



BSI Standards Publication

Wind energy generation systems

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

National foreword

This British Standard is the UK implementation of EN 61400-12-2 Ed.2.0. It is identical to IEC 61400-12-2:2022 ED2. Together with BS EN 61400-12-2:2013, it supersedes BS EN 61400-12-2:2013 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/88, Wind turbines.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

© The British Standards Institution 2022
Published by BSI Standards Limited 2022

ISBN 978 0 539 17002 3

ICS 27.180

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 October 2022.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

English Version

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

Windenergieanlagen - Teil 12- 2: Leistungsverhalten von
stromerzeugenden Windenergieanlagen auf der Grundlage
der Gondelanemometrie

This European Standard was approved by CENELEC on 2022-10-10. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and the United Kingdom.



European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

European foreword

The text of document 88/823/CDV, future edition 2 of IEC 61400-12-2, prepared by IEC/TC 88 "Wind energy generation systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 61400-12-2:2022.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2023-07-10
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2025-10-10

This document supersedes EN 61400-12-2:2013 and all of its amendments and corrigenda (if any).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Any feedback and questions on this document should be directed to the users' national committee. A complete listing of these bodies can be found on the CENELEC website.

Endorsement notice

The text of the International Standard IEC 61400-12-2:2022 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following note has to be added for the standard indicated:

IEC 61400-2 NOTE Harmonized as EN 61400-2

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60688	2021	Electrical measuring transducers for converting AC and DC electrical quantities to analogue or digital signals	EN IEC 60688 ¹	202X
IEC 61400-12-1	-	Wind energy generation systems - Part 12-1: Power performance measurement of electricity producing wind turbines	EN IEC 61400-12-1	-
IEC 61400-12-3	-	Wind energy generation systems - Part 12-3: Power performance - Measurement based site calibration	EN IEC 61400-12-3	-
IEC 61400-12-5	2022	Wind energy generation systems - Part 12-5: Power performance - Assessment of obstacles and terrain	EN IEC 61400-12-5	2022
IEC 61400-12-6	-	Wind energy generation systems - Part 12-6: Measurement based nacelle transfer function of electricity producing wind turbines	EN IEC 61400-12-6	-
IEC 61400-50-1	-	Wind energy generation systems - Part 50-1: Wind Measurement - Application of Meteorological Mast, Nacelle and Spinner Mounted Instruments	EN IEC 61400-50-1 ²	-
IEC 61869-2	-	Instrument transformers - Part 2: Additional requirements for current transformers	EN 61869-2	-
IEC 61869-3	-	Instrument transformers - Part 3: Additional requirements for inductive voltage transformers	EN 61869-3	-
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)	-	-

¹ Under preparation. Stage at the time of publication: prEN IEC 60688:2021.

² Under preparation. Stage at the time of publication: FprEN IEC 61400-50-1:2022.

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**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**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.180

ISBN 978-2-8322-5594-0

**Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.**

CONTENTS

FOREWORD	5
INTRODUCTION	7
1 Scope	9
2 Normative references	9
3 Terms and definitions	10
4 Symbols, units and abbreviated terms	14
5 Overview of test method	17
6 Preparation for performance test	19
6.1 General	19
6.2 Wind turbine	19
6.3 Test site	19
6.4 Nacelle wind speed transfer function	20
6.5 Test plan	20
7 Test equipment	20
7.1 Electric power	20
7.2 Wind speed	21
7.3 Wind direction	21
7.4 Air density	21
7.5 Rotor speed	22
7.6 Pitch angle	22
7.7 Wind turbine status	22
7.8 Data acquisition	22
8 Measurement procedure	23
8.1 General	23
8.2 Wind turbine operation	23
8.3 Data system(s) synchronisation	23
8.4 Data collection	24
8.5 Data quality check	24
8.5.1 General	24
8.5.2 Measured signals are in range and available	24
8.5.3 Sensors are operating properly	24
8.5.4 Ensure data acquisition system(s) is/are operating properly	25
8.5.5 Sector self-consistency check	25
8.6 Data rejection	25
8.7 Data correction	26
8.8 Database	26
9 Derived results	27
9.1 Data normalisation – Density correction	27
9.2 Determination of measured power curve	28
9.3 Annual energy production (AEP)	28
9.4 Power coefficient	29
9.5 Uncertainty analysis	30
10 Reporting format	30
Annex A (normative) Nacelle wind speed transfer function validity procedure	38
A.1 General	38

A.2	Measurement procedure:	38
A.3	Terrain class and slope:	38
A.4	Measurement hardware:	38
A.5	Other turbine hardware:	38
A.6	Turbine controls:	39
Annex B (normative)	Evaluation of uncertainty in measurement	40
B.1	General	40
B.2	The measurands	40
B.3	Uncertainty components	40
B.4	Wind direction uncertainty	42
Annex C (normative)	Theoretical basis for determining the uncertainty of measurement using the method of bins	43
C.1	General	43
C.2	Propagation of uncertainty through the stages of NTF/NPC measurement	44
C.3	Category A uncertainties	47
C.3.1	General	47
C.3.2	Category A uncertainty in electric power	47
C.4	Category B uncertainties	49
C.4.1	General	49
C.4.2	Category B uncertainties in climatic variations	49
C.5	Expanded uncertainty	49
Annex D (normative)	NPC uncertainty estimates and calculation	51
D.1	Methods and assumptions	51
D.1.1	General	51
D.1.2	Nacelle power curve uncertainty component estimates	51
D.1.3	Wind direction uncertainty	54
D.1.4	Contribution factors	55
D.2	Uncertainty example calculations	57
D.2.1	Example description	57
D.2.2	Example case – NTF uncertainty	57
D.2.3	Example case – NPC uncertainty	58
Annex E (normative)	Allowable anemometry instrument types	60
E.1	General	60
E.2	Calibration of sonic anemometers	60
E.2.1	General	60
E.2.2	Step 1: Wind speed calibration (required)	60
E.2.3	Step 2: Wind direction calibration (required)	61
E.2.4	Step 3: Tilting test (recommended)	61
E.3	Recalibration of sonic anemometers	61
E.4	Uncertainty of sonic and propeller anemometers	61
Annex F (informative)	Results and uncertainty considerations	62
F.1	General	62
F.2	Method for calculation of measurement uncertainty	62
F.3	Method for calculation of sampling uncertainty	66
F.4	Combined measurement and sampling uncertainty	66
Annex G (informative)	Example multi-turbine NTF/NPC uncertainty calculation	67
G.1	Overview	67
G.2	Outline of procedure:	67

G.3	Example of measurement uncertainty calculation	70
G.4	Example of sampling uncertainty calculation	74
G.5	Combined uncertainty	74
G.6	Discussion of sample size and uncertainty	74
Annex H (informative)	Organisation of test, safety and communication	76
H.1	Overview.....	76
H.2	Responsibility for test	76
H.3	Safety during test.....	76
H.4	Communication	76
H.5	Prior to test.....	76
H.6	During test	76
H.7	After test.....	77
Bibliography.....		78
Figure 1 – Procedural overview.....		18
Figure 2 – Presentation of sample data: nacelle power performance test scatter plots		34
Figure 3 – Presentation of sample data: binned power curve with uncertainty bands.....		34
Figure 4 – Example of sample data: measured power curve and C_p curve		35
Figure G.1 – Impact of multiple turbine testing on measurement uncertainty		74
Figure G.2 – Impact of multiple turbine testing on sampling uncertainty		75
Table 1 – Example of a measured power curve.....		36
Table 2 – Example of estimated annual energy production.....		37
Table B.1 – Uncertainty components in nacelle power curve evaluation		41
Table B.2 – Uncertainty components in nacelle based absolute wind direction		42
Table C.1 – Example cancellation sources		45
Table C.2 – List of category A and B uncertainties for NPC.....		48
Table C.3 – Expanded uncertainties.....		50
Table D.1 – Estimates for uncertainty components from NPC measurement		52
Table D.2 – Estimates for $u_{V5,i}$ for NPC terrain class		54
Table D.3 – Estimates for uncertainty components for wind direction		55
Table D.4 – Estimates for contribution factors for NPC		56
Table G.1 – List of correlated uncertainty components		68
Table G.2 – Sample AEP and uncertainty data from three turbines		70
Table G.3 – Component uncertainty contribution to AEP uncertainty on turbine 1		71
Table G.4 – Combination of uncertainty components across turbines.....		72

INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

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

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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

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

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.

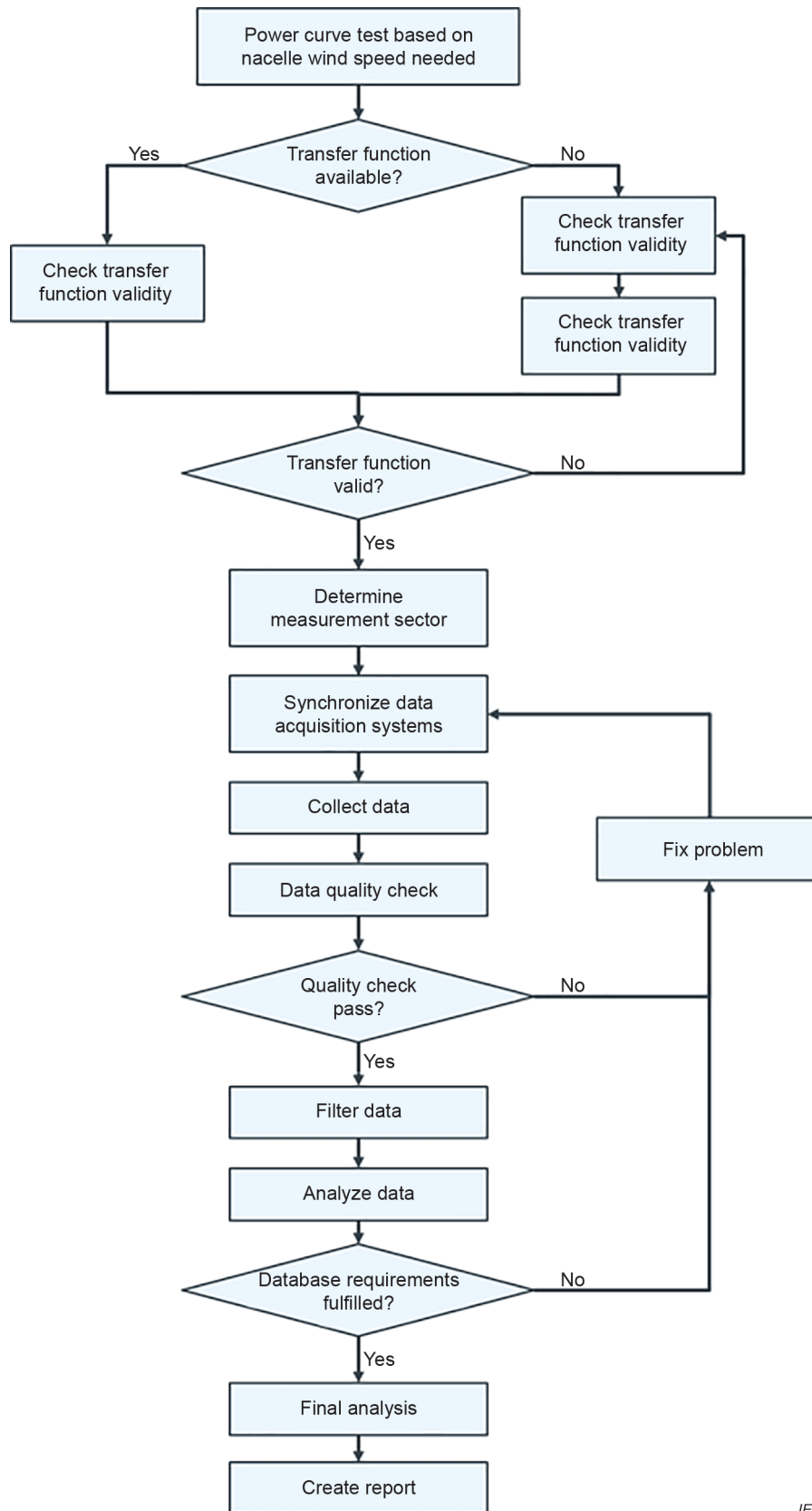
Once the transfer function is obtained by application of IEC 61400-12-6, the nacelle-anemometry method to establish a power curve, the nacelle power curve (NPC), is similar to the IEC 61400-12-1 method. In this document this part of the method is called the "performance test". Similar data to that required 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];

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