotor acceleration and deceleration torque characteristics;
- friction torque in bearings.

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.

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.

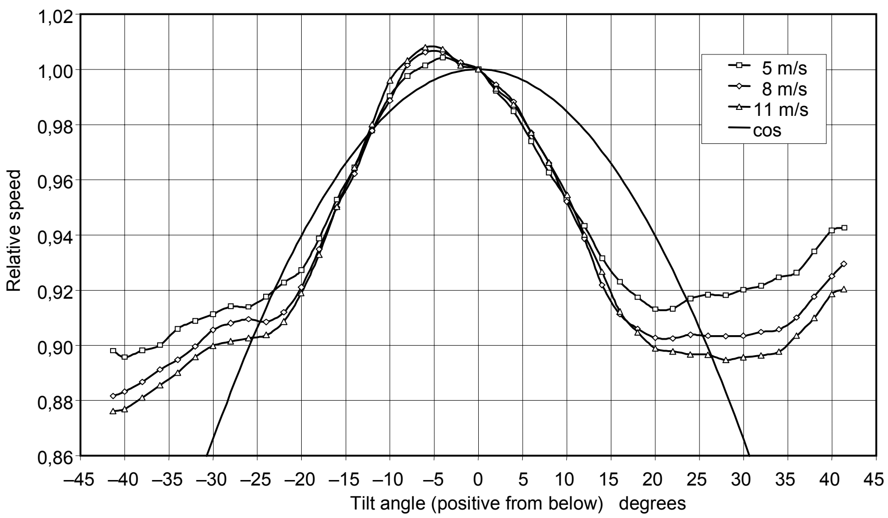

Figure J.1 – Measured angular response of a cup anemometer compared to cosine response

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.

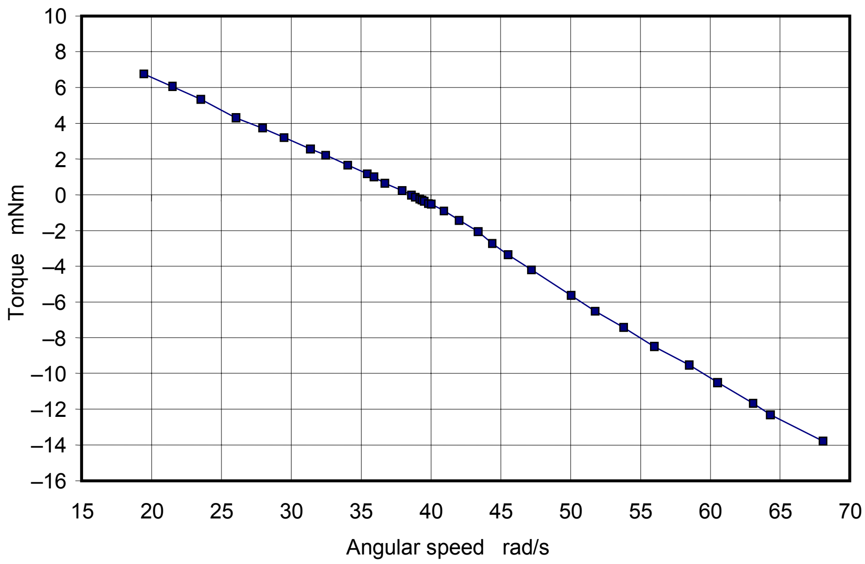

Figure J.2 – Wind tunnel torque measurements on a cup anemometer at 8 m/s

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 torque on the flywheel, which is subtracted from the measured torque. Figure J.3 shows an example of friction torque measurements.

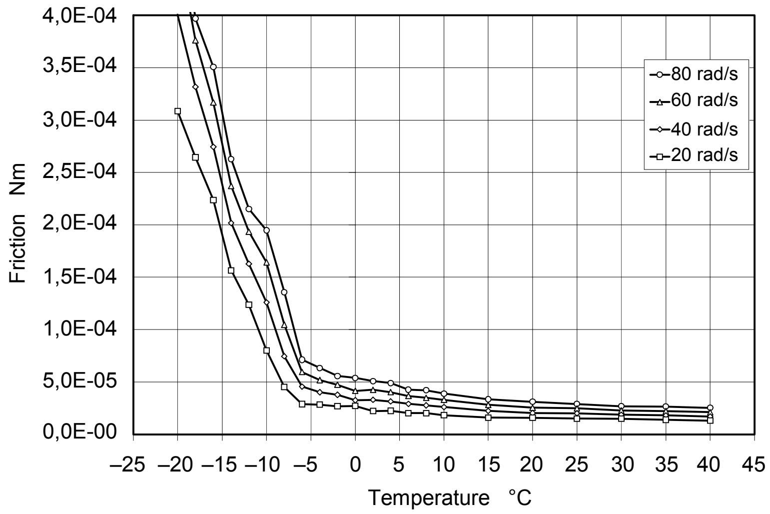

Figure J.3 – Example of bearing friction torque measurements

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

$$TI = \sigma_u / U \qquad \text{(J.1)}$$

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:

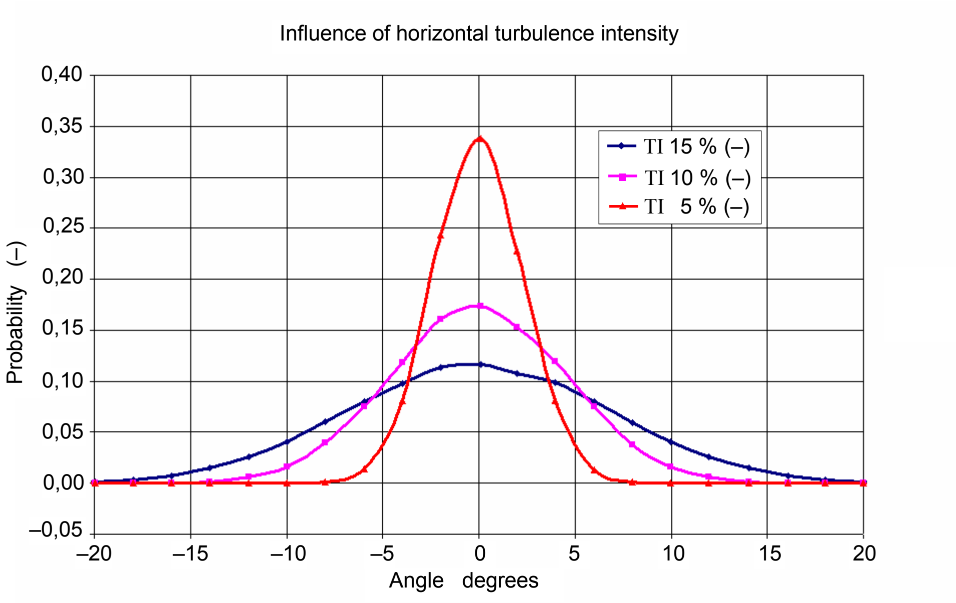

Figure J.4 – Distribution of vertical wind speed components assuming a fixed ratio between horizontal and vertical standard deviation in wind speed

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.

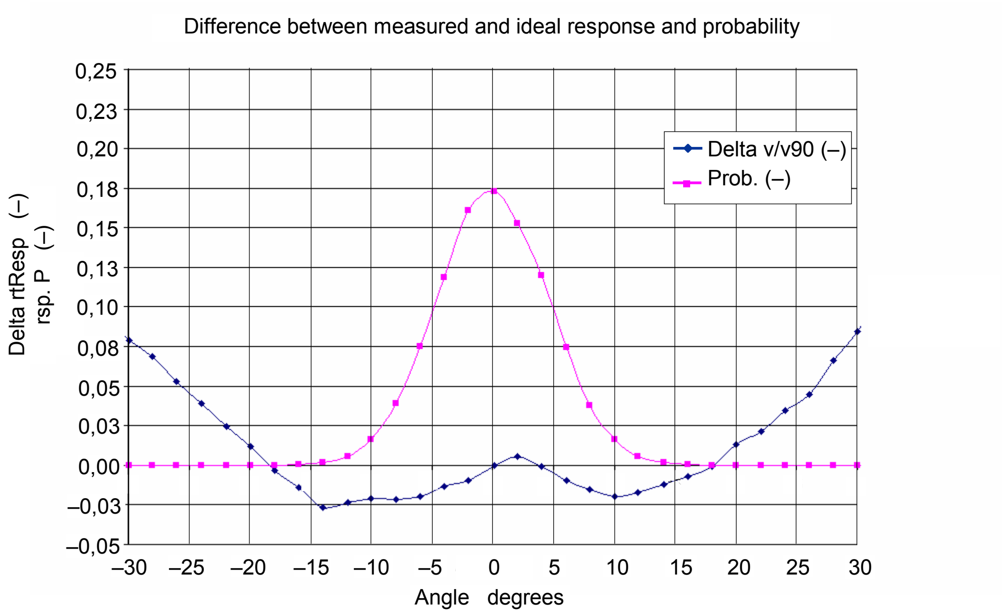

Figure J.5a

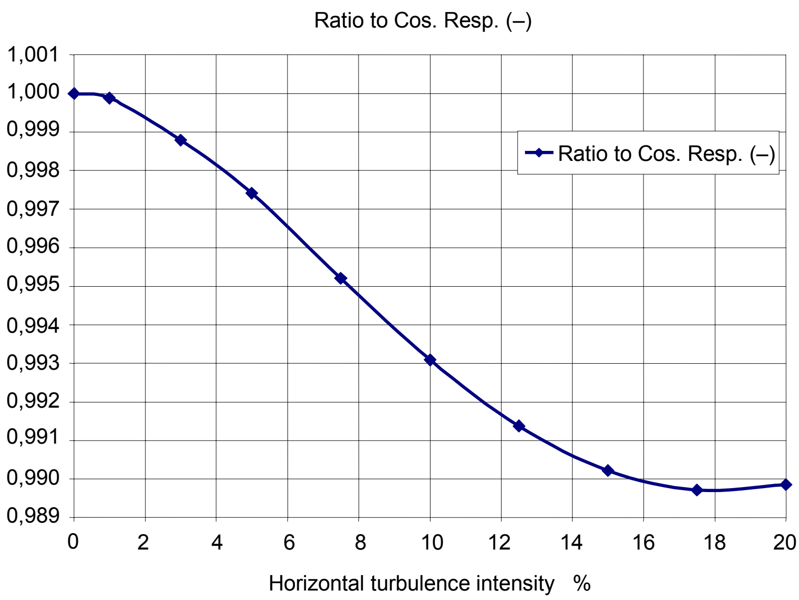

Figure J.5b

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.

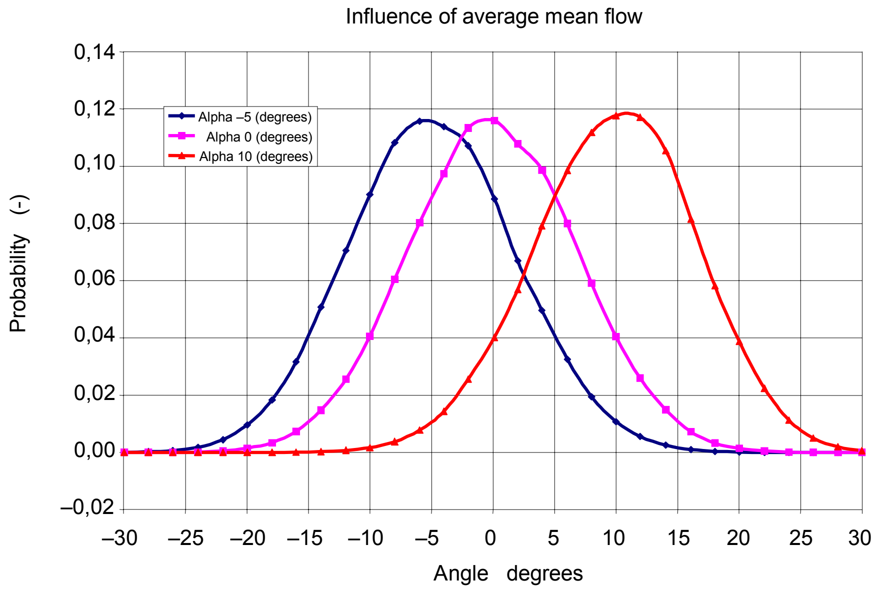

Figure J.6 – Probability distributions for three different average angles of inflow

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).

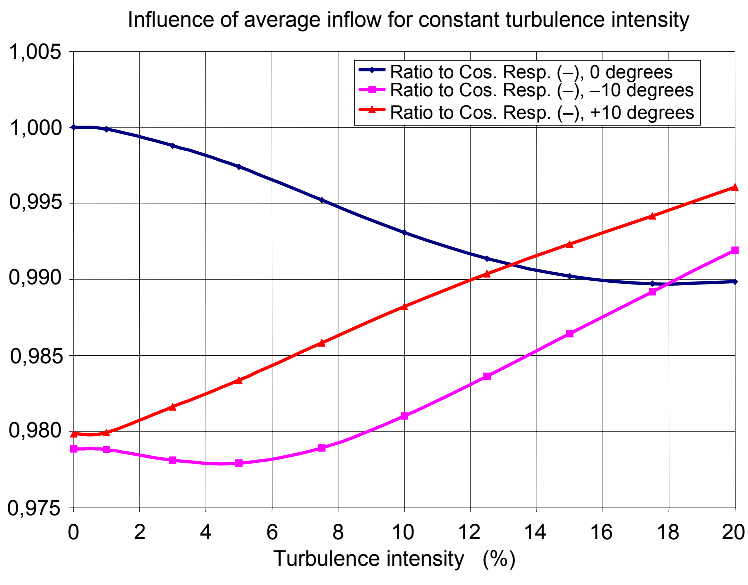

Figure J.7 – Total deviation from cosine response for three different average angles of inflow over horizontal turbulence intensity

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 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.

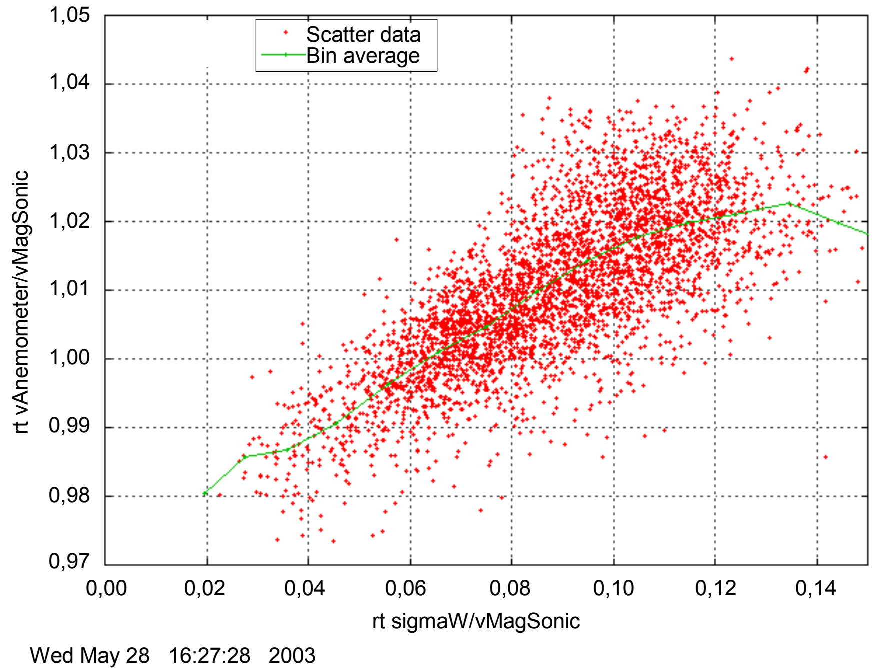

Figure J.8 – Example of an anemometer that does not fulfil the slope criterion

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.

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:

$$\alpha = A\tan\frac{w}{\sqrt{u^2+v^2}}, \quad \left|\vec{U}\right| = \sqrt{u^2+v^2+w^2} \tag{J.3}$$

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:

$$C_{QA} = C_{QA}(\lambda) = \frac{Q_A}{\frac{1}{2}\rho ARU_{eq}^{\,2}} \tag{J.6}$$

The generalized aerodynamic rotor torque coefficient is a function of the speed ratio:

$$\lambda = \frac{\omega R}{U_{eq} - U_t} \tag{J.7}$$

The friction torque is a function of the temperature and the rotational speed as found from the friction measurements:

$$Q_f = Q_f(T, \omega) \tag{J.8}$$

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.

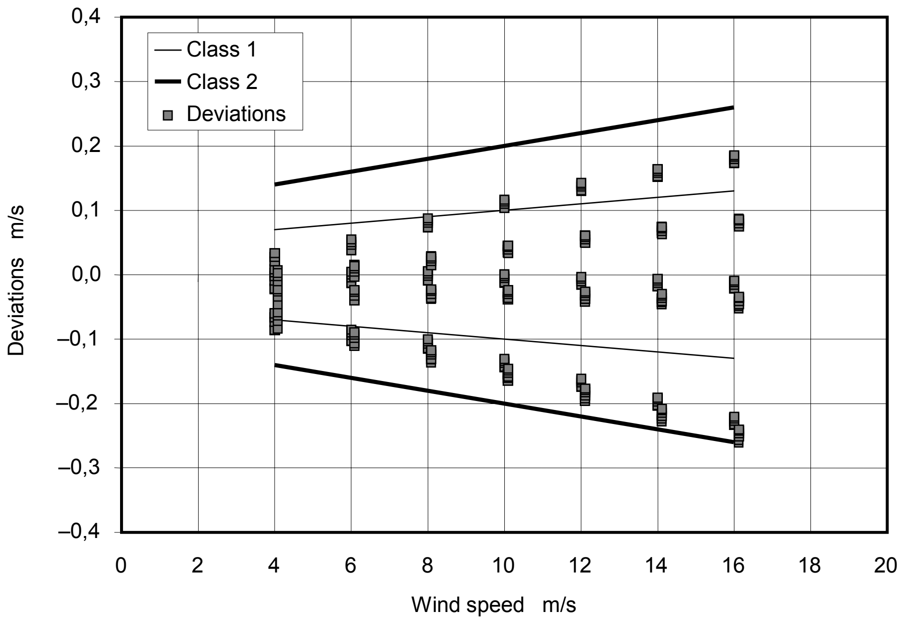

Figure J.9 – Example of deviations of a Class 2.0A cup anemometer

Annex K
(informative)

In situ comparison of anemometers

K.1 General

It shall be proved that an anemometer used for power curve measurements do 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. Another possibility is a so called in situ comparison made by comparing the primary anemometer to a control anemometer installed close to it during the measurement campaign. It should be noted that this method do not identify a gradual degradation of the calibration of the anemometer if the control anemometer degrades with a similar rate.

K.2 Prerequisite

During the measurement campaign the two anemometers are installed at the meteorological mast according to Annex G. The primary anemometer is used for the performance measurements. The other is the control anemometer, and is used for comparison. The anemometers can be installed in two variants:

- Variant 1: top mounted according to Clause G.2.
- Variant 2: alternative top mounted according to Clause G.3.

K.3 Realisation

The 10 min average values recorded during the measurement period are all taken into account. The data are filtered for a narrow wind direction sector (e.g. ±20º or ±40º 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.

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 ($v_{\text{control\_corr}}$) 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 ($v_{\text{control\_corr}}$) 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.

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