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

**Systèmes de génération d'énergie éolienne –
Partie 12-2: Performance de puissance des éoliennes de production d'électricité
fondée sur l'anémométrie de nacelle**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

**Part 12-2: Power performance of electricity producing
wind turbines based on nacelle anemometry**

FOREWORD

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IEC 61400-12-2 has been prepared by IEC technical committee 88: Wind energy generation systems. It is an International Standard.

This second edition of IEC 61400-12-2 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
88/823/CDV	88/868/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.

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

- reconfirmed,
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INTRODUCTION

This second edition contains no technical changes with respect to the previous edition but the parts that relate to wind measurements, measurement of nacelle transfer functions and assessment of obstacles and terrain have been extracted into separate standards. The separated standards comprise:

- IEC 61400-50, *Wind measurements – Overview*
- IEC 61400-50-1, *Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*
- IEC 61400-50-2, *Wind measurement – Application of ground-mounted remote sensing technology*
- IEC 61400-12, *Power performance measurements of electricity producing wind turbines – Overview*
- IEC 61400-12-1, *Power performance measurement of electricity producing wind turbines*
- IEC 61400-12-2, *Power performance of electricity producing turbines based on nacelle anemometry*
- IEC 61400-12-3, *Power performance – Measurement based site calibration*
- IEC 61400-12-5, *Power performance – Assessment of obstacles and terrain*
- IEC 61400-12-6, *Measurement based nacelle transfer function of electricity producing wind turbines.*

This procedure describes how to characterise a wind turbine's power performance characteristics in terms of a measured power curve and the estimated annual energy production (AEP) based on nacelle-anemometry. In this procedure, the anemometer is located on or near the test turbine's nacelle. In this location, the anemometer is measuring wind speed that is strongly affected by the test turbine's rotor. The procedure provides guidance on determination of measurement uncertainty including assessment of uncertainty sources and recommendations for combining them into uncertainties in reported power and AEP.

The measured power curve is determined by collecting simultaneous measurements of nacelle-measured wind speed and power output 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. In order to accurately measure the power curve, the nacelle-measured wind speed is adjusted using a transfer function to estimate the free stream wind speed. The procedure to measure such a transfer function is given in IEC 61400-12-6. The AEP is calculated by applying the measured power curve to the reference wind speed frequency distributions, assuming 100 % availability.

A key element of power performance testing is the measurement of wind speed. Even when anemometers are carefully calibrated in a quality wind tunnel, fluctuations in magnitude and direction of the wind vector can cause different anemometers to perform differently in the field. Further, the flow conditions close to a turbine nacelle are complex and variable. Therefore special care should be taken in the selection and installation of the anemometer. These issues are addressed in this document.

This document will benefit those parties involved in the manufacture, installation, planning and permitting, operation, utilisation and regulation of wind turbines. When appropriate, 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 environmental concerns. 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 intensity, and from the chosen criteria for data selection. Therefore, a user should consider the influence of these differences and the data selection criteria in relation to the purpose of the test before contracting power performance measurements.

WIND ENERGY GENERATION SYSTEMS –

Part 12-2: Power performance of electricity producing wind turbines based on nacelle anemometry

1 Scope

This part of IEC 61400-12 specifies a procedure for verifying the power performance characteristics of a single electricity-producing, horizontal axis wind turbine that is not considered to be a small wind turbine per IEC 61400-2. It is expected that this document be used when the specific operational or contractual specifications do not comply with the requirements set out in IEC 61400-12-1. The procedure can be used for power performance evaluation of specific turbines at specific locations, but equally the methodology can be used to make generic comparisons between different turbine models or different turbine settings.

The purpose of this document is to provide a uniform methodology of measurement, analysis, and reporting of power performance characteristics for individual electricity producing wind turbines utilising nacelle-anemometry methods. This document is intended to be applied only to horizontal axis wind turbines of sufficient size that the nacelle-mounted anemometer does not significantly affect the flow through the turbine's rotor and around the nacelle and hence does not affect the wind turbine's performance. The intent of this document is that the methods presented in this document be utilised when the requirements set out in IEC 61400-12-1 are not feasible. This will ensure that the results are as consistent, accurate, and reproducible as possible within the current state of the art for instrumentation and measurement techniques.

This document describes how to characterise a wind turbine's power performance in terms of a measured power curve and the estimated AEP. Guidance on uncertainty considerations relating to the power performance of the sample of turbines tested relative to the power performance of all turbines in a wind farm is provided. Guidance on the evaluation of the combined uncertainty for the case where multiple turbines are tested is also provided.

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 60688:2021, *Electrical measuring transducers for converting AC and DC electrical quantities to analogue or digital signals*

IEC 61400-12-1, *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*

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

IEC 61400-12-5:2022, *Wind energy generation systems – Part 12-5: Power performance – Assessment of obstacles and terrain*

IEC 61400-12-6, *Wind energy generation systems – Part 12-6: Measurement based nacelle transfer function of electricity producing wind turbines*

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

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 2533:1975, *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

AEP

annual energy production

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

AEP-measured

measured annual energy production

estimate of the total energy production of a wind turbine during a one-year period by applying the measured power curve to different reference wind speed frequency distributions at hub height, assuming 100 % availability, without power curve extrapolation to higher wind speeds

3.4

AEP-extrapolated

extrapolated annual energy production

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

3.5

complex terrain

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

3.6**data set**

collection of data sampled over a contiguous period

3.7**documentation**

any information regarding the test which is kept in files or data, or both, but which will not necessarily be presented in the final report

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, turbine's rotor, turbine's nacelle or other wind turbines that results in a significant deviation of the measured wind speed from the free stream wind speed

3.10**free stream wind speed**

horizontal wind speed measured upstream of the rotor of the wind turbine generator that is unaffected by rotor aerodynamics

3.11**turbulence intensity**

ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of horizontal wind speed, and taken over a specific period of time

3.12**hub height**

<wind turbines> height of the centre of the swept area of the wind turbine rotor above the ground level at the tower base

3.13**machine configuration change**

change to the turbine or intervention in the turbine operation which causes a significant change in the power performance of the turbine and which is not normal maintenance

Note 1 to entry: Examples of machine configuration change include replacements of hardware components, especially rotor blade, gearbox or generator; a change or update of the turbine software or its parameters; unplanned blade washing; turbine software updates.

3.14**measured power curve**

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

3.15**measurement period**

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

3.16

measurement sector

sector of wind directions from which data are selected for determination of:

- i) the measured power curve
- ii) the nacelle transfer function

3.17

measurement uncertainty

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

3.18

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.

3.19

nacelle

housing which contains the drive train and other elements on top of a horizontal axis wind turbine generator

3.20

NPC

nacelle power curve

measured power performance of a wind turbine expressed as net active electric power output from the wind turbine as a function of free stream wind speed

Note 1 to entry: For the NPC, the free stream wind speed is not directly measured, but rather the nacelle wind speed is measured and a nacelle transfer function is applied to arrive at the free stream wind speed.

3.21

nacelle wind speed

horizontal wind speed measured on top of or in front of the nacelle of a wind turbine

3.22

net active electric power

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

3.23

normal maintenance

any intervention which is done according to a defined regular maintenance program, independent from the fact that a power performance test is being done, 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

3.24

obstacle

object that blocks and distorts the flow of the wind, such as a building or tree

3.25

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

3.26**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

3.27**power performance**

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

3.28**rated power**

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

3.29**report**

any information regarding the test which is stated in the final documentation

3.30**roughness length**

extrapolated height at which the mean wind speed becomes zero if the vertical wind profile is assumed to have a logarithmic variation with height

3.31**site calibration**

procedure that quantifies and potentially reduces the effects of terrain and obstacles by measuring the correlation over wind direction between the wind speed measured at a reference meteorological mast and the wind speed measured at the wind turbine position

3.32**standard uncertainty**

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

3.33**swept area**

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

Note 1 to entry: For teetering rotors, it should be assumed that the rotor remains normal to the low-speed shaft.

3.34**test site**

location of the wind turbine under test and its surroundings

3.35**turbine online**

status of the wind turbine, during normal operation excluding cut-in or cut-out, but including any operation at rotor speed in normal operating range where the turbine briefly disconnects from the grid, e.g. switching between generators, generator stages, star/delta or similar

3.36**wind shear**

variation of wind speed across a plane perpendicular to the wind direction

4 Symbols, units and abbreviated terms

Symbol or abbreviated term	Description	Unit
A	swept area of the wind turbine rotor	[m ²]
AEP	annual energy production	[Wh]
AEP _m	the measured AEP on turbine m	[Wh]
AEP _s	sum of annual energy production	[Wh]
ASL	above sea level	[m]
B	barometric pressure	[Pa]
$B_{10\text{min}}$	measured air pressure averaged over 10 minutes	[Pa]
C_p	power coefficient	
$C_{p,i}$	power coefficient in bin i	
c	sensitivity factor on 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 v	
$c_{l,j}$	sensitivity factor of component l in bin j	
$c_{M,i}$	sensitivity factor of air density correction in bin i	[W/m ³ kg]
$c_{m,k,i}$	sensitivity factor of component k in bin i on turbine m	
$c_{n,l,j}$	sensitivity factor of component l in bin j on turbine n	
$c_{T,i}$	sensitivity factor of air temperature in bin i	[W/K]
$c_{V,i}$	sensitivity factor of wind speed in bin i	[W/ms ⁻¹]
$F(V)$	the Rayleigh cumulative probability distribution function for wind speed	
f_i	the relative occurrence of wind speed between $V_i - 1$ and V_i ($F(V_i) - F(V_i - 1)$) within bin i	
NT	number of tested turbines	
L	distance between turbine and met mast ($2,5D$) in terms of rotor diameters	
l_X	contribution factor for source X, as per Table D.4	
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 $\approx 8\,760$	
N_i	number of 10-minute data sets in wind speed bin i	
N_m	number of bins on turbine m	
N_n	number of bins on turbine n	
N	number of samples within sampling interval	
NPC	nacelle power curve	

Symbol or abbreviated term	Description	Unit
NTF	nacelle transfer function	
P_i	normalised and averaged power output in bin i	[W]
P_n	normalised power output	[W]
$P_{n,i,j}$	normalised power output of data set j in bin i	[W]
P_{10min}	measured power averaged over 10 minutes	[W]
P_w	the water vapour pressure	[Pa]
R_0	the gas constant (=287,05)	[J/(kg × K)]
R_w	the gas constant of water vapour (=461,5)	[J/(kg × K)]
s^{NTF}	uncertainty component of category A stemming from the nacelle transfer function	
s	uncertainty component of category A	[W]
$s^{AEP,k}$	uncertainty in AEP from category A component k	[W]
$s^{AEP,m,k}$	uncertainty in AEP from category A component k on turbine m	[W]
$s_{k,i}$	category A standard uncertainty of component k in bin i	[W]
s_i	combined category A uncertainties in bin i	[W]
$s_{P,i}$	category A standard uncertainty of power in bin i	[W]
se^{AEP}	standard error in the mean AEP of the sample	[Wh]
T	absolute temperature	[K]
T_{10min}	measured absolute air temperature averaged over 10 minutes	[K]
u	uncertainty component of category B	
$u_{dB,i}$	uncertainty component of category B for the data acquisition system for atmospheric pressure	
u^{AEP}	combined standard uncertainty in the estimated annual energy production	[Wh]
$u^{AEPratio}$	ratio of the uncertainty of the AEP and the total AEP	[Wh]
$u^{AEP,AVG}$	uncertainty in the average AEP	[Wh]
$u^{AEP,i}$	uncertainty in AEP for turbine i	
$u^{AEP,k}$	uncertainty in AEP from category B component k	[Wh]
$u^{AEP,m,k}$	uncertainty in AEP from category B component k on turbine m	[Wh]
$u_{B,i}$	category B standard uncertainty of air pressure in bin i	[W]
$u_{c,i}$	combined standard uncertainty of the power in bin i	[W]
u_{FS}	uncertainty component for free stream wind speed	[W]
u_i	combined category B uncertainties in bin i	
$u_{k,i}$	category B standard uncertainty of component k in bin i	[W]
$u_{m,k,i}$	standard uncertainty of component k in bin i on turbine m	[W][kg/m ³]
$u_{l,j}$	standard uncertainty of component l in bin j	[W]
$u_{m,i}$	category B standard uncertainty of air density correction in bin i	

Symbol or abbreviated term	Description	Unit
$u_{n,l,j}$	standard uncertainty of component l in bin j on turbine n	
$u_{P,i}$	category B standard uncertainty of power in bin i	[W]
$u_{\text{PARK AEP}}$	combined uncertainty of the wind farm AEP estimate	[Wh]
$u_{V,i}$	category B standard uncertainty of wind speed in bin i	[W]
$u_{V,k,i}$	standard uncertainty of wind speed component k in bin i	
u_{WD}	wind direction uncertainty	[°]
u_{dWD}	uncertainty of the data acquisition of the wind direction	[°]
$u_{\text{WD,SENSOR}}$	wind direction uncertainty, nacelle measured	[°]
$u_{\text{WD,YAW}}$	wind direction uncertainty, yaw component	[°]
$u_{T,i}$	category B standard uncertainty of air temperature in bin i	[K]
V	wind speed	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_{free}	measured nacelle wind speed, corrected with the nacelle transfer function	[m/s]
V_i	normalised and averaged wind speed in bin i	[m/s]
V_n	normalised wind speed	[m/s]
$V_{n,i,j}$	normalised wind speed of data set j in bin i	[m/s]
WTG	wind turbine generator	
X	the size of the population, typically the number of turbines in the wind farm	
ρ	correlation coefficient	
$\rho_{k,l,i,j}$	correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j	
$\rho_{k,m,n}$	correlation coefficient between turbine m and turbine n for component k	
$\rho_{k,m,i,l,j,n}$	correlation coefficient between uncertainty component k in bin i on turbine m and uncertainty component l in bin j on turbine n	
$\rho_{m,n,k,l,i,j}$	correlation coefficient between uncertainty component k in bin i on turbine m and uncertainty component l in bin j on turbine n	
ρ_0	reference air density	[kg/m ³]
$\rho_{10\text{min}}$	derived air density averaged over 10 minutes	[kg/m ³]
$\rho_{\text{ubi},m,n}$	correlation coefficient for pressure	
$\rho_{\text{umi},m,n}$	correlation coefficient for method	
$\rho_{\text{upi},m,n}$	correlation coefficient for electric power	
$\rho_{\text{sp},m,n}$	statistical correlation coefficient	
$\rho_{\text{uti},m,n}$	correlation coefficient for temperature	
$\rho_{\text{uvi},m,n}$	correlation coefficient for wind speed	
σ	standard deviation	
$\sigma_{P,i}$	standard deviation of the normalised power data in bin i	[W]
Φ	relative humidity (range 0 to 1)	

5 Overview of test method

This "nacelle-anemometry" power performance measurement method is similar to the standard method described in IEC 61400-12-1 in that data are obtained to characterise a wind turbine's power curve – that is power as a function of free stream wind speed. In both methods free stream wind speed is the horizontal component of free stream wind that would exist at the position of the centre of the turbine's rotor if the turbine were not present to obstruct the wind. In the IEC 61400-12-1 method, an anemometer is placed on a meteorological tower between 2 and 4 rotor diameters distance to the turbine. In flat terrain, this position provides a reasonably good estimate of the wind speed that would be at the turbine if the turbine were not present. In complex terrain, a site calibration corrects for the distortion of wind speed between the meteorological tower and the position at the centre of the turbine's rotor.

In this nacelle-anemometry method, wind is measured using an anemometer mounted on or in front of the turbine's nacelle. This position is relatively close to the centre of the turbine's rotor so surrounding terrain and obstacles have less potential to distort the wind between the desired and the actual measurement positions. However, the turbine's rotor and nacelle distort the wind significantly. Therefore it is necessary to quantify this distortion and to account for it in the test procedure. This method defines criteria to determine if a nacelle transfer function (NTF) is valid for a certain turbine.

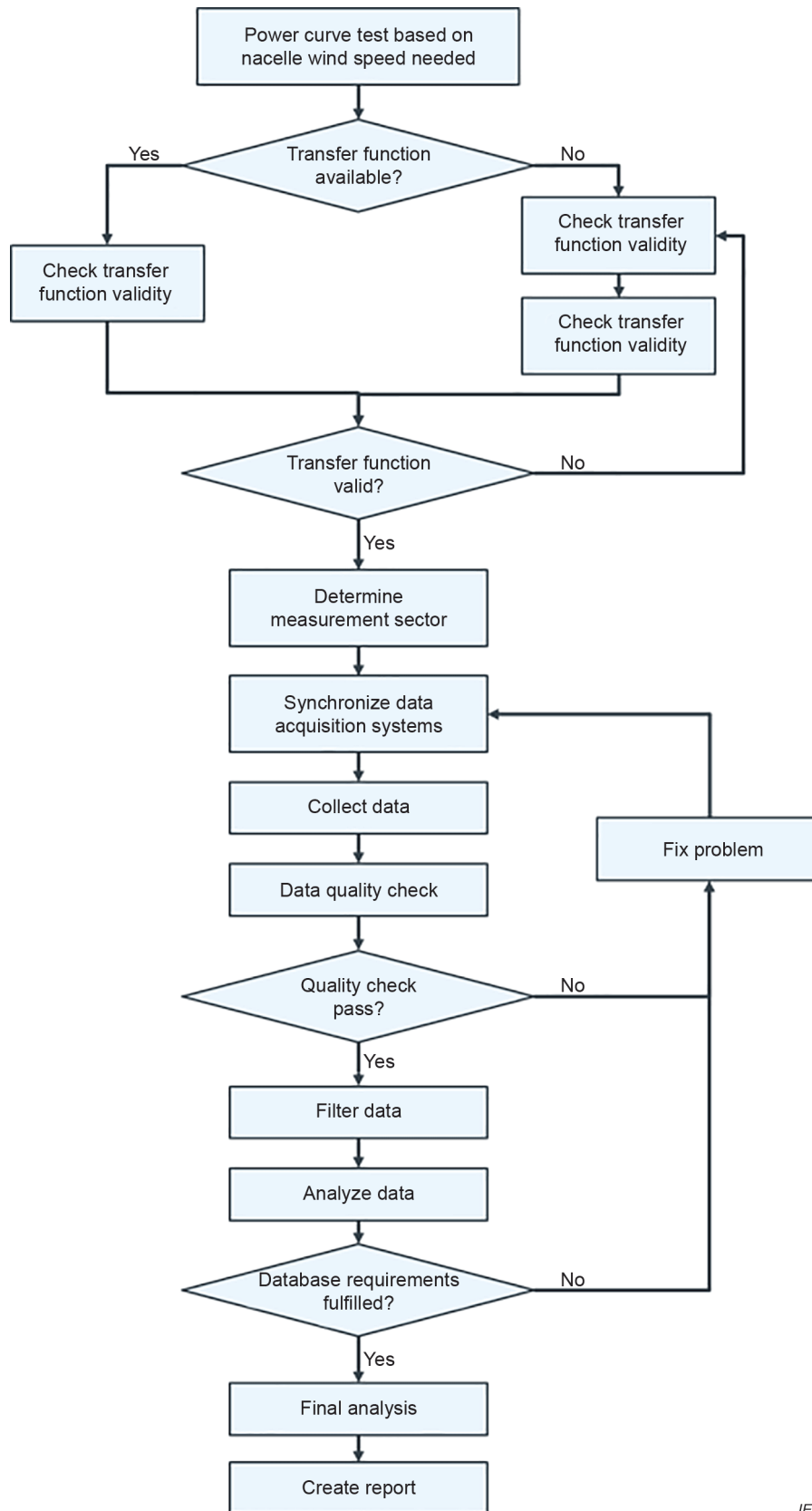
Once the transfer function is obtained by application of IEC 61400-12-6, the nacelle-anemometry method to establish a power curve, the nacelle power curve (NPC), is similar to the IEC 61400-12-1 method. In this document this part of the method is called the "performance test". Similar data to that required by the IEC 61400-12-1 test is obtained on wind speed (nacelle based wind speeds rather than meteorological tower wind speeds), wind direction (through turbine yaw position and wind vane rather than use of a wind vane on a meteorological tower), electrical power, air temperature, air pressure, and other conditions. The transfer function is applied to the measured wind speed in a manner analogous to that used for site calibration corrections. Valid data are selected and binned and the NPC is presented in tabular and graphical formats. AEP and the measurement uncertainties are determined and reported.

The following points shall be duly noted when using the method described in this document. The definition of the resulting power curve is not identical to that of IEC 61400-12-1, as the transfer function can only be established and applied when the rotor is extracting power from the wind (i.e. turbine online). As a consequence, the power curve determined according to this document does not consider occurrences during which the wind turbine is not online while it is available (start-up, stand-by for internal check, hysteresis effects, etc.). In this respect, the power curve is similar to, but not coincident with, the power curve B of IEC 61400-12-1. In extreme cases the mean power output given by the power curve determined according to this document may be significantly larger, and the AEP overestimated, as compared to IEC 61400-12-1.

Furthermore, this method is based on the assumption that the terrain effects can be separated from the rotor effects, i.e. the terrain effects are captured in the site calibration whereas the rotor effects are captured in the transfer function. The assumption that all terrain effects are captured in the site calibration also underlies the IEC 61400-12-1 methodology. However, the validity of this assumption has a stronger effect in the methodology of this document. For that reason additional uncertainty contribution due to terrain effects are taken into account. Finally, this method is based on the assumption that the transfer function and resulting power curve are not seasonally dependent. There is sufficient evidence to doubt this assumption. Therefore the uncertainty assessment reflects seasonal dependency. The user of this document is cautioned to be aware of these issues when applying this document in practice.

Note that a site calibration is not relevant to the measurement of a nacelle power curve. However, a site calibration may be required to determine the NTF.

A graphical representation of the overall nacelle power curve test method can be seen in Figure 1.



IEC

Figure 1 – Procedural overview

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 documented and reported, as detailed in Clause 10.

6.2 Wind turbine

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

The turbine configuration has significant influence on the measured nacelle power curve of the wind turbine. In particular, nacelle and rotor-based flow distortion effects will cause the wind speed as measured at the turbine nacelle to be different from, though correlated to, the free stream wind speed.

The nacelle wind speed transfer function should be measured on a turbine in similar terrain to the turbine to which the NTF will be applied to determine the NPC. If this is not possible then the NTF should be measured in flat terrain.

The turbine configuration shall be assessed for sources of influence on the NTF in order to:

- a) determine the validity of a previously generated nacelle transfer function (Annex A);
- b) evaluate the uncertainty due to wind flow distortion (Annex B, Annex C and Annex D).

All checks in accordance with Annex A shall be done as part of the wind turbine assessment.

The turbine configuration shall be reported as detailed in Clause 10.

6.3 Test site

Conditions at the test site may significantly increase uncertainty in power performance measurements. Although the proximity of the nacelle anemometer to the desired measurement position (the rotor centre) reduces the distortion that exists between an anemometer that is mounted on a meteorological tower and the turbine rotor, topography and obstructions may still influence test results.

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

- a) define a suitable measurement sector taking the location of obstacles and the terrain classification into consideration;
- b) evaluate the uncertainty in the power curve due to wind flow distortion.

The following factors shall be considered, in particular:

- 1) topographical variations and reference roughness length (as defined in IEC 61400-12-1);
- 2) other wind turbines;
- 3) turbulence as function of wind speed and wind direction;
- 4) obstacles (buildings, trees, etc.).

Two factors are particularly important:

- First, other turbines or significant obstacles upwind of the test turbine produce wakes that influence both the test turbine's power production and the nacelle anemometer's measurements. There are currently no techniques available to minimise this interference with the measurement campaign. Therefore wakes shall be avoided.

- Second, topographical variations may change the vertical angle of the wind vector at the turbine. Depending on the position of the anemometer on the nacelle, the nacelle transfer function may be altered significantly by changes in the vertical angle of wind. Therefore, the relationship of local wind speed at the nacelle anemometer to vertical wind angle should be assessed. Based on this relationship and test site topology, certain wind directions may be excluded.

The measurement sector shall be determined using the procedure described in IEC 61400-12-5. It is strongly recommended that care be taken such that the average slopes of the 10° direction sectors making up the whole measurement sector have the same sign – i.e. the terrain in the measurement sector is either sloping down towards the turbine or sloping up towards the turbine. A measurement sector that mixes up and down slopes becomes difficult as the NTF is sensitive to this. Therefore, the measurement sector shall be restricted to slopes of the same sign and only an NTF derived for a slope of the same sign and satisfying the other terrain classification validity requirements (6.4) can be used.

The test site and the measurement sector shall be reported as detailed in Clause 10.

6.4 Nacelle wind speed transfer function

This method of determining power performance of a wind turbine requires a nacelle wind speed transfer function. This transfer function predicts what the free stream wind speed would be at the position of the centre of the turbine rotor if the turbine were not present using wind speed measured by a nacelle-mounted anemometer.

If a transfer function is not available then the nacelle wind speed transfer function shall be measured in accordance with the procedure specified in IEC 61400-12-6. If a transfer function is available then it shall be checked for validity using Annex A. If the transfer function is found to be valid then it can be used for the NPC, otherwise the nacelle wind speed transfer function shall be measured in accordance with the procedure in IEC 61400-12-6.

If, during an NPC measurement, an NTF is used that has previously been measured in the same park, it may be applied to turbines with a terrain classification differing maximum one terrain class from the terrain class during the NTF measurements; the terrain shall also have the same sign of terrain slope in the measurement sector. (Note that this may apply to a park where the park is built across a range of terrain classes.)

If, during an NPC measurement, an NTF is used that has previously been measured in another park, it may only be applied to turbines with a terrain classification that is the same as the terrain class during the NTF measurements; the terrain shall also have the same sign of terrain slope in the measurement sector.

The terrain complexity is classified according to IEC 61400-12-5:2022, Clause 10. The uncertainty related to this NTF shall be evaluated as detailed in IEC 61400-12-6.

6.5 Test plan

A test plan shall be prepared prior to the test that addresses the information covered in Clause 10 of this document to the extent that it can be determined prior to the tests. The guidelines in Annex H should also be considered regarding the organisation of the test, safety and communication.

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. Both the current and voltage transformers shall be class 0,5 or better.

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

The power measurement equipment (current transformer, voltage transformer, power measurement device) shall be calibrated traceable to national standards. Alternatively, an in-situ comparison may be done to a calibrated energy meter. The in-situ procedure used as well as the results shall be documented.

7.2 Wind speed

Nacelle wind speed shall be measured according to IEC 61400-50-1. Further requirements on nacelle wind speed are presented in Annex E.

7.3 Wind direction

Nacelle wind direction shall be measured according to IEC 61400-50-1.

7.4 Air density

Air density shall be derived from the measurement of ambient air temperature and ambient absolute air pressure using Equation (3) (see Clause 9). At high temperatures, it is also recommended that the ambient relative air humidity be measured and that the air density be corrected to account for the effect of the air humidity using Equation (1).

$$\rho = \frac{1}{T} \left(\frac{B}{R_0} - \phi P_w \left(\frac{1}{R_0} - \frac{1}{R_w} \right) \right) \quad (1)$$

Where

- B is the barometric pressure [Pa];
- T is the absolute temperature [K];
- ϕ is the relative humidity (range 0 to 1)
- R_0 is the gas constant of dry air [287,05 J/kgK];
- R_w is the gas constant of water vapour [461,5 J/kgK];
- P_w is the vapour pressure [Pa];

$$P_w = 0,000\,020\,5e^{0,063\,184\,6T} \quad (2)$$

Where vapour pressure P_w depends on mean air temperature.

Air temperature, pressure, and humidity measurements shall measure the ambient air conditions (i.e. not internal nacelle conditions). If the air pressure sensor is mounted on the turbine it shall be placed such that the measurement is not affected by the blades or by other equipment from the turbine such as the ventilation system.

The temperature sensor (and humidity sensor when used) shall be mounted within 10 m of hub height, either on the turbine itself or on a local meteorological tower within a distance of four rotor diameters from the turbine. The temperature sensor shall measure the ambient outside air temperature without influence from the turbine equipment, e.g. ventilation or heating systems. If humidity is not measured and a correction for humidity at high temperatures is needed, then a value of $\phi = 0,5$ shall be used in Equation (1).

The air pressure shall be measured within 5 km from the turbine and shall be synchronised with the NPC measurement system to within 10 min. If the air pressure sensor is not mounted close to rotor centre altitude above sea level (ASL), air pressure measurements shall be corrected to the rotor centre altitude ASL according to ISO 2533.

The combined uncertainty of the temperature signal shall be less than 3 °C. The combined uncertainty of the air pressure signal shall be less than 10 hPa.

7.5 Rotor speed

The turbine rotor speed should be measured or verified by checking that the relevant parameter settings of the turbine have not changed during the test duration. This measurement will be used to ensure the validity of the application of the NTF.

7.6 Pitch angle

The turbine blade pitch angles are recommended to be measured or verified by checking that the relevant parameter settings of the turbine have not changed during the test duration. This measurement will be utilised to ensure the validity of the application of the nacelle wind speed transfer function.

7.7 Wind turbine status

Sufficient status signals shall be identified, verified and monitored to allow the rejection criteria of 8.6 to be applied. The status signal shall identify curtailed situations such as noise reduced operation or power deregulation conditions. Typically, a generator grid connection status signal is sufficient. Obtaining these parameters from the turbine controller's data system, if available, is adequate. Obtaining an "availability" status signal to ascertain the operational status of the wind turbine (available or not available) is recommended. The definition of each status signal shall be reported.

It is recommended to keep track of online and offline operation of the turbine as described in Clause 10 (Table 1).

7.8 Data acquisition

A data acquisition system having a sampling rate per channel of at least 1 Hz shall be used to collect measurements and store pre-processed data.

The turbine controller data system (i.e. SCADA system) may be used for data acquisition as long as it fulfils the requirements and gives sufficient insight into the traceability of the signals and signal processing.

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

comparing these inputs against the recorded readings. This shall be done using instrumentation that is calibrated traceable to national standards. As a guideline, the uncertainty of the data acquisition system should be negligible compared with the uncertainty of the sensors.

Any influence or operation performed by the data acquisition system on the data shall be reported. The following checks shall be done:

- a) any averaging or filtering of the data by the data acquisition system shall be reported in such detail that its effect on the data and the uncertainty of the data can be established;
- b) any internal calibrations, applied offsets or corrections applied to the data shall be reported in such detail that the calibrations, applied offsets or corrections can be undone during data processing;
- c) the uncertainty of the whole signal chain shall be calculated for each signal;
- d) a correct treatment of the wind direction north jump (360° to 0° transition or vice versa) averaging shall be verified.

If the conditions in this Subclause 7.8 cannot be fulfilled due to the fact that a turbine controller data system is used, a separate, independent data system that is capable of fulfilling these requirements shall be installed and used instead.

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 accurately determine the power performance characteristics of the wind turbine. The measurement procedure shall be reported, 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 measurement uncertainty, as described in Annex B. During the measurement period, data shall be periodically checked to ensure high quality and repeatability of the test results. These checks shall be reported. Test logs shall be maintained to document all important events during the power performance test.

8.2 Wind turbine operation

During the measurement period, the wind turbine shall be in normal operation, as prescribed in the wind turbine operations manual (or equivalent), and the machine configuration shall not be changed. The operational status of the wind turbine shall be documented by the status signals as described in Clause 7 and it shall be stated in the report that the operational status has not changed throughout the test. Normal maintenance of the turbine shall be carried out throughout the measurement period, and such work shall be noted in the test log. Any special maintenance actions, such as frequent blade washing, which ensure good performance during the test shall in particular be noted. Such special maintenance actions shall by default not be made unless agreed by contractual parties prior to commencement of the test.

8.3 Data system(s) synchronisation

If during one test the signals are measured with more than one data acquisition system, the synchronisation of all systems shall be ensured throughout the measurement period. The maximum synchronisation difference between any two data acquisition systems shall be less than 1 % of the averaging time. Any violation of this synchronisation requirement shall be reported. The pressure measurement is excluded from this criterion.

It is recommended to avoid synchronisation problems by measuring with one single measurement system. The recommended time convention is coordinated universal time (UTC)

or a reference to the UTC time base. The time correction applied for each update shall be logged. The selected time reference shall be reported.

8.4 Data collection

Data shall be collected continuously at a sampling rate of 1 Hz or faster. The data acquisition system should as a minimum store statistics of data sets of all signals as follows:

- a) 10-min mean value;
- b) 10-min standard deviation;
- c) 10-min maximum value;
- d) 10-min minimum value.

If the data collection system present in the turbine cannot do this for all signals, then the 10-min minimum, 10-min maximum, 10-min standard deviation and 10-min mean shall be stored for all wind speed and power signals. For the other signals storing a 10-min mean signal will suffice.

Selected data sets shall be based on 10-min periods derived from contiguous measured data. Data shall be collected until the requirements defined in 8.8 are satisfied.

The standard analysis will be based on the 10-min statistics of the measured data. This has been chosen to keep the results closely linked to IEC 61400-12-1.

It is important to note that the choice to use 10-min statistics in itself influences the result of the power performance test, for instance through the effect of turbulence. Originally, the 10-min period was selected, amongst other reasons, to allow for the time the wind needs to flow from mast to turbine and to ensure reasonable correlation between wind speed and power. In the case of nacelle anemometry, this is no longer needed and there are arguments to reduce the averaging time to a period of less than 10 min.

In order to keep the link with IEC 61400-12-1 and at the same time not prevent more accurate reporting, the choice has been made to always report the standard result based on 10-min statistics, but to allow analysis based on shorter averaging periods to be reported as well. The validity of the applied transfer function shall be checked when using shorter averaging periods.

8.5 Data quality check

8.5.1 General

To ensure the data included in the final valid database of results are accurate, quality control steps shall be performed on the data during, or prior to, the data reduction and analysis process. Subclauses 8.5.2 to 8.5.5 list examples of quality control methods, but do not include all methods that may be required. Data points that fail to meet the quality control criteria defined by the user shall be removed from the valid database. All data filtering methodology shall be reported thoroughly as required by Clause 10. These steps are in addition to the check/calibration of the measurement system as described in 7.8.

8.5.2 Measured signals are in range and available

Ensure that each data set in which a required signal is outside the signal range is excluded from the valid database. Similarly, exclude data sets in which one or more of the required signals are unavailable or not operating for one or more samples. These exclusions shall be reported and described as per the requirements listed in Clause 10.

8.5.3 Sensors are operating properly

The individual data set average, maximum, minimum and standard deviation statistics of the measured signals shall be checked periodically to ensure the values are consistent with the expected values (e.g. no significant signal noise or data when the sensors are influenced by

their mounting structure or other sensors). Manually interrogating time-series and/or scatter plots of a subset of the measured data (database sampling) is suggested, in addition to automated techniques, in order to ensure all irregularities are identified. Additionally, compare like signals to each other (e.g. primary and control wind speed on meteorological tower; turbine-measured power and independent power signal; turbine yaw position to meteorological tower, or nearby wind direction measurement) to ensure the deviations are consistent with the expected values. Suspect data should be excluded from the valid database. These exclusions shall be reported and described as per the requirements listed in Clause 10.

8.5.4 Ensure data acquisition system(s) is/are operating properly

Steps should be taken to verify that the data acquisition system operates properly throughout the measurement period. These steps include, but are not limited to:

- a) ensuring data records are not repeated;
- b) investigating the cause for any significant data gaps in measured signals;
- c) investigating any discontinuities in measured signals that do not correspond to data gaps.

If any issues are found, these findings shall be documented and reported. The checks themselves shall also be reported.

8.5.5 Sector self-consistency check

Once a (draft) NPC is available the sector self-consistency check in IEC 61400-12-5:2022, 8.2 shall be done.

8.6 Data rejection

Certain data sets shall be excluded from the database to ensure:

- a) analysis and results are commensurate with normal operating conditions of the turbine;
- b) corrupted and inaccurate data are excluded.

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

- 1) external conditions other than wind speed are out of the operating range of the wind turbine;
- 2) external conditions are out of the operating range of the test instruments;
- 3) turbine is not online (except for turbines that temporarily go offline as part of normal operation, e.g., generator switching. These effects shall be captured in the power curve and the precise filter applied shall be reported);
- 4) turbine is output-limited by external factors such as the power grid; this shall be documented in situ, for instance with a logbook or status-signal from the turbine;
- 5) failure or degradation (e.g. due to icing) of test equipment;
- 6) 10-min average wind direction outside the measurement sector;
- 7) blade icing events and snow cover on the nacelle;
- 8) wind speed is out of the applicability range of the nacelle wind speed transfer function;
- 9) data from time periods where the NTF is not valid shall be excluded (i.e. wrong parameter settings in the turbine);
- 10) turbine cannot operate because of a turbine fault condition;
- 11) turbine is manually shut down or in a test or maintenance operating mode.

Any other rejection criteria shall be clearly reported. All data rejected for these reasons shall be clearly documented and reported.

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

turbulence intensity, wind shear) that occur during the measurement period may be selected as special databases.

If it is to be expected that the grid frequency varies by more than 1 % during an average time of 600 s, the grid frequency shall be measured. Measurement data collected when the grid frequency is outside the nominal grid frequency ± 1 % shall be separately classified or shall be neglected.

8.7 Data correction

For the selected data sets the following data corrections shall be made to the following measurements:

- a) air pressure correction to rotor centre altitude ASL (if required by 7.4);
- b) the absolute wind direction shall be calculated from the nacelle yaw position and the nacelle vane signal;
- c) signal modifications applied by the wind turbine controller shall be taken into account to ensure correct final values;
- d) data may be corrected for any calibrations, applied offsets or corrections performed by the data acquisition system in order to ensure the highest data quality, as applicable and as long as clearly reported;
- e) nacelle wind speed shall be corrected to free stream wind speed using a valid transfer function based on a measurement according to IEC 61400-12-6;
- f) any other corrections made to the data shall be reported clearly and in detail.

The data correction details shall be reported as detailed in Clause 10.

8.8 Database

After data normalisation (see 9.1) the selected data sets shall be sorted using the "method of bins" procedure (see 9.2). The selected data sets shall at least cover a wind speed range extending from 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 cut-in to a wind speed at which "AEP-measured" is greater than or equal to 95 % of "AEP-extrapolated" (see 9.3). The report shall state which of the two definitions has been used to determine the range of the measured power curve. The wind speed range shall be divided into 0,5 m/s contiguous bins centred on multiples of 0,5 m/s.

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

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

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

In order to complete the power curve at high wind speeds the following procedure can be used. For wind speeds above 1,6 times the wind speed at 85 % of rated power the measurement sector can be opened.

The following condition has to be fulfilled when using the above two extended procedures: AEP-measured from extended procedures deviates less than 1 % from AEP-extrapolated up to the highest complete wind speed bin for the extended procedures (for the Rayleigh distribution in 9.3).

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

9 Derived results

9.1 Data normalisation – Density correction

The air density shall be determined from measured air temperature, air pressure and relative humidity according to the equation:

$$\rho_{10\min} = \frac{1}{T_{10\min}} \left(\frac{B_{10\min}}{R_0} - \phi P_w \left(\frac{1}{R_0} - \frac{1}{R_w} \right) \right) \quad (3)$$

where

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

T is the measured absolute air temperature averaged over 10 min;

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

R_0 is the gas constant of dry air 287,05 J/(kgK);

ϕ is the relative humidity (range 0 to 1);

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

P_w is the vapour pressure [Pa].

$P_w = 0,000\,020\,5 \cdot e^{0.0613846T}$, where vapour pressure P_w depends on mean air temperature T [K].

The selected data sets shall be normalised to at least one reference air density. The reference air density shall be the average of the measured air density of the valid, collected data set at the site during the test period, 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 normalisation shall be applied to the measured power output according to the equation:

$$P_n = P_{10\min} \cdot \frac{\rho_0}{\rho_{10\min}} \quad (4)$$

where

P_n is the normalised power output;

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

ρ_0 is the reference air density.

For a wind turbine with active power control, the normalisation shall be applied to the wind speed according to Equation (5):

$$V_n = V_{\text{free}} \left(\frac{\rho_{10\min}}{\rho_0} \right)^{1/3} \quad (5)$$

where

V_n is the normalised wind speed;

V_{free} is the measured nacelle wind speed, corrected with the NTF.

9.2 Determination of measured power curve

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

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j} \quad (6)$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{n,i,j} \quad (7)$$

where

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

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

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

$P_{n,i,j}$ is the normalised 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.

9.3 Annual energy production (AEP)

Generic AEP is estimated by applying the measured power curve to different reference wind speed frequency distributions. A Rayleigh distribution, which is identical to a Weibull distribution with a shape factor of 2, shall be used as the reference wind speed frequency distribution. AEP estimations shall be made for hub height annual average wind speeds of 4 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 (8):

$$\text{AEP} = N_h \sum_{i=1}^N [F(V_i) - F(V_{i-1})] \left(\frac{P_{i-1} + P_i}{2} \right) \quad (8)$$

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 normalised and averaged wind speed in bin i ;

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

$$F(V) = 1 - \exp\left(-\frac{\pi}{4} \left(\frac{V}{V_{\text{ave}}}\right)^2\right) \quad (9)$$

where

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

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

V is the wind speed.

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

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

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

AEP-measured shall be obtained from the measured power curve by assuming zero power for all wind speeds above and below the range of the measured power curve.

AEP-extrapolated shall be obtained from the measured power curve by assuming zero power for all wind speeds below the lowest wind speed in the measured power curve and constant power for wind speeds 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 B, Annex C and Annex D, shall be reported for the AEP-measured for all given annual average wind speeds.

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

- a) uncertainty of the wind resource;
- b) uncertainty of turbine availability;
- c) uncertainty due to wind flow and wake modelling.

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 the following equation:

$$C_{P,i} = \frac{P_i}{\frac{1}{2} \rho_0 A V_i^3} \quad (10)$$

where

- $C_{P,i}$ is the power coefficient in bin i ;
- V_i is the normalised and averaged wind speed in bin i ;
- P_i is the normalised and averaged power output in bin i ;
- A is the swept area of the wind turbine rotor;
- ρ_0 is the reference air density.

9.5 Uncertainty analysis

An uncertainty analysis shall be done in accordance with Annex B, Annex C and Annex D. In certain circumstances it may be useful to calculate an average power curve from multiple tests, in which case the guidelines of Annex F and Annex G should be followed.

10 Reporting format

The test shall be reported in such detail that every significant procedural step and test condition can be reviewed, and, if necessary, repeated. This document differentiates between documentation and reporting. The measurement party shall maintain all documentation for future reference, even in the event that the documentation is not reported. The documents should be retained for a prescribed period of time, typically ten years per ISO 17025. An example of such documentation would be turbine maintenance records. The following list items are the minimum nacelle power performance test reporting requirements.

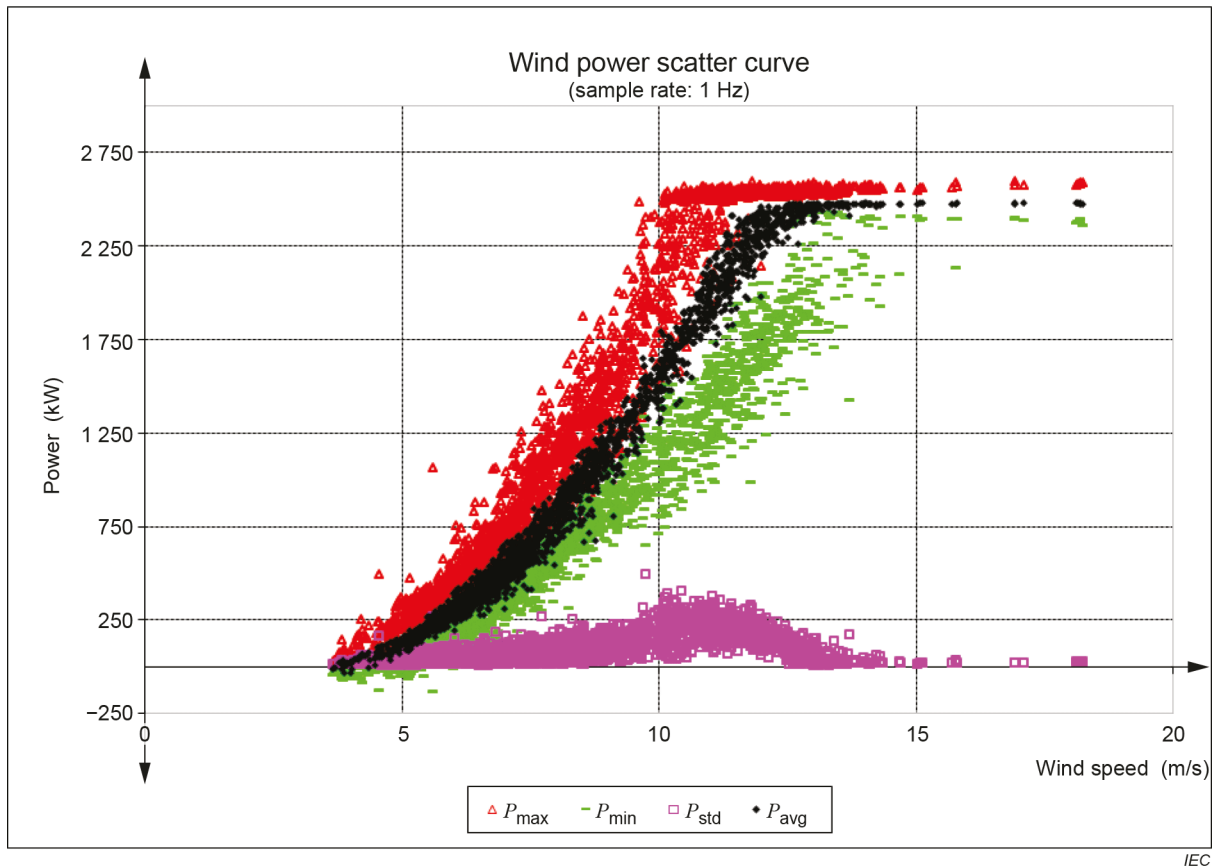
The test report shall contain, at a minimum, the following information:

- a) An identification and description of the specific wind turbine configuration under test, in such detail as to be able to assess transfer function validity (see 6.2), including:
 - 1) turbine make, type, serial number, production year, nacelle description (e.g. drawings, measurements, photos) and type, hub description.
 - 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, zero pitch offset, and normal pitch angle(s);
 - 6) tower type, tower height and hub height;
 - 7) aviation light type, size, location, and a description of other ancillary equipment on the nacelle;
 - 8) description of the control system (device and software version) including but not limited to documentation of status signals being used for data reduction; turbine control parameters, as far as relevant to the transfer function test (e.g., pitch, yaw, nacelle wind speed and wind direction, rotational speed and power), by agreement between involved parties;
 - 9) 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;

- 10) drawings and photographs of the nacelle anemometer and wind direction instrument location and mounting type, pre- and post- or in-situ calibration, data acquisition method, data acquisition averaging time (if multiple instruments a clear identifier of the primary measurements shall be reported);
 - 11) nacelle anemometer and vane signal type, signal conditioning, signal chain description.
- 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 with such scale as to detail 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 under test, meteorological masts (if applicable), significant obstacles, other wind turbines, vegetation type and height, and measurement sector;
 - 3) results of site assessment, as reported according to IEC 61400-12-3;
 - 4) if a site calibration is undertaken on the same site to establish the nacelle transfer function, the limits of the final measurement sector(s) shall also be reported;
 - 5) terrain description including estimates of the slope angle for various directions;
 - 6) nominal site-specific air density.
- c) A description of the test equipment, inclusive of the site calibration, nacelle transfer function, nacelle power curve tests (see Clause 7):
- 1) identification of the sensors and data acquisition system(s) for each measurement parameter, including documentation of calibrations for the sensors, transmission lines, and data acquisition system;
 - 2) description of the arrangement of anemometers on the mounting structure on the nacelle, following the requirements and descriptions in IEC 61400-50-1;
 - 3) sketch of the arrangement of the mounting structure showing principle dimensions of the structure and instrument mounting fixtures;
 - 4) description of in-situ calibration method (if applicable) and documentation of results that show that the calibration is maintained;
 - 5) results of the end to end calibration for power, wind speed, wind direction, temperature and pressure.
- d) A description of the measurement procedure:
- 1) reporting of the procedural steps, test conditions, sampling rate, averaging time, measurement period;
 - 2) documentation of the data filtering, including exact filter criteria limit values, filtering order and the total number of data points removed;
 - 3) documentation of all corrections applied to the data;
 - 4) a summary of the test log book that records all important events during the power performance test; including a listing of all maintenance activities that occurred during the test and a listing of any special actions (such as blade washing) that were completed to ensure good performance;
 - 5) identification of any data rejection criteria beyond those listed in 8.6;
 - 6) if more than one measurement system was used, a statement regarding the synchronisation of all systems shall be included. The maximum time difference registered between these systems shall be documented and a graph or table showing the time corrections made during the measurement campaign on each measurement system shall be shown.
- e) 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 other important meteorological parameters including (refer to 8.4 to 8.8):

- 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 3;
 - 2) scatter plots of mean wind speed as a function of wind direction;
 - 3) special databases consisting of data collected under special operational or atmospheric conditions, per 8.6, should also be presented as described above;
 - 4) if measured, rotational speed and pitch angle should be presented with a scatter plot including binned values versus wind speed and a table with the binned values;
 - 5) definition of status signals, and plots of status signals during the measurement period.
- f) Presentation of measured power curve for the selected reference air density (see 9.1 and 9.2):
- 1) the power curve shall be presented in a table similar to Table 1. For each wind speed bin, the table shall list:
 - normalised and averaged wind speed;
 - normalised and averaged power output;
 - number of data sets;
 - calculated C_p value;
 - standard uncertainties of category A (see Annex B and Annex C);
 - standard uncertainties of category B (see Annex B and Annex C);
 - combined standard uncertainty (see Annex B and Annex C);
 - 2) the power curve shall be presented in a graph similar to Figure 2 and Figure 4. The graph shall show as a function of normalised and averaged wind speed:
 - normalised and averaged power output;
 - combined standard uncertainty;
 - 3) the C_p curve shall be presented in a graph similar to Figure 4; in the graph the swept area of the rotor shall be indicated;
 - 4) both the graph and the table shall state the reference air density, used for the normalisation.
- g) Presentation of measured power curve for site-specific air density (see 9.1 and 9.2):
- If the site average air density is not within 0,05 kg/m³ of the reference air density then a second presentation of the measured power curve shall be made. This presentation shall be the same as for the reference air density but shall show the power curve results obtained by normalisation to the site-specific air density.
- If more than one reference air density is selected, then a presentation of the measured power curve for all other reference air densities shall be made. This presentation shall be the same as for the reference air density but shall show the power curve results obtained by normalisation to the further selected reference air densities.
- h) Presentation of measured power curves collected under special operational and atmospheric conditions (see 8.6):
- Power curves, derived from subsets of the database for special operational or atmospheric conditions, may also be reported. If this is the case, a power curve should be reported as for sea level air density, but with clear indication in all plots and tables of the special operational and/or atmospheric conditions.
- i) Presentation of estimated AEP for the reference air density (see 9.3):
- 1) a table similar to Table 2 such that each annual average hub height wind speed shall include:
 - AEP-measured;
 - standard uncertainty of AEP-measured (see Annex B and Annex C);
 - 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.
- j) Presentation of estimated annual energy production for site-specific air density (see 9.3):
- If the site average air density is not within 0,05 kg/m³ of the selected reference air density, then a second table of AEP shall be presented. This presentation shall be the same as for the reference air density, but shall show AEP results obtained by normalisation to the site-specific air density.
- If more than one reference air density is selected, then further AEP tables shall be presented for each reference air density. This presentation shall be the same as for the reference air density, but shall show AEP results obtained by normalisation to the further reference air densities.
- k) A reference to the report where the results of measuring the nacelle transfer function as per IEC 61400-12-6 are reported, including the uncertainty of the NTF.
- l) Uncertainty of measurement (see Annex B):
- Uncertainty assumptions on all uncertainty components shall be provided as well as assumptions regarding contribution of uncertainties and correlated/uncorrelated uncertainties, as described in Annex B, Annex C and Annex D.
- m) Deviations from the procedure:
- Any deviations from the requirements of this document shall be clearly reported in a separate clause. Each deviation shall be supported with the technical rationale and an estimate of its effect on the test results.



NOTE The fitted transfer function was used to create the estimate of free stream wind speed from the measured nacelle wind speed.

Figure 2 – Presentation of sample data: nacelle power performance test scatter plots

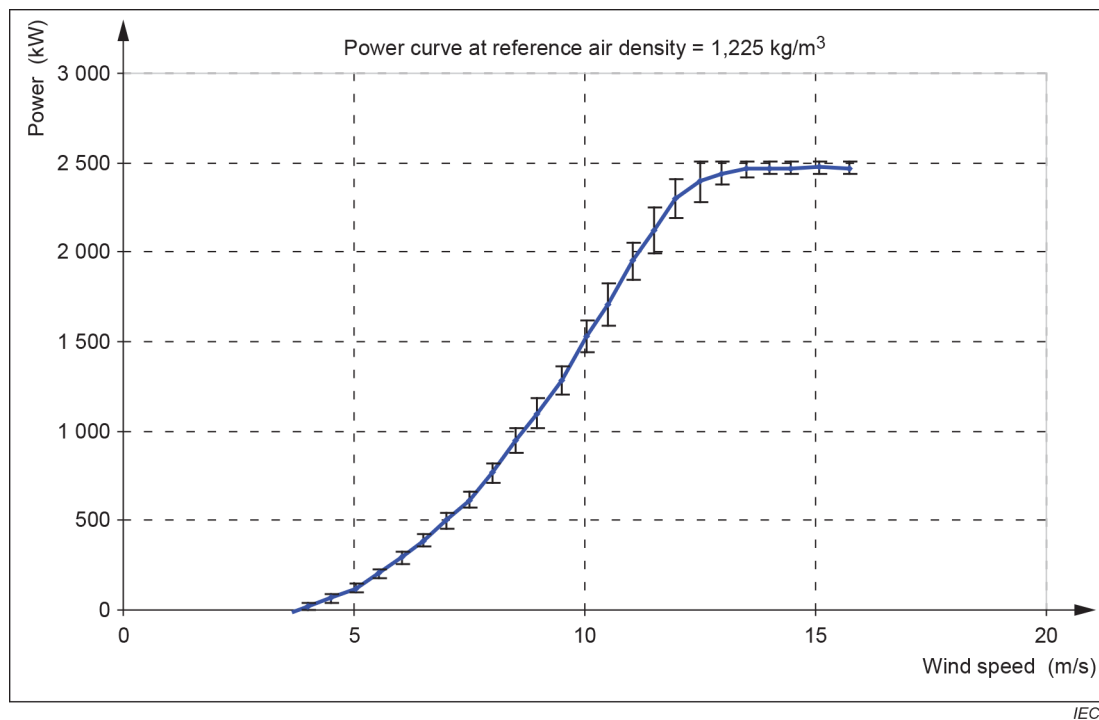


Figure 3 – Presentation of sample data: binned power curve with uncertainty bands

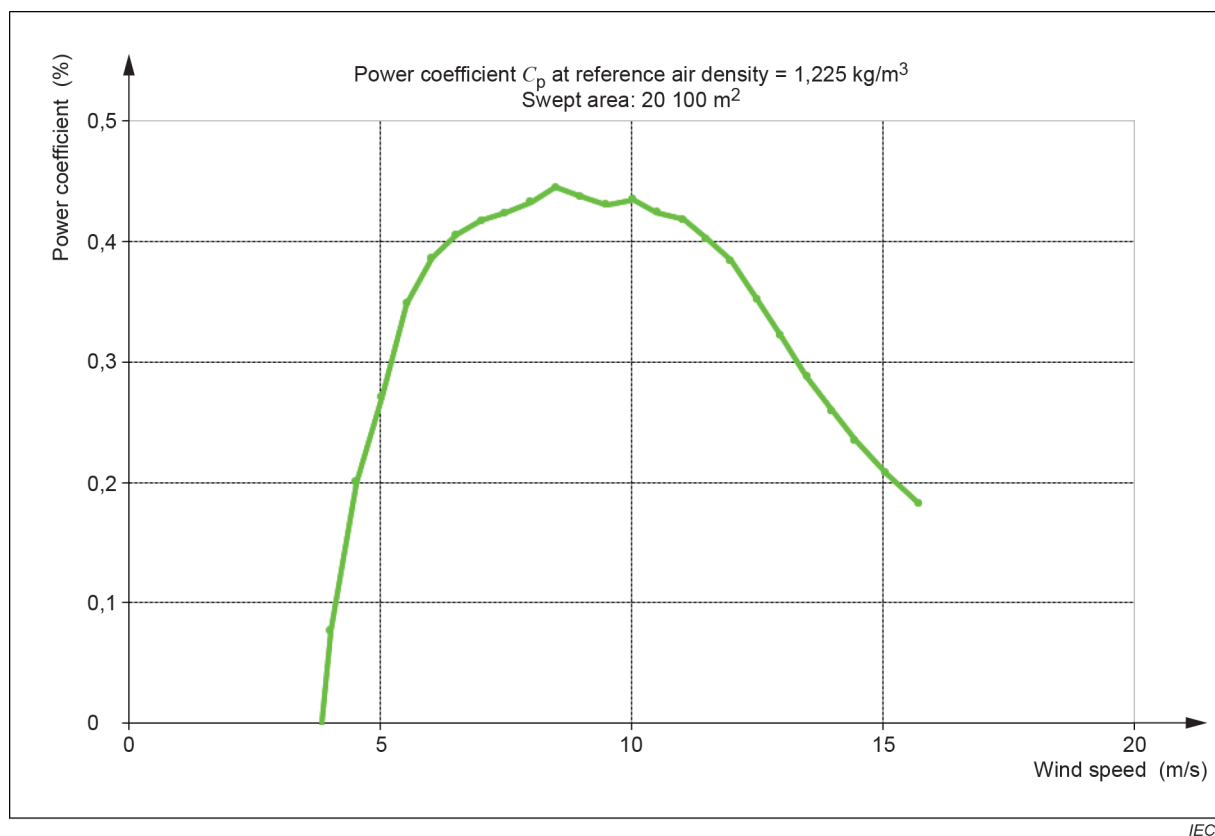


Figure 4 – Example of sample data: measured power curve and C_p curve

Table 1 – Example of a measured power curve

Wind turbine and corrected nacelle speed							
Reference air density: 1,225 kg/m ³					Category A	Category B	Combined uncertainty
Bin no.	$V_{\text{free stream}}$ wind speed	Power Output	C_p	No. of data sets	Standard uncertainty	Standard uncertainty	Standard uncertainty
	m/s	kW		#	s_i kW	u_i kW	u_{ci} kW
7	3,71	–9,3	–0,053	3	2,35	20,43	20,56
8	4,00	17,2	0,077	24	5,21	23,37	23,94
9	4,52	64,2	0,201	27	5,57	23,89	24,53
10	5,03	119,9	0,272	77	3,49	25,89	26,12
11	5,53	204,6	0,349	124	3,32	33,49	33,65
12	6,02	293,4	0,386	200	3,26	36,25	36,40
13	6,51	389,0	0,406	231	3,41	40,48	40,62
14	7,00	498,8	0,418	240	4,46	46,40	46,62
15	7,48	616,7	0,424	203	5,42	53,19	53,47
16	7,99	768,8	0,433	165	7,23	65,46	65,86
17	8,49	946,0	0,445	163	7,86	81,83	82,21
18	8,97	1 098,1	0,438	118	10,89	75,82	76,60
19	9,50	1 282,5	0,431	90	12,11	87,63	88,47
20	10,03	1 526,5	0,435	86	12,84	117,68	118,38
21	10,50	1 707,7	0,424	84	12,41	105,27	105,99
22	11,03	1 950,9	0,419	111	10,61	129,94	130,37
23	11,48	2 119,7	0,403	112	12,68	109,25	109,98
24	11,98	2 296,7	0,385	113	8,87	110,43	110,78
25	12,5	2 393,5	0,352	80	5,49	64,97	65,20
26	12,97	2 440,6	0,322	49	5,34	45,24	45,55
27	13,50	2 462,5	0,288	29	2,56	35,00	35,10
28	13,99	2 469,1	0,260	17	1,01	32,57	32,58
29	14,45	2 469,1	0,235	5	1,32	32,24	32,27
30	15,07	2 472,3	0,208	3	0,46	32,32	32,33
31	15,72	2 472,0	0,183	3	0,56	32,27	32,27

Table 2 – Example of estimated annual energy production

Estimated annual energy production (database A) Turbine: type = Wind turbine + nacelle anemometer TF, location = IEC PT IEC 61400-12-2 Reference air density: 1,225 kg/m ³ Cut-out wind speed: 25 m/s (extrapolation by constant power from last bin)					
Hub height annual average wind speed (Rayleigh) m/s	AEP-measured (measured power curve) MWh	Standard uncertainty in AEP MWh	Standard uncertainty in AEP %	AEP - extrapolated (extrapolated power curve) MWh	
4	1 256	197	15,5	1 256	
5	2 732	359	13,2	2 738	
6	4 505	520	11,7	4 579	
7	6 186	618	10,2	6 518	Incomplete
8	7 484	647	8,9	8 360	Incomplete
9	8 306	665	8,3	9 988	Incomplete
10	8 695	659	7,9	11 335	Incomplete
11	8 753	609	7,3	12 372	Incomplete

Annex A

(normative)

Nacelle wind speed transfer function validity procedure

A.1 General

The transfer function can be significantly affected by turbine hardware and control. This annex describes the criteria that need to be checked to assess if a transfer function measured at one turbine can be applied to another. The criteria in this annex refer to a comparison of a measurement of a NTF on one turbine and the application of the NTF on another turbine (or the same turbine at a later date). The validity criteria in Clause A.2 to Clause A.6 shall be checked to ensure that they are identical and within the given limits given before the test is started.

If any of these validity criteria are not met, another transfer function shall be used. The validity check shall be reported in such detail that each of the 9 checks in this annex is supported by evidence. Note that also the sector self-consistency check (see IEC 61400-12-5:2022, 8.2) shall be done before a valid test result can be reported. However, the checks in IEC 61400-12-5:2022, 8.2 can only be done after an NPC is available whereas the checks in this annex can be done before a test is started.

A.2 Measurement procedure:

The averaging time the data points are based on to calculate the transfer function shall be the same as the averaging time the data points are based on to calculate the nacelle power curve.

A.3 Terrain class and slope:

The terrain class when the NTF was established shall be the same as the terrain class when the NTF will be applied, unless the NTF is measured in the same wind farm as where it is applied in which case the terrain class may vary by ± 1 .

The sign of slope of the 10 degree sectors in the measurement sector shall be compared as well – a positive slope cannot be mixed with a negative slope.

The sign of the slope of the terrain in the measurement sector when the NTF was established shall be the same as the sign of the slope of the terrain in the measurement sector when the NTF will be applied.

A.4 Measurement hardware:

- a) anemometer and vane type;
- b) anemometer and vane location (relative to the mounting structure) within 5 mm;
- c) location of anemometer, vane and mounting structure on the nacelle within 100 mm.

A.5 Other turbine hardware:

- a) the blade type, including aerodynamic devices mounted on the blade;
- b) nacelle shape, within 100 mm;
- c) the size and location of equipment mounted on the nacelle (such as aviation lights); location within 100 mm.

A.6 Turbine controls:

- a) the control software and version to the extent that the changes significantly affect the power performance of the turbine as estimated by the manufacturer;
- b) all parameters (and changes to those parameters) related to control of pitch, yaw, rotational speed, power and any other parameters to the extent that these parameters (and changes to these parameters) significantly affect the power performance of the turbine as estimated by the manufacturer; this is to be checked by comparing specific parameters and their related values.
- c) operational modes (e.g., noise reduced operation, power curtailment).

Annex B (normative)

Evaluation of uncertainty in measurement

B.1 General

This annex addresses the requirements for the determination of uncertainty in measurement. The theoretical basis for determining the uncertainty using the method of bins can be found in Annex C and an example of estimating uncertainties in Annex D.

The measured NTF and NPC shall each be supplemented with an estimate of the uncertainty of the results due to uncertainty in the measurement as well as other factors such as terrain. The estimate shall be based on ISO/IEC GUIDE 98-3, Guide to the expression of uncertainty in measurement (GUM:1995). The guidance for the NTF uncertainty assessment is covered in IEC 61400-12-6 and the results of that assessment shall be further incorporated in the evaluation of the NPC uncertainty.

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

B.2 The measurands

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

B.3 Uncertainty components

Table B.1 and Table B.2 provide minimum uncertainty parameters that shall be included in the uncertainty analysis of the NPC.

Table B.1 – Uncertainty components in nacelle power curve evaluation

Measured parameter	Uncertainty component	Uncertainty category
Electric power	Current transformers	B
	Voltage transformers	B
	Power transducer or power measurement device	B
	Data acquisition system	B
	Variability of electric power	A
Wind speed	Nacelle anemometer calibration due to wind speed	B
	Nacelle anemometer calibration due to direction	B
	Operational characteristics	B
	Mounting effects	B
	Flow distortion due to terrain (inflow)	B
	NTF (from IEC 61400-12-6)	B
	Data acquisition system	B
Air temperature	Temperature sensor	B
	Radiation shielding	B
	Mounting effects	B
	Data acquisition system	B
Air pressure	Pressure sensor	B
	Mounting effects	B
	Data acquisition system	B
Method	Air density correction	B
	Dynamic power measurement	B
	Seasonal variation	B
	Variation in inflow to rotor	B
	Turbulence influence on binning	B

The components mentioned in Table B.1 and Table B.2 constitute a minimum list of uncertainty components. Components can be added as needed.

NOTE The implicit assumption of the method of this document is that the 10-min mean power yield from a wind turbine is fully explained by the simultaneous 10-min mean wind speed measured by the nacelle anemometer (related to the free stream wind speed by a turbine-type specific measured NTF) and the air density. This is not the case. Other flow variables affect both the power yield and the NTF. Thus identical wind turbines will yield different power and different nacelle wind speeds at different sites even if the free stream hub height wind speed and air density are the same. These other variables include turbulent fluctuations of wind speed (in three directions), the inclination of the flow vector relative to horizontal scale of turbulence, and shear of mean wind speed over the rotor. Currently, analytical tools offer little help in identification of the impact of these variables and experimental methods encounter equally serious difficulties.

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

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

Quantification of this apparent uncertainty is difficult. Depending on site conditions and climate, the uncertainty in the nacelle power curve can be around 10 % or more. In general terms, the uncertainty can be expected to increase as the complexity of the site conditions under which the NTF was measured and the complexity of the site conditions under which the NPC was measured diverge, with increasing complexity of topography and with increasing frequency of non-neutral atmospheric conditions. This document addresses this issue by adding uncertainty components such as seasonal variation and inflow to rotor.

B.4 Wind direction uncertainty

The uncertainty of the wind direction does not directly influence the uncertainty of the power curve or the uncertainty of the annual energy production but it does influence the calculation of the measurement sector. Therefore some estimates of the contributing uncertainty components are given here.

The uncertainty in the wind direction measurement consists of three components: the uncertainty in the yaw position, the uncertainty in the nacelle wind vane and the uncertainty in the data acquisition system. Furthermore the uncertainty in the yaw position consists of the uncertainty in the alignment of the sensor (or sensor mounting) and of the signal resolution (or sensor uncertainty). The uncertainty in the nacelle measured wind direction consists of the calibration uncertainty (sonic sensors only), the in-situ calibration uncertainty and the effects the rotor and terrain have on the measurement (the terrain includes up-flow effects for the specific site).

Table B.2 – Uncertainty components in nacelle based absolute wind direction

Measured parameter	Uncertainty component	Uncertainty category
Yaw position	Field calibration	B
	Signal resolution	B
Nacelle measured wind direction	Calibration – sensor mounting position uncertainty (sonic sensors only)	B
	Calibration – bin averaged wind direction difference due to wind direction (sonic sensors only)	B
	Calibration – bin averaged wind direction difference due to non-vertical flow (sonic sensors only)	B
	Sensor alignment	B
	Rotor effect on average measured wind direction	B
	Terrain effects on average measured wind direction	B
Data acquisition system	Signal transmission	B
	System accuracy	B
	Signal conditioning	B

Annex C (normative)

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

C.1 General

The corrected wind speed derived from application of a nacelle transfer function (NTF) has uncertainty associated with measurement of the NTF and also with transferral of the NTF to the same or other turbines (of the same type) experiencing in-flow conditions different from those prevailing during measurement of the NTF relationship.

In evaluating the uncertainty, $u_{c,i}$, in the wind speed output from bin i of a measured NTF or in the power in bin i of a nacelle power curve, the combined standard uncertainty can be expressed in its most general form by:

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

where

- $c_{k,i}$ is the sensitivity factor of component k in bin i ;
- $u_{k,i}$ is the standard uncertainty of component k in bin i ;
- $c_{l,j}$ is the sensitivity factor of component l in bin j ;
- $u_{l,j}$ is the standard uncertainty of component l in bin j ;
- M is the number of uncertainty components in each bin;
- $\rho_{k,l,i,j}$ is the correlation coefficient between uncertainty component k in bin i and uncertainty component l in bin j (in Equation (C.1) only the diagonal elements, $j = i$, are used).

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

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

where

- f_i is the relative occurrence of wind speed between V_{i-1} and V_i ($F(V_i) - F(V_{i-1})$) within bin i ;
- $F(V)$ is the Rayleigh cumulative probability distribution function for wind speed;
- N is the number of bins;
- N_h is the number of hours in one year $\approx 8\,760$.

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

- a) uncertainty components are either fully correlated ($\rho = 1$, implying linear summation to obtain the combined standard uncertainty) or independent ($\rho = 0$, implying quadratic summation, i.e. the combined standard uncertainty is the square root of summed squares of the uncertainty components);
- b) all category A uncertainty components are mutually independent and category A and B uncertainty components are independent (irrespective of whether they are from the same bin or from different bins), while category B uncertainty is fully correlated with category B uncertainties from the same origin in a different bin (e.g. uncertainty in power transducer in different bins).

Note that where the NPC is derived across multiple wind turbines simultaneously the NTF measurement uncertainty is fully correlated across turbines and those components of the NTF uncertainty associated with site and in-flow conditions may also be considered fully correlated as long as the same NTF is used on all turbines.

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

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

where

- M_A is the number of category A uncertainty components;
- M_B is the number of category B uncertainty components;
- $s_{k,i}$ is the category A standard uncertainty of component k in bin i ;
- s_i are the combined category A uncertainties in bin i ;
- u_i are the combined category B uncertainties in bin i .

It should be noted that $u_{c,i}^2$ is not independent of bin size due to the dependency of s_i on the number of data sets in the bin (see Equation (C.3) and Equation (C.9)).

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

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

The significance of the second term in Equation (C.4) is that each individual category B uncertainty component progresses through to the corresponding AEP uncertainty, applying the assumption of full correlation across bins for the individual components. Finally, the cross-bin combined uncertainty components are added quadratically into a resulting AEP uncertainty.

C.2 Propagation of uncertainty through the stages of NTF/NPC measurement

The uncertainty evaluation shall recognise that certain uncertainties carry through to different stages of the NTF/NPC measurement and therefore are at risk of being overestimated if the above assumptions concerning the independence between category B uncertainties are fully applied. This can be avoided by considering a degree of cancellation between uncertainties.

The examples in Table C.1 illustrate some of the situations where a degree of cancellation may be assumed to apply.

Table C.1 – Example cancellation sources

Uncertainty source	Cancels with uncertainty source	Conditional upon
Operational characteristics of reference anemometer on the reference mast during site calibration of the NTF test turbine site	Operational characteristics of reference anemometer on reference mast during NTF measurement on test turbine	The same model of anemometer (and preferably the same anemometer) is used on the reference mast during the site calibration measurement and during the NTF measurement and similar incoming flow conditions prevail.
Mounting effects of the reference anemometer on the reference mast during site calibration of the NTF test turbine site	Mounting effects of the reference anemometer on the reference mast during the NTF measurement	Precisely the same mounting configuration is used for the reference anemometer during the site calibration and NTF measurements.
Operational characteristics of nacelle anemometer on test turbine during determination of NTF	Operational characteristics of nacelle anemometer on the test turbine during determination of NPC	The same model of nacelle anemometer is used on the NTF and NPC test turbines and similar incoming flow conditions prevail.
Mounting effects for the nacelle anemometer on the test turbine during determination of the NTF	Mounting effects for the nacelle anemometer on the test turbine during determination of the NPC	The same mounting configuration is used on the NTF and NPC test turbines and similar flow conditions prevail.
Terrain effect on NTF during NTF measurement	Terrain effect on NTF during derivation of NPC	The terrain characteristics at the NTF measurement turbine and the terrain characteristics at the NPC test turbine are identical (i.e. the same turbine in both cases) or are very similar (i.e. neighbouring turbines on a ridge).

In all of the cases in Table C.1, the degree of cancellation will decrease as the differences between the atmospheric conditions and/or site conditions prevailing during each stage of the measurement increase. These differences may arise as a result of carrying out different stages of the measurement on different sites (e.g. measuring the NTF on a simple site and using the NTF during the measurement of the NPC on a complex site) or during different seasons (e.g. measuring the NTF during the summer and measuring the NPC on the same or a different site during the winter).

This cancellation is already implicit in the IEC 61400-12-1 uncertainty analysis, but is made explicit here. An example of implicit cancellation in the IEC 61400-12-1 analysis can be found in Annex E where the uncertainties for the site calibration are calculated. The operational characteristics of the anemometer are in principle a contributing factor to the site calibration uncertainty. As both anemometers are required to be of the same type, this uncertainty contribution is assumed to be cancelled and therefore is not included in the calculation.

The examples in Annex E go through an estimate of the category A and B uncertainties for each bin of a measured power curve. The uncertainty of the power curve is derived, and finally the uncertainty of AEP is estimated. The example follows ISO/IEC GUIDE 98-3 and the assumptions made above.

Using the combination of the category B uncertainty components according to Equation (C.3) and taking the cancellation factors into account, all uncertainty components within each bin can be combined first to express the combined category B uncertainty of each measured parameter, as for example for the wind speed:

$$u_{V,i}^2 = \sum_k^M l_{V,k}^2 u_{V,k,i}^2 \quad (\text{C.5})$$

where

- $u_{V,i}$ is the total uncertainty of the wind speed in bin i ;
- $u_{V,k,i}$ is the standard uncertainty of wind speed component k in bin i (see Table C.2);
- $l_{V,k}$ is the cancellation factor for uncertainty component k ;
- M is the number of wind speed uncertainty components.

Note cancellation factors are included in Equation (C.6). For $l = 1$ there is no cancellation and Equation (C.6) reverts to the one used in IEC 61400-12-1. For $l < 1$ there is a degree of cancellation, and for $l = 0$ there is full cancellation. The following rules apply to cancellation:

- Because of the complex causes of the uncertainties it is difficult to accurately determine the cancellation. To yield a reasonable, but conservative estimate of the overall uncertainty the cancellation factor shall not be applied to the first appearance of an uncertainty term, only to subsequent appearances. If for instance the same anemometer is used in the site calibration as during the NTF measurement, then the calibration uncertainty of the anemometer on the permanent met-mast is fully taken into account ($l = 1$) in the uncertainty of the site calibration factors, but will cancel fully or partially in the TF-uncertainty. A full cancellation ($l = 0$) is appropriate if the two measurements are done in a short enough time span such that no drift in the calibration factors should be expected, otherwise a partial cancellation should be used ($1 > l > 0$).
- Statistical uncertainties never cancel and so they do not have a cancellation term.
- There is no full cancellation apart from the example as given in the first dashed list item, but in some cases there may be partial cancellation.
- The estimates given in Annex C have to be taken as lower boundaries for cancellation; even lower values can only be used when backed up by evidence.

Then the standard uncertainties of the measurands can be combined to get the total uncertainty in bin i using Equation (C.6). Equation (C.7) can be used to calculate the standard uncertainty of the AEP.

$$u_{c,i}^2 = s_{P,i}^2 + u_{P,i}^2 + c_{V,i}^2 u_{V,i}^2 + c_{T,i}^2 u_{T,i}^2 + c_{B,i}^2 u_{B,i}^2 + c_{m,i}^2 u_{m,i}^2 \quad (\text{C.6})$$

The subscripts in Equation (C.6) are as given in Table C.2. Note the uncertainties due to the data acquisition system are part of the uncertainty of each measurement parameter and flow distortion due to terrain is included in the uncertainty of wind speed.

To calculate the uncertainty in AEP the uncertainty of each category B component needs to be combined over bins before adding the different components together, to accurately account for the correlations between bins.

$$u_{AEP}^2 = N_h^2 \sum_{i=1}^N f_i^2 \sum_{k=1}^{M_A} c_{k,i}^2 s_{k,i}^2 + N_h^2 \sum_{k=1}^{M_B} \left(\sum_{i=1}^N f_i c_{k,i} l_k u_{k,i} \right)^2 \quad (\text{C.7})$$

Equation (C.7) is identical to Equation (C.4) except that the cancellation factor l is included in Equation (C.7).

C.3 Category A uncertainties

C.3.1 General

The category A uncertainty that needs to be considered is the uncertainty of the measured and normalized electric power data in each bin, the variance in the site calibration (when performed) and the variance in the NTF (please note that this latter contribution is estimated in IEC 61400-12-6 but needs to be included in the assessment of the NPC uncertainty).

C.3.2 Category A uncertainty in electric power

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

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1} \sum_{j=1}^{N_i} (P_i - P_{n,i,j})^2} \quad (\text{C.8})$$

where

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i ;

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

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

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

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

$$s_i = s_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \quad (\text{C.9})$$

where

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

$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i ;

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

Table C.2 – List of category A and B uncertainties for NPC

Category B: Instruments	Note	Standard	Symbol	Sensitivity
Power output			$u_{P,i}$	$c_{P,i} = 1$
Current transformers *	a	IEC 61869-2	$u_{P1,i}$	
Voltage transformers *	a	IEC 61869-3	$u_{P2,i}$	
Power transducer or	a	IEC 60688	$u_{P3,i}$	
Power measurement device	c			
Data acquisition system (transmission, accuracy and conditioning) *	cd		$u_{P4,i}$	
	bcd		$u_{dP,i}$	
Wind speed			$u_{V,i}$	
Anemometer calibration uncertainty due to wind speed *	ab	IEC 61400-50-1	$u_{V1,i}$	
Anemometer calibration uncertainty due to direction (if sonic or propeller) *	b		$u_{V2,i}$	
Operational characteristics *				
Mounting effects *	cd	IEC 61400-50-1	$u_{V3,i}$	$c_{V,i} = \left \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right $
Flow distortion due to terrain *	c	IEC 61400-12-1 & IEC 61400-12-3	$u_{V4,i}$	
NTF (from IEC 61400-12-6) *	cd		$u_{V5,i}$	
Data acquisition system (transmission, accuracy and conditioning) *	bc		$u_{V6,i}$	
	bcd		$u_{dV,i}$	
Air density				
Temperature			$u_{T,i}$	$c_{T,i} = \frac{c_{V,i} \cdot V_i}{3 \cdot T_{Data,i}}$
Temperature sensor *	a		$u_{T1,i}$	NOTE For a stall-regulated turbine, sensitivity remains the same as IEC 61400-12-1
Radiation shielding *	cd		$u_{T2,i}$	
Mounting effects *	cd		$u_{T3,i}$	
Data acquisition system (transmission, accuracy and conditioning) *	bcd	ISO 2533	$u_{dT,i}$	$c_{B,i} = \frac{c_{V,i} \cdot V_i}{3 \cdot B_{Data,i}}$
Air pressure			$u_{B,i}$	NOTE For a stall-regulated turbine, sensitivity remains the same as IEC 61400-12-1
Pressure sensor *	a		$u_{B1,i}$	
Mounting effects *	c		$u_{B2,i}$	
Data acquisition system (transmission, accuracy and conditioning) *	bcd		$u_{dB,i}$	
Category B: method				
Method			$u_{M,i}$	
Air density correction *	cd		$u_{M3,i}$	$c_{M,i} = 1$
Dynamic power measurement *	cd		$u_{M4,i}$	$c_{T,i}$ and $c_{B,i}$
Seasonal variation on NPC *	d		$u_{M5,i}$	$c_{M,i} = 1$
Variation rotor inflow *	de		$u_{M6,i}$	$c_{M,i} = 1$
Turbulence effect on binning *	cd		$u_{M7,i}$	$c_{M,i} = 1$