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

**Systèmes de génération d'énergie éolienne –
Partie 12-1: Mesurages de performance de puissance des éoliennes de
production d'électricité**



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WIND ENERGY GENERATION SYSTEMS –**Part 12-1: Power performance measurements
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This third edition of IEC 61400-12-1 is part of a structural revision that cancels and replaces the performance standards IEC 61400-12-1:2017 and IEC 61400-12-2:2013. The structural revision contains no technical changes with respect to IEC 61400-12-1:2017 and IEC 61400-12-2:2013, but the parts that relate to wind measurements, measurement of site calibration and assessment of obstacle and terrain have been extracted into separate standards.

The purpose of the re-structure was to allow the future management and revision of the power performance standards to be carried out more efficiently in terms of time and cost and to provide a more logical division of the wind measurement requirements into a series of separate standards which could be referred to by other use case standards in the IEC 61400 series and subsequently maintained and developed by appropriate experts.

The text of this International Standard is based on the following documents:

Draft	Report on voting
88/822/CDV	88/867/RVC

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

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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

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INTRODUCTION

IEC TC 88 has made this third edition in order to reduce the complexity of the previous edition. Wind measurement procedures have been extracted from the performance standard, recognizing that wind measurements need to be referenced from other standards, such as in loads, noise and resource assessment measurements. IEC TC 88 recommends that the restructured standards gradually take over the previous standards before Maintenance Cycle Reports are written on the restructured standards introducing new technical requirements. Revision of the restructured documents should be proposed at the same time to incorporate such technical changes, recommendations, clarifications and simplifications.

The purpose of the IEC 61400-12 series is to provide a uniform methodology that will ensure consistency, accuracy and reproducibility in the measurement and analysis of power performance by wind turbines. This document has been prepared with the anticipation that it would be applied by:

- a) a wind turbine manufacturer striving to meet well-defined power performance requirements and/or a possible declaration system;
- b) a wind turbine purchaser in specifying such performance requirements;
- c) a wind turbine operator who can be required to verify that stated, or required, power performance specifications are met for new or refurbished units;
- d) a wind turbine planner or regulator who needs to be able to accurately and fairly define power performance characteristics of wind turbines in response to regulations or permit requirements for new or modified installations.

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

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

A key element of power performance testing is the measurement of wind speed. This document specifies the use of cup or sonic anemometers or remote sensing devices (RSD) in conjunction with anemometers to measure wind. Even though suitable procedures for calibration, validation and classification are adhered to, the nature of the measurement principle of these devices can potentially cause them to perform differently. These instruments are robust and have been regarded as suitable for this kind of test with the limitation of some of them to certain classes of terrain.

Recognizing that, as wind turbines become ever larger, a wind speed measured at a single height is increasingly unlikely to accurately represent the wind speed through the entire turbine rotor, this document introduces an additional definition of wind speed. Whereas previously wind speed was defined as that measured at hub height only, this can now be supplemented with a

so-called rotor equivalent wind speed (REWS) defined by an arithmetic combination of simultaneous measurements of wind speed at a number of heights spanning the complete rotor diameter between lower tip and upper tip. The power curves defined by hub height wind speed and REWS are not the same and indeed the wind speed distributions defined by hub height wind speed and REWS are also not the same such that the annual energy production (AEP) is defined by the combination of a measured power curve and wind speed distribution, both of which are based on an identical definition of wind speed.

The technical requirements in this document have been extracted from and are identical to those in IEC 61400-12-1:2017. The corrections in IEC 61400-12-1:2017/Cor.1:2019, IEC 61400-12-1:2017/Cor.2:2020 and IEC 61400-12-1:2017/Cor.3:2021 have been incorporated in this document. Specifically, technical corrections have been applied to Equations (E.8), (E.44) and (E.17). A further technical correction to Equation (E.45) has been made to correct inconsistent units in the components of the summation. Refer to IEC 61400-12:2022 for an overview of the re-structuring of the IEC 61400-12 series and the relationships between different parts of the standard.

Procedures for calibration, classification and uncertainty of cup anemometers and ultrasonic anemometers are given in IEC 61400-50-1. Procedures for calibration, classification and uncertainty of remote sensing devices are given in IEC 61400-50-2. Special care should be taken in the selection of the instruments chosen to measure the wind speed because it can influence the result of the test.

WIND ENERGY GENERATION SYSTEMS –

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

1 Scope

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

Considerations which can be of relevance to the assessment of uncertainty of power performance tests on multiple turbines are presented in Annex R on an informative basis.

This document defines 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. Uncertainty sources of wind measurements are assessed from procedures described in the relevant wind measurement equipment standards while uncertainty of the power curve and annual energy production are assessed by procedures in this document.

2 Normative references

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

IEC 60688, *Electrical measuring transducers for converting AC and DC electrical quantities to analogue or digital signals*

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

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

IEC 61400-12-3, *Wind energy generation systems – Part 12-3: Power performance – Measurement based site calibration*

IEC 61400-12-5, *Wind energy generation systems – Part 12-5: Power performance – Assessment of obstacles and terrain*

IEC 61400-50-1, *Wind energy generation systems – Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*

IEC 61400-50-2, *Wind energy generation systems – Part 50-2: Wind measurement – Application of ground mounted remote sensing technology*

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

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

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

ISO 2533, *Standard Atmosphere*

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

3 Terms and definitions

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

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

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

3.1

accuracy

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

3.2

annual energy production

AEP

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

3.3

atmospheric stability

measure of tendency of the wind to encourage or suppress vertical mixing

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

3.4

complex terrain

terrain surrounding the test site that features significant variations in topography and terrain obstacles (3.18) that can cause flow distortion

3.5

cut-in wind speed

lowest wind speed at which a wind turbine will begin to produce power

3.6

cut-out wind speed

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

3.7

data set

collection of data sampled over a continuous period

3.8

extrapolated power curve

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

3.9

flow distortion

change in air flow caused by obstacles, topographical variations, or other wind turbines that results in the wind speed at the measurement location being different from the wind speed at the wind turbine location

3.10

hub height

<of a wind turbine> height of the centre of the swept area of the wind turbine rotor above the ground at the tower

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

3.11

maximum power

P_{60}

maximum one-minute average power output a small wind turbine in normal steady-state operation will produce

Note 1 to entry: Peak instantaneous power output can be higher than maximum power.

Note 2 to entry: This definition applies only to small wind turbines as referred to in Annex H.

3.12

measured power curve

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

3.13

measurement period

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

3.14

measurement sector

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

3.15

method of bins

data reduction procedure that groups test data for a certain parameter into intervals (bins)

Note 1 to entry: The method of bins is normally used for wind speed bins but is also applicable to other parameters.

Note 2 to entry: For each bin, the number of data sets or samples and their sum are recorded, and the average parameter value within each bin is calculated.

3.16

net active electric power

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

3.17**normal maintenance**

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

3.18**obstacle**

obstruction that blocks the wind and creates distortion of the flow

Note 1 to entry: Buildings and trees are examples of obstacles.

3.19**pitch angle**

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

3.20**power coefficient**

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

3.21**power performance**

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

3.22**rated power**

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

3.23**reference power**

averaged power level in the 11 m/s wind speed bin

Note 1 to entry: This definition applies only to small wind turbines as referred to in Annex H.

3.24**rotor equivalent wind speed**

wind speed corresponding to the kinetic energy flux through the swept rotor area when accounting for the variation of the wind speed with height

SEE: Equation (5)

3.25**special maintenance**

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

3.26**standard uncertainty**

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

3.27

swept area

<for a horizontal axis wind turbine> projected area of the moving rotor upon a plane normal to the axis of rotation

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

3.28

test site

location of the wind turbine under test and its surroundings

3.29

uncertainty in measurement

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

3.30

wind measurement equipment

meteorological mast-mounted instruments or remote sensing device

3.31

wind shear

change of wind speed with height across the wind turbine rotor

3.32

wind shear exponent

α

exponent of the power law defining the variation of wind speed with height

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

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

where

v_h is the hub height wind speed;

H is the hub height (m);

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

α is the wind shear exponent.

3.33

wind veer

change of wind direction with height across the wind turbine rotor

4 Symbols, units and abbreviated terms

Symbol or abbreviated term	Description	Unit
A	swept area of the wind turbine rotor	[m ²]
A_i	area of the i -th wind turbine rotor segment	[m ²]
A_w	Weibull scale factor	

Symbol or abbreviated term	Description	Unit
AEP	annual energy production	[Wh]
B	barometric pressure	[Pa]
$B_{10\min}$	measured air pressure averaged over 10 min	[Pa]
C_P	assumption of constant power coefficient	
$C_{P,i}$	power coefficient in bin i	
$C_{P,\max}$	maximum power coefficient	
c	sensitivity factor of a parameter (the partial differential)	
$c_{B,i}$	sensitivity factor of air pressure in bin i	[W/Pa]
$c_{d,i}$	sensitivity factor of data acquisition system in bin i	
$c_{k,i}$	sensitivity factor of component k in bin i	
$c_{l,i}$	sensitivity factor of component l in bin i	
$c_{l,j}$	sensitivity factor of component l in bin j	
$c_{m,i}$	sensitivity factor of v_{eq} on wind speed at height m in wind speed bin i	
$c_{n,i}$	sensitivity factor of v_{eq} on wind speed at height n in wind speed bin i	
$c_{RH,i}$	sensitivity factor for relative humidity in bin i	
$c_{T,i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{V,i}$	sensitivity factor of wind speed in bin i	[Ws/m]
$c_{\rho,i}$	sensitivity factor of air density correction in bin i	[Wm ³ /kg]
D	rotor diameter	[m]
D_e	equivalent rotor diameter	[m]
D_n	rotor diameter of neighbouring and operating wind turbine	[m]
d	meteorological mast diameter	[m]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
f_i	the relative occurrence of wind speed in a wind speed interval bin i	
f_r	wind shear correction factor as calculated in 9.1.3.3	
$f_{r,MM}$	wind shear correction factor, measured using meteorological mast mounted instruments	
$f_{r,RSD}$	wind shear correction factor, measured using a remote sensing device	
$f_{r,X,i}$	wind shear correction factor in wind speed bin i	
$f(v)$	wind speed distribution within 10 min period	
H	hub height of wind turbine	[m]
h	height of obstacle	[m]
I_{ref}	reference turbulence intensity (Annex M)	
i	wind speed bin referring to bin averaging of power curve	
k	class number	
k	Weibull shape factor	
L	distance between the wind turbine and the wind measurement equipment	
L_e	distance between the wind turbine or the wind measurement equipment and an obstacle	[m]
L_n	distance between the wind turbine or the wind measurement equipment and a neighbouring and operating wind turbine	[m]

Symbol or abbreviated term	Description	Unit
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 $\approx 8\,760$	[h]
N_i	number of 10 min data sets in wind speed bin i	
n	number of available measurement heights ($n \geq 3$)	
n_h	number of available measurement heights	
P_o	porosity of obstacle (0: solid, 1: no obstacle)	
P_i	normalized and averaged power output in bin i	[W]
$P_{I=0}(v)$	zero turbulence power curve	
P_{kin}	kinetic energy in the wind across the rotor height range	
P_n	normalized power output	
$P_{n,i,j}$	normalized power output of data set j in bin i	[W]
P_{rated}	rated power	
$P_{sim}(v)$	simulated 10 min average of measured power output	
P_w	vapour pressure	[Pa]
P_{10min}	measured power averaged over 10 min	[W]
P_{60}	maximum one-minute average power output	
$\overline{P(v)}$	10 min average of measured power output	
$\overline{P_{sim,I}(v)}$	simulated 10 min average of measured power output according to the above condition a): Equation (M.1) applied for the measured wind speed distribution	
$\overline{P_{sim,I_{ref}}(v)}$	simulated 10 min average of measured power output according to the above condition b): Equation (M.1) applied for the measured average wind speed and for the reference turbulence intensity I_{ref} by assuming a Gaussian wind speed distribution.	
R	rotor radius	[m]
R_0	gas constant of dry air (287,05)	[J/kgK]
R_d	distance to meteorological mast centre	[m]
REWS	rotor equivalent wind speed	
R_w	gas constant of water vapour (461,5)	[J/kgK]
RSD	remote sensing device	
r	correlation coefficient	
s	category A standard uncertainty component	
$s_{k,i}$	category A standard uncertainty of component k in bin i	
s_i	combined category A uncertainties in bin i	
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
s_{sc}	category A standard uncertainty of site calibration	[m/s]
$s_{sc,i}$	category A standard uncertainty of site calibration in bin i	
T	absolute temperature	[K]

Symbol or abbreviated term	Description	Unit
T_i	average temperature in bin i	
$T_{10\min}$	measured absolute air temperature averaged over 10 min	[K]
t	time	[s]
U	wind speed	[m/s]
U_i	wind speed in bin i	[m/s]
u	category B standard uncertainty component	
u_{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u_{\text{AD},i}$	uncertainty related to the air density bin i	
$u_{\text{AD,method},i}$	uncertainty related to the air density correction bin i	
$u_{\text{B},i}$	category B standard uncertainty of air pressure in bin i	[Pa]
$u_{\text{B,cal},i}$	uncertainty related to the calibration of the pressure sensor bin i	[Pa]
$u_{\text{B,mnt},i}$	uncertainty related to the mounting of the pressure sensor bin i	[Pa]
$u_{\text{c},i}$	combined standard uncertainty of the power in bin i	[W]
$u_{\text{d},i}$	standard uncertainty of the data acquisition system for the full range of a certain measurement channel bin i	
$u_{\text{d,SA},i}$	uncertainty due to system accuracy in bin i	
$u_{\text{d,SC},i}$	uncertainty due to signal conditioning in bin i	
$u_{\text{d,ST},i}$	uncertainty due to signal transmission in bin i	
$u_{\text{d,VT},i}$	uncertainty related to the data acquisition of the signals of the wind speed sensors according to IEC 61400-50-1 bin i	
$u_{\text{dVS},i}$	uncertainty related to the data acquisition of the wind speed signal bin i	
$u_{\text{dB},i}$	uncertainty related to the data acquisition of the signal of the pressure sensor bin i	[Pa]
$u_{\text{dP},i}$	uncertainty component related to the data acquisition of the power signal bin i	
$u_{\text{dRH},i}$	uncertainty related to the data acquisition of the signal from the humidity sensor bin i	[%]
$u_{\text{dT},i}$	uncertainty related to the data acquisition of the signal of the temperature sensor bin i	[°C]
$u_{\text{dWV},i}$	uncertainty related to the data acquisition of the signal from the wind direction sensor (wind vane or sonic anemometer) bin i	
$u_{\text{dWR},i}$	uncertainty related to the data acquisition of the signal from the wind direction sensor (remote sensing device) bin i	
u_i	combined category B uncertainties in bin i	
$u_{f_{\text{r},X},i}$	standard uncertainty of $f_{\text{r},X,i}$ in wind speed bin i	
$u_{k,i}$	category B standard uncertainty of component k in bin i	
$u_{l,i}$	standard uncertainty of component l in bin i	
$u_{l,j}$	standard uncertainty of component l in bin j	
$u_{\text{M},i}$	uncertainty related to the applied methodology bin i	
$u_{\text{M,cc},i}$	uncertainty related to the measurement in a cold climate bin i	
$u_{\text{M,shear},i}$	uncertainty related to missing information regarding shear across the whole rotor bin i	
$u_{\text{M,sfx},i}$	uncertainty related to the unquantifiable seasonal effects on the turbine bin i	

Symbol or abbreviated term	Description	Unit
$u_{M,ti,i}$	uncertainty related to missing information regarding turbulence when no hub-height meteorological mast wind speed signal is available bin i	
$u_{M,tinorm,i}$	uncertainty related to turbulence normalization bin i	
$u_{M,upflow,i}$	uncertainty related to missing information regarding upflow across the whole rotor bin i	
$u_{M,veer,i}$	uncertainty related to missing information regarding wind veer across the whole rotor bin i	
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
$u_{P,CT,i}$	uncertainty component due to the current transformer bin i	
$u_{P,PT,i}$	uncertainty component due to the power transducer bin i	
$u_{P,VT,i}$	uncertainty component due to the voltage transformer bin i	
$u_{REWS,i}$	uncertainty of rotor equivalent wind speed in bin i	
$u_{REWS.shear,i}$	uncertainty of the REWS wind speed based on the multiple wind speed measurements the REWS bin i	
$u_{REWS.veer,i}$	uncertainty related to the influence of veer on the REWS bin i	
$u_{RH,i}$	category B standard uncertainty of relative humidity in bin i	
$u_{RH,cal,i}$	uncertainty related to the calibration of the humidity sensor bin i	[%]
$u_{RH,mnt,i}$	uncertainty related to the mounting of the humidity sensor bin i	[%]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
$u_{T,cal,i}$	uncertainty component of the temperature sensor bin i	[°C]
$u_{T,mnt,i}$	uncertainty related to the mounting of the temperature sensor bin i	[°C]
$u_{T,shield,i}$	uncertainty related to the radiation shielding of the temperature sensor bin i	[°C]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[m/s]
$u_{v_h,i}$	standard uncertainty of $v_{h,i}$ in wind speed bin i	
$u_{v_{eq},final,i}$	standard uncertainty of final rotor equivalent wind speed in bin i	
$u_{v_{eq},k,i}$	standard uncertainty sub-component k of v_{eq} in wind speed bin i	
$u_{v_{eq},l,i}$	standard uncertainty sub-component l of v_{eq} in wind speed bin i	
$u_{v_{eq},X,i}$	standard uncertainty of $v_{eq,X,i}$ in bin i	
$u_{v_{eq},X,k,i}$	standard uncertainty component k of rotor equivalent wind speed as measured with the remote sensing device in bin i , to be analysed according to Equation (E.32) bin i	
$u_{VHW,i}$	uncertainty on the hardware used and is one of $u_{VS,i}$, $u_{VR,i}$ or $u_{REWS,i}$ bin i	
$u_{v_{h,X,i}}$	standard uncertainty of $v_{h,X,i}$ bin i	
$u_{v_{h,X,k,i}}$	standard uncertainty component k of hub height wind speed as measured with the remote sensing device in bin i	
$u_{v_M,i}$	uncertainty related to the method applied bin i	
$u_{v_m,k,i}$	standard uncertainty sub-component k of wind speed measurement at height m in wind speed bin i	
$u_{v_n,k,i}$	standard uncertainty sub-component k of wind speed measurement at height n in wind speed bin i	

Symbol or abbreviated term	Description	Unit
$u_{VR,i}$	uncertainties in the wind speed measurement from RSD	
$u_{VR,class}$	uncertainty related to the classification of the RSD bin i	
$u_{VR,class,i}$	uncertainty related to the classification of the remote sensing device according to IEC 61400-50-2	
$u_{VR,flow,i}$	uncertainty related to the flow variation across the measurement volume of the RSD bin i	
$u_{VR,isc,i}$	uncertainty due to the in-situ test bin i	
$u_{VR,mnt,i}$	uncertainty related to the mounting of the RSD bin i	
$u_{VR,mon,i}$	uncertainty related to the monitoring of the RSD bin i	
$u_{VR,ver,i}$	uncertainty due to the verification test bin i	
$u_{VREWS,i}$	uncertainty of the rotor equivalent wind speed (REWS) bin i	
$u_{VREWS,shear,i}$	uncertainty due to the influence on REWS from the shear measurement across the rotor bin i	
$u_{VREWS,veer,i}$	uncertainty related to the classification of the RSD bin i	
u_{VS}	uncertainty related to wind speed (cup or sonic)	
$u_{VS,class,i}$	uncertainty related to the classification of the sensors bin i	
$u_{VS,igt,i}$	uncertainty related to the flow distortion from lightning finial bin i	
$u_{VS,mnt,i}$	uncertainty related to the mounting of the sensors bin i	
$u_{VS,postcal,i}$	uncertainty related to the flow distortion from the terrain bin i	
$u_{VS,precal,i}$	uncertainty on the hardware used and is one of $u_{VS,i}$, $u_{VR,i}$ or $u_{REWS,i}$ bin i	
$u_{VT,i}$	uncertainty related to the flow distortion from the terrain bin i	
$u_{VT,class,i}$	uncertainty related to the classification of the sensors for the site calibration according to IEC 61400-50-1	
$u_{VT,coc,i}$	uncertainty related to calibration of the sensors according to IEC 61400-12-3 before the test	
$u_{VT,coc,i,j}$	uncertainty related to the change of correction value between bins	
$u_{VT,igt,i}$	uncertainty related to a possible top-mounted lightning finial bin i	
$u_{VT,mnt,i}$	uncertainty related to the mounting of the sensors bin i	
$u_{VT,precal,i}$	uncertainty related to the calibration of the sensors before the test bin i	
$u_{VT,postcal,i}$	uncertainty related to the in-situ calibration (Annex K) and/or the post-calibration of the sensor (IEC 61400-50-1) during and/or after the site calibration bin i	
$u_{VT,rmv,i}$	uncertainty related to removal of the wind direction sensor between the site calibration and the power performance test bin i	
$u_{VT,sv,i}$	uncertainty related to seasonal variation between the site calibration and the power performance test bin i	
$u_{v,X,k,i}$	standard uncertainty of component k of either $v_{h,X,i}$ or $v_{eq,X,i}$ bin i	
$u_{WR,i}$	uncertainty related to the wind direction measured with an RSD bin i	
$u_{WR,align,i}$	uncertainty related to the alignment of the RSD bin i	
$u_{WR,fv,i}$	uncertainty related to the flow variation in different probe volumes bin i	
$u_{WR,class,i}$	uncertainty related to the classification of the RSD bin i	
$u_{WR,mda,i}$	uncertainty related to the magnetic declination angle bin i	

Symbol or abbreviated term	Description	Unit
$u_{WR,mon,i}$	uncertainty related to the in-situ monitoring of the signal from the wind direction monitoring by the RSD device bin i	
$u_{WR,ver,i}$	uncertainty related to the verification test of the RSD bin i	
$u_{WV,i}$	uncertainty related to the wind direction measured with a mast mounted wind direction sensor (wind vane or sonic anemometer) bin i	
$u_{WV,bo,i}$	uncertainty related to the boom orientation on which the wind direction sensor is mounted bin i	
$u_{WV,cal,i}$	uncertainty related to the calibration of the wind direction sensor bin i	
$u_{WV,mda,i}$	uncertainty related to the magnetic declination angle bin i	
$u_{WV,nm,i}$	uncertainty related to north marking of the wind direction sensor bin i	
$u_{WV,oe,i}$	uncertainty related to the influence of the mast on the free stream wind direction at the point of measurement bin i	
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_{eq}	measured equivalent wind speed	
V_n	normalized wind speed	[m/s]
V_{10min}	measured wind speed averaged over 10 min	[m/s]
v	transversal wind speed component	[m/s]
$\bar{v}$	mean flow air speed	[m/s]
v_{eq}	measured equivalent wind speed	[m/s]
$v_{eq,final}$	final rotor equivalent wind speed	[m/s]
$v_{eq,i}$	equivalent wind speed in bin i	
$v_{eq,MM}$	equivalent wind speed based on meteorological mast measurements	[m/s]
$v_{eq,RSD}$	equivalent wind speed based on remote sensing device measurements	[m/s]
$v_{eq,X,i}$	rotor equivalent wind speed as measured with the remote sensing device in bin i	
v_h	hub height wind speed	[m/s]
$v_{h,i}$	wind speed at hub height in bin i	
$v_{h,i}$	wind speed measured at hub height in bin i by cup or sonic anemometer bin i	
$v_{h,MM}$	wind speed measured at hub height with meteorological mast	[m/s]
v_{hn}	hub height wind speed normalized for a specific wind shear profile	[m/s]
$v_{h,RSD}$	wind speed measured at hub height by the remote sensing device	[m/s]
$v_{h,X,i}$	wind speed measured by remote sensing device in bin i	
v_i	wind speed measured at height bin i	[m/s]
$v_{m,i}$	wind speed at height m in wind speed bin i	
v_{rated}	rated wind speed	
v_{zi}	wind speed at height zi	[m/s]
WME	wind measurement equipment	
w	vertical wind speed component	[m/s]
w_i	weighting function to define deviation envelope	

Symbol or abbreviated term	Description	Unit
z	height above ground	[m]
z_i	height of the i -th wind turbine rotor segment	[m]
z_m	wind speed measurements of successive measurement heights	[m]
α	wind shear exponent from power law	[°]
κ	von Karman constant 0,4	
ρ	air density	[kg/m ³]
ρ_i	average air density in bin i	
$\rho_{k,l,i}$	correlation coefficient between the uncertainty component k height m and n in wind speed bin i	
$\rho_{k,l,i,j}$	correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j	
$\rho_{m,n,k,i}$	correlation coefficient between the uncertainty component k height m and n in wind speed bin i	
$\rho_{u_{v_{eq,X,i}}, u_{v_{h,X,i}}}$	correlation coefficient between uncertainty components $u_{v_{eq,X,i}}$ and $u_{v_{h,X,i}}$ in bin i	
$\rho_{u_{v_{eq,X,i}}, u_{v_{h,X,i},k,i}}$	correlation coefficient between standard uncertainty components $u_{v_{eq,X,i}}$ and $u_{v_{h,X,i},k,i}$ in bin i	
ρ_0	reference air density	[kg/m ³]
ρ_{10min}	derived air density averaged over 10 min	[kg/m ³]
σ	standard uncertainty	
$\sigma_{P,i}$	standard deviation of the normalized power data in bin i	[W]
σ_{10min}	standard deviation of parameter averaged over 10 min	
Φ	relative humidity (range 0 % to 100 %)	
Φ_i	average relative humidity (range 0 % to 100 %) in bin i	
$\Phi_{m,i}$	wind direction at m -th height relative to wind direction at hub height in wind speed bin i	
ϕ_i	angle difference between the wind direction at hub height and segment i	

5 Power performance method overview

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

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

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

$$P_{\text{kin}} = \int_A \frac{1}{2} \rho V^3 dA \quad (2)$$

NOTE 1 If the wind speed changes (i.e. if the turbulence intensity is greater than zero) during a certain time period, then the kinetic power (averaged over this time period) is higher than in the case of a constant wind speed, whereas a wind turbine has only a limited possibility to transform this additional kinetic power into additional electric power. This issue is not taken into further consideration here. As a simplification, the Equations (2), (3), (4) are considered valid here, even in the case of a turbulence intensity greater than zero. The impact of wind speed changes on the time averaged kinetic power and the associated impact on the wind turbine power curve are treated by the turbulence normalization procedure as included in Annex M.

Here the wind speed V , measured at a point in space over the rotor area, is the horizontal wind speed.

NOTE 2 Wind turbine power seems to correlate better with the horizontal wind speed definition than with a vector wind speed definition for a one point hub height wind speed measurement.

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

$$P_{\text{kin}} = \int_A \frac{1}{2} \rho (V \cos(\varphi - \varphi_{\text{hub}}))^3 dA \quad (3)$$

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

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

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

Here the index i refers to the height within the rotor area.

NOTE 3 However, when wind speed is mentioned in this document it is by default referring to the hub height wind speed definition unless specifically stated to be this energy equivalent wind speed definition.

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

At sites with low and homogeneous wind shear and wind veer over the rotor (and for turbines with small rotor diameters in possibly more complex wind flow conditions), the wind speed measured at hub height can be a good representation of the kinetic energy to be captured by the rotor. Hub height wind speed is the wind speed upon which power curves have historically been defined in all previous editions of IEC 61400-12-1. For that reason, the wind speed measured at hub height is the default definition of wind speed and shall always be measured and reported, even when more comprehensive measurements of wind speed are available over the rotor height.

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

If wind shear and wind veer are not measured over the full height of the rotor there is added uncertainty in the equivalent wind speed. This uncertainty decreases as more wind speed and wind direction measurement heights are used. If measurements are limited to hub height only and there is no measurement of wind shear over the most significant parts of the rotor, then this implies an uncertainty in determination of the equivalent wind speed.

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

NOTE 4 For small turbines refer to IEC 61400-2.

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

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

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

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

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

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

NOTE 5 For vertical axis wind turbines the wind veer is omitted in Equation (3) (setting $\varphi_i = \varphi_{\text{hub}}$).

- c) air density is measured at hub height and the power curve is normalized to a site average air density during the measurement period or to a pre-defined reference air density;
- d) turbulence is measured at hub height and the power curve is presented without a turbulence normalization;
- e) the power curve can be normalized to a broader range of climatic conditions (e.g. specific air density, turbulence intensity, vertical shear and veer).

NOTE 6 The power curve normalization is only valid for limited ranges of climatic conditions from the actual site conditions.

In this document, all necessary procedures for measurements, calibration, classification, data correction, data normalization and determination of uncertainties are either provided within this document or referred to in the relevant wind measurement standards. However, if not all parameters are sufficiently measured, then uncertainty shall be applied due to the lack of

measurement. This applies, for example, to the measurement of a power curve of a large wind turbine with only a hub height wind speed sensor. In this case an uncertainty shall be applied for the variability of the wind shear and of the wind veer.

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

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

Wind measurement configuration	1. Meteorology mast at hub height and remote sensing at all heights	2. Meteorology mast below hub height and remote sensing at all heights	3. Meteorology mast above hub height	4. Meteorology mast at hub height
Typical application	Large wind turbines ^a in flat terrain (see Annex B)	Large wind turbines in flat terrain (see Annex B)	Large and small wind turbines in all types of terrain	Large and small wind turbines in all types of terrain
Wind measurement sensors	IEC 61400-50-1 for cup and sonic anemometers and IEC 61400-50-2 for remote sensing	IEC 61400-50-1 for cup and sonic anemometers and IEC 61400-50-2 for remote sensing	IEC 61400-50-1 for cup and sonic anemometers	IEC 61400-50-1 for cup and sonic anemometers
Normalization procedures for climate-specific power curve determination	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density, wind shear; 9.1.5 and 9.1.3.4	Air density; 9.1.5
Additional uncertainty due to lack of wind shear measurement	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	No additional uncertainty dependent on measurement height coverage; E.11.2.2	Additional gross uncertainty for large wind turbines due to lack of vertical wind shear; E.11.2.2
Optional normalization procedures ^b	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4	Turbulence, wind veer and upflow angle; 9.1.6 and 9.1.4. Meteorological mast flow distortion; 9.1.2. Site calibration; Annex C.	Turbulence and upflow angle; 9.1.6. Site calibration; Annex C.
^a Refer to IEC 61400-2 for definition of large and small turbines. ^b Upflow influences the power curve and can be measured with 3D sonic anemometers or upflow vanes. If an upflow angle normalization is applied then the method should be documented (uncertainty on upflow is considered in Annex E). However no specific procedure is described in this document on how to normalize for upflow angle.				

6 Preparation for performance test

6.1 General

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

6.2 Wind turbine and electrical connection

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

6.3 Test site

6.3.1 General

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

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

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

- a) choose the position of the wind measurement equipment;
- b) define a suitable measurement sector;
- c) determine if a site calibration is required then determine the appropriate flow corrections by measurement according to Annex C;
- d) evaluate the uncertainty due to wind flow distortion.

The following factors shall be considered, in particular:

- 1) topographical variations and roughness;
- 2) other wind turbines;
- 3) obstacles (buildings, trees, etc.).

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

6.3.2 Location of the wind measurement equipment

Care needs to be taken in locating the wind measurement equipment. The wind measurement equipment shall not be located too close to the wind turbine, since the wind speed will be influenced in front of the wind turbine. Also, it shall not be located too far from the wind turbine, since the correlation between wind speed and electric power output will be reduced. The wind speed measurement instrumentation shall be positioned at a distance from the wind turbine of between 2 and 4 times the rotor diameter D of the wind turbine. A distance of 2,5 times the rotor diameter D is recommended. In the case of a vertical axis wind turbine, refer to Clause H.3.

Prior to carrying out the power performance test and in selecting the location for the wind measurement equipment, account should be taken of the requirement to exclude measurements from all sectors in which either the wind measurement equipment or the wind turbine will be subject to flow disturbance and hence the wind measurement equipment location should be chosen to ensure that valid sectors remain.

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

6.3.3 Measurement sector

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

For all neighbouring wind turbines and significant obstacles, the directions to be excluded due to wake effects shall be determined using the procedure in IEC 61400-12-5. The disturbed sectors to be excluded due to the wind measuring equipment being in the wake of the wind turbine under test are shown in Figure 1 for distances of $2D$, $2,5D$ and $4D$. Reasons to reduce the measurement sector(s) might be special topographic conditions or unexpected measurement data from directions with complicated structures. All reasons for reducing the measurement sector shall be clearly documented.

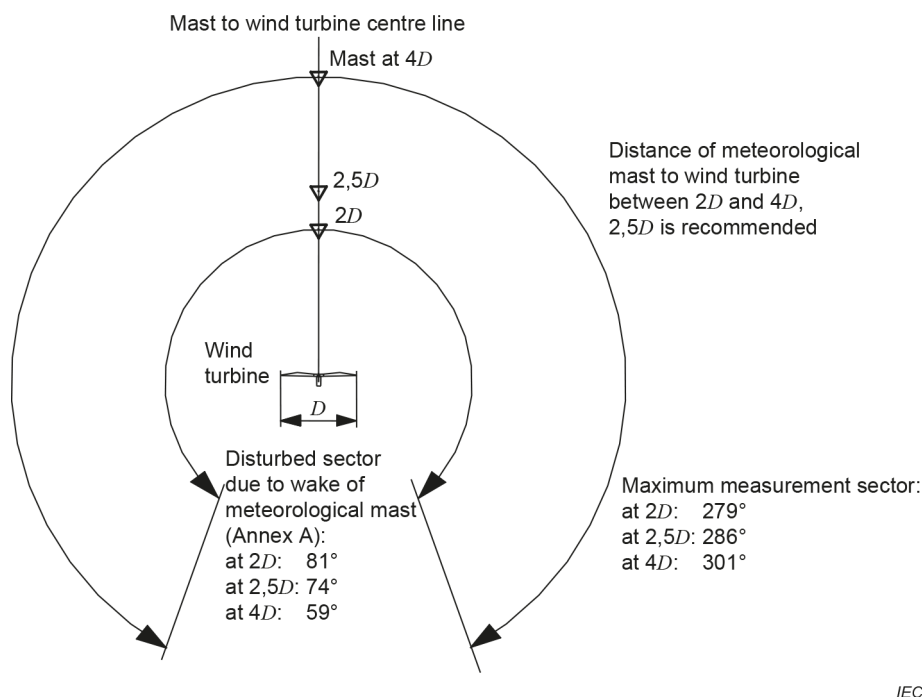


Figure 1 – Requirements as to distance of the wind measurement equipment and maximum allowed measurement sectors

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

The test site shall be assessed for sources of wind flow distortion due to topographical variations. The assessment in Annex B shall identify whether the power curve can be measured without a site calibration. If the criteria of Annex B are met, the wind flow regime of the site does not need a site calibration. However, in assuming that no flow correction is necessary, the applied uncertainty due to flow distortion of the test site shall be a minimum of 2 % of the measured wind speed if the wind measurement equipment is positioned at a distance between 2 and 3 times the rotor diameter of the wind turbine and 3 % or greater if the distance is between 3 and 4 times the rotor diameter, unless objective evidence can be provided quantifying a different uncertainty.

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

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

7 Test equipment

7.1 Electric power

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

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

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

7.2 Wind speed

7.2.1 General

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

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

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

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

The different possible sensor configurations comprise meteorological mast top-mounted and side-mounted anemometers (see IEC 61400-50-1) and remote sensing devices (see IEC 61400-50-2). These provide measurements of hub height wind speed, rotor equivalent wind speed and wind shear profile. IEC 61400-50-1 describes the general, common requirements and procedures for mast top-mounted and side-mounted cup and sonic anemometers wind measurements. IEC 61400-50-2 describes the general common requirements and procedures for remote sensing wind measurements.

7.2.2 General requirements for meteorological mast mounted anemometers

The following requirements apply to all cup and sonic anemometer applications as described in IEC 61400-50-1.

The arrangement of anemometers for power performance tests shall include a primary hub height anemometer and a control anemometer.

The anemometer shall meet the requirements in Annex I and IEC 61400-50-1 for cup and sonic anemometers. For power performance measurements an anemometer with a class better than 1,7A or 1,7C shall be used. Additionally, in terrain that requires a site calibration, it is recommended that a class better than class 2,5B, 2,5D or 1,7S be used; see Annex I, Annex J and IEC 61400-50-1 regarding classification classes.

The anemometer shall be calibrated according to Annex F and IEC 61400-50-1 before the measurement campaign and, if required, calibrated again after the measurement campaign (post-calibration). It is required to check and document that the anemometer maintains the validity of its calibration throughout the measurement period. This can be achieved by comparing the initial calibration results with the outcome of the post-calibration; alternatively, the in-situ anemometer comparison following the procedure in Annex K and IEC 61400-50-1 is permissible.

Where a post-calibration is carried out, the difference between the regression lines of calibration and post-calibration shall be within $\pm 0,1$ m/s in the range 4 m/s to 12 m/s. Only the calibration before the measurement campaign shall be used for the performance test. Calibration of the anemometer shall be made according to the procedure in Annex F and IEC 61400-50-1. If the maximum difference between the regression lines of calibration and post-calibration is outside of $\pm 0,1$ m/s in the range of 4 m/s to 12 m/s, then the standard uncertainty of the anemometer calibration $u_{VS,precal,i}$ shall be increased (at least to this maximum difference, but not to more than $\pm 0,2$ m/s). If the difference is above $\pm 0,2$ m/s then the in-situ anemometer comparison described in Annex K and IEC 61400-50-1 is to be used to identify the point in time when the deviation in the data occurred and the subsequent faulty data shall be rejected. If the in-situ test cannot determine the point at which the deviation began, then the post-calibration difference is added as an uncertainty.

As an alternative, the in-situ calibration procedure described in Annex K and IEC 61400-50-1 shall be used to check the anemometer integrity throughout the measurement period. In this procedure a control anemometer is used to monitor the primary anemometer. Where a cup anemometer is used as the primary anemometer, then either a cup anemometer or a sonic anemometer may be used as the control anemometer. Where a sonic anemometer is used as the primary anemometer, then the control anemometer shall be a cup anemometer. In the case where a REWS derived power curve is obtained from taller than hub height meteorological mast measurements, there shall be a side-mounted primary anemometer at hub height on the mast with an associated control anemometer satisfying the mounting requirements in Annex G and IEC 61400-50-1.

The uncertainty in wind speed measurement derives from several sources of uncertainty as specified in IEC 61400-50-1. Specifically, the uncertainties in calibration, uncertainty due to operational characteristics (classification of anemometry) and uncertainties due to mounting effects shall all be derived from IEC 61400-50-1.

7.2.3 Top-mounted anemometers

Where wind speed measurements are made with a top-mounted anemometer, the requirements given in IEC 61400-50-1 with respect to mounting apply. The installed height of the sensor above ground level shall be verified by measurement and the measurement method and its standard uncertainty documented. For the purpose of defining ground level, an estimate of the mean elevation over a radius of 2 m around the mast base or 5 m radius around the turbine base can be made. The sensor height measurement uncertainty should exclude the uncertainty

of the ground level estimate. For offshore conditions, ground level should be considered as mean sea level.

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

The standard uncertainty of the measurement of the height of the wind speed sensor above the estimated ground level shall be less than or equal to 0,2 m. The control anemometer shall be mounted according to the requirements in IEC 61400-50-1. Where a lightning finial is present and meets the requirements of IEC 61400-50-1 with regard to separation from the top-mounted anemometer and wake interference, then no additional uncertainty due to flow distortion from the finial need be considered.

7.2.4 Side-mounted anemometers

The mounting shall follow the requirement for side-mounted anemometers in IEC 61400-50-1. The installed height of the side-mounted anemometers above ground level (see 7.2.3 for ground level definition and height measurement guidance) shall be verified by measurement and the measurement method and its uncertainty documented. The height measurement standard uncertainty shall be less than or equal to 0,2 m.

An anemometer operating in the wake of the meteorological mast is highly disturbed. Measurements obtained in this condition shall not be used in the power performance analysis.

Correction of side-mounted anemometers for meteorological mast flow distortion is permitted and further described in IEC 61400-50-1. The technical basis for the correction and the effect of the correction shall be documented. The booms shall have identical orientations to ensure similarity of flow distortion between different heights. The meteorological mast and boom design should have similar flow distortion effect at the sensor with a maximum allowed difference in wind speed distortion of 1 % between all different heights. The meteorological mast cross-sectional dimensions should be consistent at each elevation; thus in the case of free-standing meteorological masts where the meteorological mast cross-sectional area is larger at the lower elevations, special care should be taken to follow the recommendations in IEC 61400-50-1. An alternative option is to mount a second anemometer at each measurement height on a separate boom and to limit the measurement sector such that the wind speed measurements do not deviate by more than 1 %.

7.2.5 Remote sensing device (RSD)

Remote sensing devices that assume horizontal flow uniformity through the scanned volume limit the application of these technologies to non-complex terrain conditions for power performance testing as defined by Annex B. The RSD shall be verified before the measurement campaign or in situ according to IEC 61400-50-2. The remote sensing device can be used to measure hub height wind speed, wind shear profile, wind veer and/or the rotor equivalent wind speed based on measurements at more than one height (see 7.2.8). In any case the RSD shall be simultaneously compared with a top-mounted anemometer on a meteorological mast at a height not less than the minimum of the wind turbine rotor lower tip-height or 40 m as defined in IEC 61400-50-2. Requirements on the top-mounted anemometer are identical to those specified in 7.2.3.

The uncertainty of the RSD wind speed measurements shall be derived according to IEC 61400-50-2.

7.2.6 Rotor equivalent wind speed measurement

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

- a) Where a hub height top-mounted anemometer satisfying the requirements of 7.2.3 is used together with an RSD satisfying the requirements of 7.2.5 and the terrain meets the requirements of Annex B, then the measurements from the hub height anemometer and RSD are combined to determine the rotor equivalent wind speed according to 9.1.3.
- b) Where an anemometer not at hub height but otherwise satisfying the requirements for top-mounted anemometers of 7.2.3 is used with an RSD satisfying the requirements of 7.2.5 and the terrain meets the requirements in IEC 61400-12-5:2022, Clause 9, then the RSD measurements are used directly to determine the rotor equivalent wind speed according to 9.1.3.
- c) Where a taller than hub height meteorological mast is used with side-mounted measurements distributed across the rotor height, including an anemometer at hub height, then the side-mounted anemometer wind speed measurements may be used directly to measure the rotor equivalent wind speed according to 9.1.3.

7.2.7 Hub height wind speed measurement

There are three options for measuring hub height wind speed as described in a) to c) as follows.

- a) Where a hub height meteorological mast is used, the hub height wind speed measurements shall meet the requirements described in 7.2.3.
- b) If the terrain meets the requirements in IEC 61400-12-5:2022, Clause 9, then the hub height wind speed can be measured with an RSD meeting the requirements of 7.2.5 and noting specifically the requirement to compare the RSD against a simultaneous top-mounted anemometer.
- c) A meteorological mast that is taller than the hub height may be used to better capture the wind speeds across the rotor area. In this case the hub height wind speed shall be measured with a side-mounted sensor on a boom following the requirements described in 7.2.4.

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

7.2.8 Wind shear measurements

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

Wind shear measurements shall either be performed using side-mounted anemometers as described in 7.2.4 or by a single remote sensing instrument as described in 7.2.5. Further specifications on wind shear measurement using remote sensing instruments or meteorological mast measurements are given in IEC 61400-50-2 and IEC 61400-50-1, respectively.

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

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

- a) $H \pm 1,0 \%$;
- b) between $H - R$ and $H - (2/3R)$;
- c) between $H + (2/3R)$ and $H + R$,

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

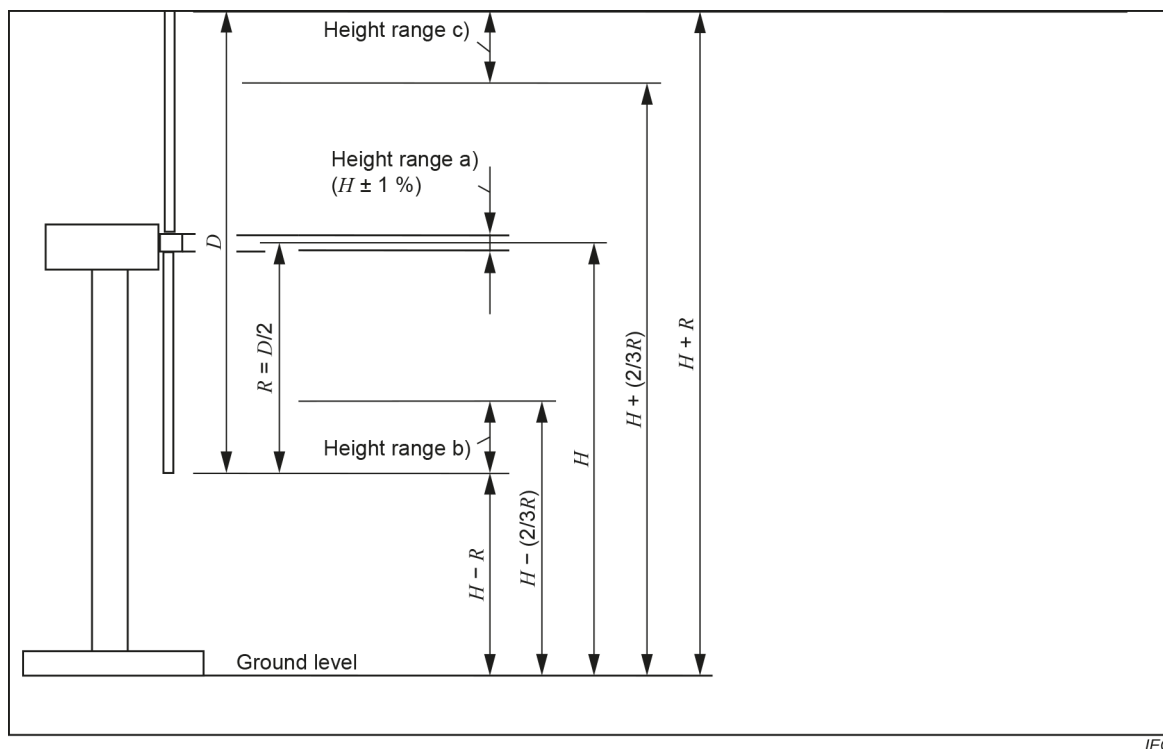


Figure 2 – Wind shear measurement heights appropriate to measurement of rotor equivalent wind speed

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

- a) a side-mounted anemometer as near to hub height as possible whilst still satisfying the requirements in IEC 61400-50-1 for separation from the top-mounted anemometer;
- b) between $H - R$ and $H - (2/3R)$ and satisfying the requirements in IEC 61400-50-1 for side mounted anemometers;

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

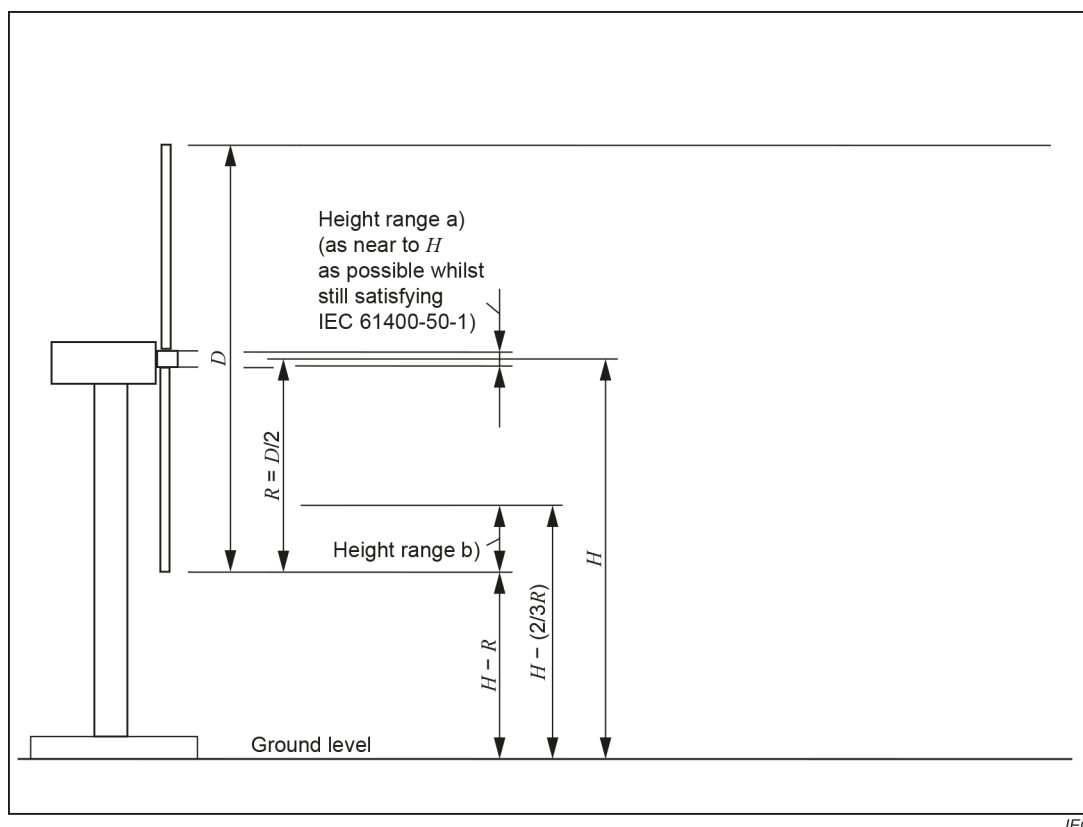


Figure 3 – Wind shear measurement heights when no wind speed measurements above hub height are available (for wind shear exponent determination only)

7.3 Wind direction

Wind direction measurements are used as an input to the site calibration, for filtering data to the valid direction sector and for determining wind veer. Wind direction shall be measured with a wind direction sensor. This may be a wind vane or a 2D or 3D sonic anemometer or an RSD. Where a sonic anemometer is used, it shall be used in conjunction with a conventional wind vane as a control. If an RSD is used, it should be subjected to a verification test on the wind direction according to IEC 61400-50-2.

The instantaneous horizontal wind direction shall be determined and averaged over 10 min. Vector averaging (averaging of cosine and sine components of instantaneous wind direction values taking arctan of the average values and adjusted to the 0° to 360° scale) is one method for deriving the average wind direction. Another method is to extend the wind direction scale for values above 360° and calculating the 10 min average, then adjusting the average value to the 0° to 360° range. Data measured within the dead band of a wind vane, usually at the north mark of the wind direction sensor body, are usually not defined (open circuit or short circuit) and shall be excluded. The combined calibration, operation, and orientation standard uncertainty of the wind direction measurement shall be less than 5°. The wind direction sensor shall be calibrated according to Annex N and IEC 61400-50-1.

7.4 Air density

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

Except in the case where a meteorological mast shorter than hub height is being used in conjunction with a remote sensing device, temperature, barometric pressure and relative

humidity sensors shall be located within 10 m of the hub height on the meteorological mast at a minimum of 1,5 m below the primary anemometer whilst meeting the mounting requirements for other instruments defined in IEC 61400-50-1.

The temperature sensor shall be mounted in a radiation shield.

The barometric 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. Air pressure measurements shall always be corrected to the appropriate hub height according to ISO 2533.

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

If the meteorological mast available for the power performance test is shorter than hub height (specifically when a shorter meteorological mast is used in conjunction with a remote sensing device as defined in Annex L), temperature, humidity and pressure sensors shall be located at a height within 1,5 m to 10 m of the primary anemometer. Atmospheric pressure shall be adjusted to hub height in accordance with this document. Furthermore, the air temperature shall be adjusted to hub height assuming that the atmosphere varies according to ISO 2533. Alternatively, a temperature sensor shall be mounted on the wind turbine nacelle. The sensor shall be mounted at least 1 m above the nacelle and upwind of any existing ventilation systems.

7.5 Rotational speed and pitch angle

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

7.6 Blade condition

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

7.7 Wind turbine control system

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

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

7.8 Data acquisition system

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

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

8 Measurement procedure

8.1 General

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

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

8.2 Wind turbine operation

During the measurement period, the wind turbine shall be in normal operation, as specified in the wind turbine operations manual, and the machine configuration shall not be changed. The operational status of the wind turbine shall be reported as described in Clause 10. Normal maintenance of the wind turbine shall be carried out throughout the measurement period, but such work shall be noted in the test log. Any special maintenance actions, such as frequent blade washing, which ensure good performance during the test shall in particular be noted. Such special maintenance actions should be avoided.

8.3 Data collection

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

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

- a) mean value;
- b) standard deviation;
- c) maximum value;
- d) minimum value.

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

8.4 Data rejection

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

- a) external conditions other than wind speed are out of the operating range of the wind turbine;
- b) the wind turbine cannot operate because of a wind turbine fault condition;
- c) the wind turbine is manually shut down or in a test or maintenance operating mode;
- d) failure or degradation (e.g. due to icing) of measurement equipment;
- e) wind direction outside the measurement sector(s) as defined in 6.3.3;
- f) wind directions outside valid (complete) site calibration sectors;
- g) any special atmospheric condition filtered during the site calibration shall also be filtered during the power curve test.

Any other rejection criteria shall be clearly reported.

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

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

8.5 Database

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

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

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

If a single incomplete bin is preventing completion of the test, then that bin value can be estimated by linear interpolation from the two adjacent complete bins.

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

9 Derived results

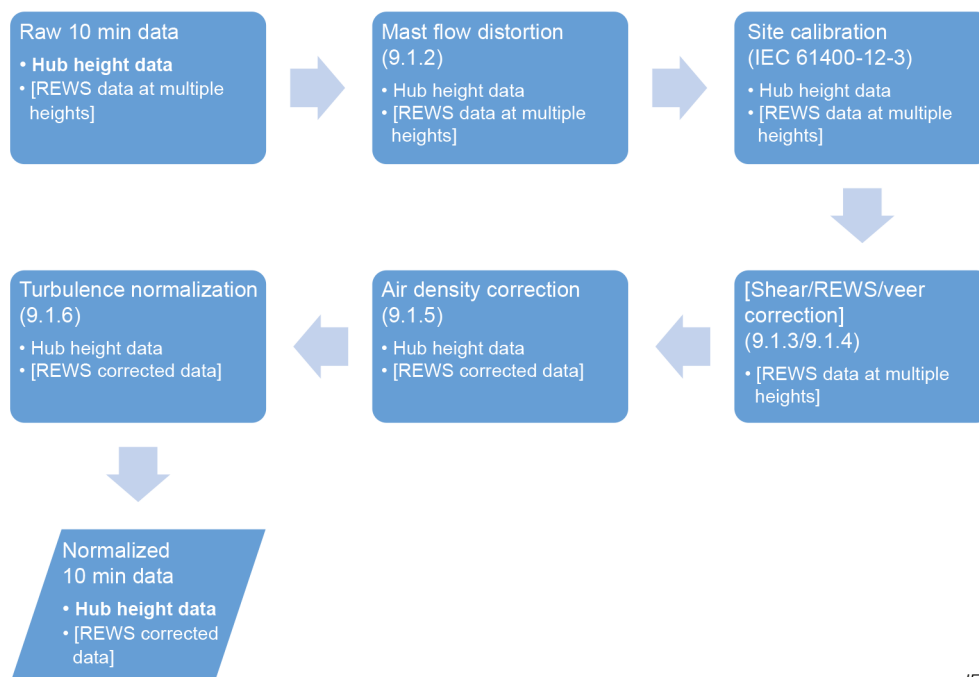
9.1 Data normalization

9.1.1 General

In 9.1.3 to 9.1.6, three methods of normalization are described for the main atmospheric drivers on the power curve results: air density, wind shear, wind veer, and turbulence intensity.

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

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



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

Figure 4 – Process of application of the various normalizations

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

Correction of the wind speeds from side mounted anemometers for meteorological mast flow distortion is permitted (the requirement in Annex S and IEC 61400-50-1 for a maximum of 1 % meteorological mast flow distortion before application of the correction is still required). Any correction method shall be documented and reported following the requirements of Clause 10.

The impact of the meteorological mast flow distortion on the wind shear measurement may be minimized by reducing the measurement sector where meteorological mast flow distortion is below a certain limit. The technical basis for any such reduction in sector width shall be documented. IEC 61400-50-1 gives a possible method for determining the flow distortion correction for a lattice mast.

9.1.3 Wind shear correction (when REWS measurements available)

9.1.3.1 General

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

- the rotor equivalent wind speed;
- the wind shear correction factor;
- the wind shear corrected wind speed.

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

9.1.3.2 Rotor equivalent wind speed

The rotor equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical wind shear. Where the wind speeds for at least three measurement heights are available (see 7.2.6), the rotor equivalent wind speed is defined as:

$$v_{\text{eq}} = \left(\sum_{i=1}^{n_h} v_i^3 \frac{A_i}{A} \right)^{1/3} \quad (5)$$

where

n_h is the number of available measurement heights ($n_h \geq 3$);

v_i is the wind speed measured at height i ;

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

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

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

$$A_i = \int_{z_i}^{z_{i+1}} c(z) dz = g(z_{i+1}) - g(z_i) \quad (6)$$

where

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

The rotor width at height z is:

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

where

R is the rotor radius;

H is the hub height.

The integrated function is:

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

The following is an example of REWS calculation for one 10 min wind speed profile.

In this example, a wind turbine is assumed to have a hub height of 80 m and a rotor diameter of 100 m. The wind speed was measured at five heights with a meteorological mast. If the heights could have been chosen, ideally they would have been evenly distributed (40 m, 60 m, 80 m, 100 m and 120 m). This example shows a case where the heights were fixed independently from the REWS evaluation purpose. The segment limits were set in the middle of two consecutive measurements. The resulting REWS is equal to 9,38 m/s, see Table 3.

Table 3 – Example of REWS calculation

Measurement heights	Wind speed	Segment weighting ^a	Segment inferior limit height (z_i)	Segment superior limit height (z_{i+1})	Segment height
m	m/s	%	m	m	m
116	11,46	16,31	108	130	22
100	10,43	21,04	90	108	18
80	9,24	25,3	70	90	20
60	7,81	23,16	50	70	20
40	6,05	14,24	30	50	20

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

9.1.3.3 Wind shear correction factor

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

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

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

where

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

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

9.1.3.3.2 Case 2: Meteorological mast above hub height

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

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

where

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

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

NOTE $f_{r,MM}$ is for reporting purposes only.

9.1.3.4 Wind shear correction of wind speed

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

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

$$v_{eq,final} = f_{r,RSD} v_{h,MM} \quad (11)$$

9.1.4 Wind veer correction

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

9.1.5 Air density normalization

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

$$\rho_{10min} = \frac{1}{T_{10min}} \left(\frac{B_{10min}}{R_0} - \Phi P_w \left(\frac{1}{R_0} - \frac{1}{R_w} \right) \right) \quad (12)$$

where

ρ_{10min} is the derived 10 min averaged air density;

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

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

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

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

R_w is the gas constant of water vapour, 461,5 [J/kgK];

P_w is the vapour pressure equal to $0,000\,020\,5 \exp(0,063\,184\,6\,T_{10min})$ [Pa];

Vapour pressure P_w depends on mean air temperature over the 10 min.

The selected data sets shall be normalized to at least one reference air density. The reference air density shall be the average of the measured air density of the valid collected data at the site during the test period (see 8.4), or alternatively a pre-defined nominal air density for the site. The average measured air density shall be rounded to the nearest 0,01 kg/m³ and reported in accordance with Clause 10.

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 Equation (13):

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

where

P_n is the normalized power output;

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

ρ_0 is the reference air density.

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

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

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

where

V_n is the normalized wind speed;

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

9.1.6 Turbulence normalization

Wind turbine power curve measurements are influenced by the turbulence intensity. A significant part of the turbulence intensity effect is caused by the averaging of the measured power output and the measured wind speed over 10 min periods. It is recommended to remove this effect from the measurements by normalizing the power curve data to a reference turbulence intensity according to Annex M. The reference turbulence intensity shall be defined prior to the power curve test. It may be defined as a function of the wind speed at hub height. If not defined otherwise, a reference turbulence intensity of 10 % shall be applied. The uncertainty of the turbulence normalization shall be accounted for. If no turbulence normalization of the power curve data is performed, the uncertainty of the power curve due to turbulence effects shall be estimated. As a recommendation use the uncertainty method described in Annex M. Turbulence intensity is measured differently by cup anemometers, remote sensing devices and ultrasonic anemometers. This should be considered when interpreting the results.

9.2 Determination of the measured power curve

The power curve shall be determined based on the hub height wind speed and, if measured, the rotor equivalent wind speed. However, the uncertainty in a power curve derived from hub height measurements only is subject to higher uncertainty due to the lack of knowledge of other influential wind condition parameters. Therefore, to account for the vertical wind shear, wind veer and turbulence intensity and to reduce power curve measurement uncertainty, it is recommended to consider the rotor equivalent wind speed as the representative wind speed and the turbulence normalized power output according to Annex M as the relevant power output. The derivation of power curves based on wind speed normalized for a specific wind shear profile (see Annex P) and the turbulence normalized power output are options that are recommended if a comparison between different power curves is wanted or if the power curves are applied for wind resource assessment.

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

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

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j} \quad (15)$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{n,i,j} \quad (16)$$

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 10 and where REWS power curves are measured, the hub height wind speed power curve shall also be presented. The hub height wind speed power curve shall always be presented for comparison whenever a REWS power curve is measured.

9.3 Annual energy production (AEP)

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

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

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

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

where

AEP is the annual energy production;
 N_h is the number of hours in one year $\approx 8\,760$;
 N is the number of bins;
 V_i is the normalized and averaged wind speed in bin i ;
 P_i is the normalized and averaged power output in bin i .

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

where

$F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;
 V_{ave} is the annual average wind speed;
 V is the wind speed.

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

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

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

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

where

$F(V)$ is now the Weibull cumulative probability distribution function for wind speed;
 V is the wind speed;
 A_w is the Weibull scale factor;
 k is the Weibull shape factor.

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

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

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

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

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

9.4 Power coefficient

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

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

where

- $C_{P,i}$ is the power coefficient in bin i ;
- V_i is the normalized and averaged wind speed in bin i ; (matching the defined wind speed as either rotor equivalent wind speed or hub height wind speed);
- P_i is the normalized and averaged power output in bin i ;
- A is the swept area of the wind turbine rotor;
- ρ_0 is the reference air density.

10 Reporting format

The test report shall contain the following information.

- a) Identification and description of the specific wind turbine configuration under test (see 6.2), including:
 - 1) wind turbine make, type, serial number, production year;
 - 2) rotor diameter and a description of the verification method used or reference to rotor diameter documentation;
 - 3) rotor speed or rotor speed range;
 - 4) rated power and rated wind speed;
 - 5) blade data: make, type, serial numbers, number of blades, fixed or variable pitch, and pitch angle(s);

- 6) hub height and tower type;
 - 7) description of the control system (device and software version) and documentation of status signals being used for data reduction;
 - 8) description of grid conditions at the wind turbine, i.e. voltage, frequency and their tolerances, and a drawing indicating where the power transducer is connected, specifically in relation to an internal or external transformer and self-consumption of power.
- b) A description of the test site (see 6.3), including:
- 1) photographs of all measurement sectors preferably taken from the wind turbine at hub height;
 - 2) a test site map showing the surrounding area covering a radial distance of at least 20 times the wind turbine rotor diameter and indicating the topography, location of the wind turbine, wind measurement equipment, significant obstacles, other wind turbines, and measurement sector;
 - 3) results of site assessment, i.e. the limits of the valid measurement sector(s);
 - 4) if site calibration is undertaken, the limits of the final measurement sector(s) shall also be reported, including the rationale for any changes from the results of the site assessment;
 - 5) a table of the coordinates and elevation of the test wind turbine, wind measurement equipment and any significant obstacles considered in the assessment of obstacles.
- c) A description of the test equipment (see Clause 7):
- 1) identification of all sensors, wind measurement equipment and data acquisition system, including documentation of calibrations of sensors, wind measurement equipment, transmission lines, and data acquisition system;
 - 2) sketch of the arrangement of the meteorological mast showing dimensions of the mast and instrument mounting, to document conformance with IEC 61400-50-1;
 - 3) description of method to ensure the calibration of the wind measurement equipment was maintained over the duration of the measurement period and documentation of results that show that the calibration is maintained.
- d) A description of the measurement procedure (see Clause 8):
- 1) documentation of the procedural steps, test conditions, sampling rate, averaging time, and measurement period, including:
 - documentation of the calibrations, corrections or transfer functions applied by the data logger and/or by post-processing;
 - 2) a test log book that records all important events during the power performance test, including:
 - a listing of all maintenance activities that occurred during the test;
 - a listing of any special actions (such as blade washing) that were completed to ensure good performance;
 - 3) a complete list of all filter criteria used to produce the reported result, including:
 - the parameter, measurement or time period or combination of parameters being filtered on;
 - the range or logical criteria for the filter;
 - the justification for the filter;
 - the order that the filters were applied shall be reported with the number of points removed each iteration. Alternatively, the number of data points the filter would remove from the database by itself;
 - the starting number of datasets in the database and the final number of datasets after all filters have been applied.
- e) Presentation of measured data (see 8.3 to 8.5). Data from each selected data set shall be presented in both tabular and graphical formats, providing statistics of measured power

output as a function of wind speed and of important meteorological parameters including (where REWS measurements are available, the measured data shall be presented separately for both the hub height data and the REWS data):

- 1) scatter plots of mean, standard deviation, maximum, and minimum power output as a function of wind speed (plots shall include information on sample frequency). An example is shown in Figure 5;
 - 2) scatter plots of mean wind speed and turbulence intensity as a function of wind direction;
 - 3) scatter plots of the turbulence intensity as a function of wind speed, and the average turbulence intensity in each wind speed bin shall be presented;
 - 4) special databases consisting of data collected under special operational or atmospheric conditions should also be presented as described above;
 - 5) if measured, rotational speed and pitch angle shall be presented with a scatter plot including binned values versus wind speed and a table with the binned values;
 - 6) definition of status signals and plots of status signals during the measurement period;
 - 7) scatter plots of air density as a function of wind direction and wind speed including average per bin;
 - 8) scatter plot of the wind shear exponent versus time of day and as function of wind speed. The wind shear exponent in the lower rotor half and in the upper rotor half shall be presented separately. In addition, the average values of both wind shear exponents per wind speed bin shall be represented;
 - 9) the average wind shear exponent or equivalent representation of the site wind shear conditions during the test;
 - 10) wind shear correction factor according to 9.1.3.3, if applicable based on measurement set up (use Equation (9) or Equation (10) depending on measurement configuration);
 - 11) the average air density measured during the test.
- f) Presentation of measured power curve for the reference air density (see 9.1 and 9.2) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:
- 1) the power curve shall be presented in a table similar to Table 4. For each wind speed bin, the table shall list:
 - normalized and averaged wind speed;
 - normalized and averaged power output;
 - number of data sets;
 - calculated C_p value;
 - standard uncertainties of category A (see Annex D and Annex E);
 - standard uncertainties of category B (see Annex D and Annex E);
 - combined standard uncertainty (see Annex D and Annex E);

In addition to presenting the measured power curve in a table according to f) 1), the measured power curve can be presented as bin-centre values. The recommended method is to use a cubic spline for interpolation between the bin-values in the table to represent the measured wind speed, power and power coefficient values at the bin centre.
 - 2) the power curve shall be presented in a graph similar to Figure 6. The graph shall show the following as a function of normalized and averaged wind speed:
 - normalized and averaged power output;
 - combined standard uncertainty;
 - 3) the C_p curve shall be presented in a graph similar to Figure 7;
 - 4) both the graph and the table shall state the reference air density used for the normalization;

- 5) if cut-out wind speed has been reached during the measurement period, the power curve and C_p curve – or the parts of the curves influenced by the cut-out hysteresis – can be presented in a similar way to items f) 1), f) 2), f) 3) and f) 4).
- g) Presentation of measured power curves collected under special operational and atmospheric conditions:
 - 1) power curves derived from subsets of the database for special operational or atmospheric conditions might also be reported. If this is the case, a power curve should be reported in the same way as for the reference air density but with the density derived from the average of the measured air density of the subsets of the database or alternatively using a pre-defined nominal air density for the site.
- h) Presentation of estimated annual energy production for the reference air density (see 9.3) for the hub height wind speed derived power curve and also the REWS derived power curve if measured:
 - 1) a table similar to Table 5 for each annual average hub height wind speed shall include:
 - AEP-measured;
 - standard uncertainty of AEP-measured (see Annex D and Annex E);
 - AEP-extrapolated;
 - 2) the table shall also state:
 - reference air density;
 - cut-out wind speed;
 - 3) if at any annual average wind speed AEP-measured is less than 95 % of AEP-extrapolated, the table shall also include the label "incomplete" in the column of values of AEP-measured;
- i) Presentation of measured power coefficient (see 9.4):
 - 1) measured power coefficient should be presented as a function of wind speed in a table and a graph in which the swept area of the rotor shall be indicated.
- j) Presentation of results of site calibration (see IEC 61400-12-3 for reporting requirements):
 - 1) if a site calibration is undertaken, it shall be presented in the report as a table;
 - 2) the table shall for each wind direction bin present:
 - minimum and maximum wind direction limits;
 - the bin-averaged wind direction;
 - the characteristics of the wind speed correction;
 - number of hours of data;
 - combined standard uncertainty of the wind speed ratio for 6 m/s, 10 m/s and 14 m/s;
 - 3) the report shall furthermore include graphs and tables as required in IEC 61400-12-3.
- k) Uncertainty of measurement (see Annex D):
 - 1) uncertainty assumptions on all uncertainty components shall be provided (mast wind measurement uncertainty shall be derived according to IEC 61400-50-1 and remote sensing wind measurements shall be derived according to IEC 61400-50-2).
- l) Deviations from the procedure:
 - 1) any deviations from the requirements of this document 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.