# EVALUATION OF SITE-SPECIFIC WIND CONDITIONS

## Version 2
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**List of abbreviations**

| | |
|---|---|
| AEP | annual energy production |
| CFD | Computational Fluid Dynamics |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| LIDAR | LIght Detection And Ranging |
| MCP | Measure Correlate Predict |
| MEASNET | Measuring Network of Wind Energy Institutes |
| RSD | Remote Sensing Device (e.g. SODAR or LIDAR) |
| SODAR | SOund Detection And Ranging |

# 1 Foreword

MEASNET is a network of measurement institutes, which has been established to harmonise wind energy-related measurement procedures, in order to allow mutual recognition and interchangeability of results and to achieve uniform interpretation of standards and recommendations. The institutes of MEASNET are all actively performing wind energy related measurements and evaluations. In order to apply agreed "MEASNET procedures", each institute must document the skills and quality of measurements and evaluations and participate in mutual evaluation exercises.

# 2 Introduction

The „Evaluation of site-specific wind conditions" is the MEASNET procedure agreed upon by the MEASNET members to be mutually used and accepted. The procedure is considered internationally to be the most complete and most accepted procedure on which a common interpretation and understanding has been exercised in accordance with the MEASNET Quality Evaluation Program, based on the objective of continuously improving quality, traceability and comparability.

In order to keep the guideline as comprehensive yet clear and brief as possible, applicable regulations are cited as appropriate, and additional requirements are formulated, as required.

# 3 Definition and Purpose of Site Assessment

The expression "*site-specific conditions*" as used in the context of this document is defined as the set of meteorological site conditions relevant for the design, operation and structural integrity of a wind turbine. The meteorological site conditions addressed in this document relate to *wind conditions*, where parameters such as air density or air temperature are included as far as they affect the wind flow.

The expression "*site assessment*" is defined, as commonly used in wind energy context, as acronym for "assessment of site specific (wind) conditions".

The results of the "Evaluation of site-specific wind conditions" performed by a MEASNET accredited measurement institute, as defined here, provide a traceable basis for the assessment of the certification body concerning the conformity of the design parameters with the site-specific conditions, according to IEC 61400-1 ([1] or [2]). Implicitly, the derived conditions which will influence the installation, operation and maintenance (O&M), loading, durability, performance and energy yield of wind turbines installed at the site.

According to IEC 61400-1, the site-specific conditions can be broken down into wind conditions, other environmental conditions, soil conditions and electrical conditions. Additionally, each condition can be subdivided into normal and extreme conditions [1], [2]. The present document focuses on the site-specific wind conditions and ambient conditions as far as they affect the wind flow.

The process of site assessment includes the gathering (measurement), processing (evaluation) and interpretation of meteorological data. All these steps are handled in the present guideline, meaning that for each of these steps the scope of and the requirements on the work are described. The following diagram illustrates the main components of the evaluation process as described within this guideline.

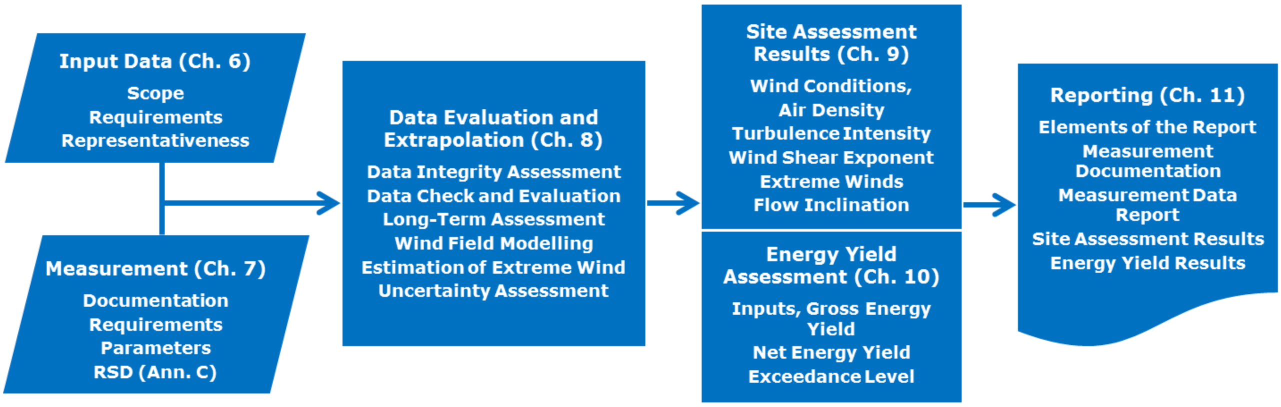


Figure 1: Evaluation process of site-specific wind conditions. In parentheses the chapters are shown where the respective topics are handled.

The process illustrated above may require considerable time to be completed, and its evolution must be constantly re-examined and modified according to the outcome of each phase. As a general rule the process may be divided into two phases:

- *Measurement*: On-site measurement of wind conditions and documentation thereof.
- *Data Evaluation and Extrapolation* and preparation of *Derived Results*, including documentation of the data and results.

Each of the site assessment phases depicted above may be performed and reported separately provided that:

- All relevant phase-specific requirements of the current document are fulfilled
- When input from previous phases is used, it must be documented that this input fulfils the requirements of the current document
- Proper reference is made to all inputs used (measurement data, analysis results), in order to be unambiguously identified

The specific data requirements are highlighted in the respective chapters and in the related reporting chapter.

# 4 Normative References

This document in its entirety shall comply with the following reference documents:

- IEC 61400-1:1998 Wind turbine generator systems - Part 1: Safety Requirements, 2$^{nd}$ Ed., 1998 [1].
- IEC 61400-1:2005 Wind turbines - Part 1: Design Requirements, 3$^{rd}$ Ed., 2005 [2].
- IEC 61400-12-1 Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 1$^{st}$ Ed., 2005 [4].
- IEC 61400-12-1, Ed. 2, regarding requirements on remote sensing devices. This document is available at CDV [20] at time of completing this document.
- ISO 2533: 1975-05, Standard Atmosphere [7]
- ISO/IEC Guide 98:1995 - Guide to the Expression of uncertainty in measurement [11]

# 5 Handling of Deviations to the Guideline

The guideline defines methodologies and requirements for a site assessment procedure, which will lead to well-founded results according to advanced state-of-the-art techniques/-procedures. In practise, cases may occur in which all requirements of input data or methods cannot be met, leading to deviations to the guideline.

In general, such deviations must be identified and clearly described within the site assessment report. However, as the impact of certain deviations – upon the calculated uncertainties or upon the significance of the derived results – can be difficult to assess, some rules for handling of deviations are defined below. These rules aim to maintain the significance of the proposed procedure for such cases as much as possible.

- Deviations to the guideline are described in the site assessment report in an extra chapter called “Deviations to the MEASNET Guideline ‘Evaluation of Site-Specific Wind Conditions’.
- A summary of the deviations and a comment on each’s significance, with reference to the chapter “Deviations to the MEASNET Guideline ‘Evaluation of Site-Specific Wind Conditions’”, shall be included in the summary of the site assessment report.
- Each deviation to the guideline shall be considered in the uncertainty assessment of the site assessment. If no possibility of analytical or empirical derivation of a typical uncertainty range for a specific deviation exists, substitute values shall be defined and considered as additional uncertainty component.

Regarding the wording within the guideline text it is defined, that all formulations using “*must*” or “*shall*” describe *mandatory requirements*, which have to be handled as deviations when not completely fulfilled. Formulations using “should”, “recommended” or “preferably” describe recommended requirements, which are not to be handled as deviations when not fulfilled.

# 6 Input Data

The evaluation of site-specific wind conditions is based on specific input data and information which must be available. In this chapter the required input data is described.

## 6.1 Site Inspection

In order to properly assess site conditions, a current site visit shall be performed. During this site visit the following aspects/information should be assessed and documented:

- panoramic photos
- coordinates of the site with full information on coordinate system
- orographic conditions
- surface roughness conditions
- presence of obstacles
- position(s)/coordinates of the measurement mast(s)
- measurement equipment (if already on site)

The information acquired during the site visit can be relevant for the design of an appropriate measurement campaign and layout of the measurement system, as well as for the evaluation steps described in Chapter 8.

## 6.2 Topographic Data

As a basis for the site assessment and flow modelling to be performed, a comprehensive and relevant description of the topography of the site is required. The topographic description will consist of the following:

- description and/or photo documentation of the site and typical elements in the surroundings of the site
- topographical maps/data of the site showing the orography and roughness conditions
- satellite imagery or aerial photos

The topographic data form the basis to set up the digital topographical model of the site and surroundings as required for the specific calculation model. Consequently, the topographic input data must meet the requirements of the selected modelling approach (Section 8.4) regarding extent, resolution, accuracy and included information.

## 6.3 Relevant Meteorological Parameters

Main input data for the site assessment procedure are measurement data relating to different meteorological parameters. These form the input for calculation procedures which extrapolate these parameters to the relevant positions and heights. The following meteorological parameters are required as input for the procedure:

- wind speed *
- wind direction *
- wind speed standard deviation / turbulence *
- air temperature
- air pressure
- humidity
- flow inclination

From this list, each parameter marked with asterisk (*) is an essential input for the site assessment procedure, so that these have to be measured directly at the site, traceable according to ISO/IEC 17025 and according to the requirements as described in the following.

The additional parameters are also recommended to be measured at the site, but they can also be derived from available non-site-specific data or from estimations. The related requirements are also described in the following sections.

## 6.4 Representativeness of Wind Measurements

The proper design of a measurement campaign – such that the required input data is provided for all wind turbines of a wind farm project – can be based on a site-specific analysis of the particularities and influence factors at the site. Such a site-specific expert analysis is recommended in order to define a measurement campaign (measurement type, height(s) and position(s), sensor layout, etc.) which will provide the required data with sufficient accuracy and in the most efficient manner.

In the context of

(i) designing an appropriate measurement campaign for a developer,

(ii) providing guidelines so that a developer can design its own measurement programme or

(iii) assessing the validity of a campaign that has already been implemented by a third party,

a number of minimum requirements for an appropriate measurement campaign for simplified cases are described in the following sections.

The height of the primary wind speed measurement level shall be at least 2/3 of the planned hub height. Measurement heights closer to the planned hub height will reduce the uncertainty of the vertical extrapolation of the wind conditions and hence are generally recommended, and might also be required in special cases.

For the definition of the number of required wind measurements it is assumed that the wind conditions measured at one position can be extrapolated with tolerable uncertainty using the wind field modelling approaches described in this guideline (Section 8.4) within a radius around the mast called "*representativeness radius*". All wind turbines shall be located in the representativeness radius of at least one mast.

In order to define the representativeness radius for different terrain types, two exemplary terrain classes are defined. The simple terrain class (Figure 2) describes flat terrain with no noticeable terrain elevation variations, where the wind conditions are mainly influenced by terrain roughness conditions. The complex terrain class (Figure 3) corresponds to a site with considerable orographic variation (relief) and significant slopes. In Table 1**:** Definition of measurement campaign requirements for different terrain classes.

the representativeness radii, e.g. the maximum distance of any wind turbine from the nearest measurement mast, are defined for each of these classes.

For less complex, hilly terrain the representativeness radius should be obtained by interpolation between the defined classes. For even more complex, mountainous sites, smaller values for the representativeness radius must be assumed. These should be determined on the basis of a site-specific analysis.

The indicated representativeness radii are valid *for homogenous roughness conditions*. In the case of non-homogeneous roughness conditions within the wind farm area or surroundings –

potentially leading to mast measurements influenced by a surface roughness values different than those observed by the wind turbine(s) – the representativeness radius may not be applicable in all directions. In such cases a site-specific analysis concerning an appropriate measurement layout shall be performed.

| **Terrain type** | **Minimum measurement height** | **Representativeness radius of a mast (max. distance of any wind turbine to the next mast)** |
|---|---|---|
| Simple terrain (Figure 2) | 2/3 hub height | 10 km |
| Complex terrain (Figure 3) | 2/3 hub height | 2 km |

Table 1: Definition of measurement campaign requirements for different terrain classes.

Figure 2: Example of a *simple terrain* site as defined by this guideline. Such a site has only minor relief which leads to a negligible influence of orographic effects on wind conditions. The latter are therefore mainly influenced by roughness conditions.

Figure 3: Example of a *complex terrain* site as defined by this guideline. Such a site is characterised by orographic features with terrain slopes greater than 0.3 (approx. 17°), which have a significant influence on wind conditions.

# 7 Measurement

The basis of the site assessment, as described in this guideline, is site-specific measurements of wind and possibly further parameters. The operation of the measurement can be part of the site assessment procedure, but can also be performed independently, leading to specific demands on the documentation of the measurement.

The general requirements on documentation and the technical requirements for the measurements are described in the following sections with reference to different standards or recommendations. Specific demands on data checking and integrity are addressed in the subsequent Sections 8.1 and 8.2.

## 7.1 Measurement Documentation

As a basis for the assessment of the measurement equipment and evaluation of the measured data, complete documentation of the measurement equipment and the measurement location shall be available.

Generally, gaps in the documentation of the measurement will lead to increased measurement uncertainties, which are described and considered within the data evaluation process.

The documentation shall include all main aspects as summarised in the following, and described in detail in Appendix A:

- Location of the measurement
- Measurement equipment
- Measurement history
- Measurement data

## 7.2 Wind Speed

On-site measurement of wind speed shall be performed in accordance with IEC 61400-12-1 [4]. The anemometers must be calibrated according to the MEASNET guideline [5] by a MEASNET approved institute, preferably during a single calibration campaign.

An anemometer based mast measurement may be complemented by remote sensing measurements, in order to extrapolate the wind measurement to other heights or positions, taking the uncertainty related to these techniques into account. Recommendations concerning verification, mounting, configuration and testing (see Annex C) shall be taken into account.

The top anemometer shall be mounted on one vertical tube in compliance with IEC-61400-12-1 [4]. If a lightning arrestor is installed, it shall be mounted away from the prevailing wind direction. In order to minimise flow distortion effects, the lightning arrestor shall be located at least 50 times the arrestor’s diameter from the anemometer. The exact dimensions and position shall be reported.

The measurement level of the primary wind speed measurement, which is mainly relevant for determining the hub height wind conditions, shall be at least 2/3 of the planned hub height (see Section 6.4). The primary anemometer shall have a backup sensor installed according to IEC 61400-12-1 [4] in order to allow in-situ comparison and filling of data gaps.

In order to assess the wind shear and determine the wind profile at the site, at least one additional anemometer with a significant difference in measurement height (at least 20 m) shall be used. When choosing measurement heights, it should be taken into account that the most important heights are those which lie within the rotor-swept area.

These additional anemometer(s) shall be mounted on separate boom(s) as described in IEC 61400-12-1 [4], as well as in the IEA guidelines [6] concerning direction and length of the booms. The aim is to minimise flow distortion effects to the greatest possible degree with respect to the complete 360°-sector. The flow distortion in the wake of the mast must be considered in the estimation of uncertainties.

The anemometer booms should be oriented in the same direction. If the prevailing wind direction is known then booms should be installed with a 45° offset from the prevailing wind direction for tubular masts, or 90° from the prevailing wind direction for lattice masts. No other instrument shall be installed on the same boom.

Wind speeds shall be measured as 10-min. averages, preferably with a sampling rate of 1 Hz or faster. The data acquisition system shall record and save the averages and standard deviations, and should also record the minima and maxima.

The measurement period shall cover at least 12 complete and consecutive months for at least one mast at the site, in order to appropriately assess seasonal variations. If data from more than one mast is available, correlation between the different masts should be performed in order to extend the measurement period for each mast and to fill data gaps. The uncertainty related to the correlation procedure shall be taken into account.

The measurement is considered incomplete, if one or more of the following conditions are fulfilled:

- The measurement period of none of the masts at the site covers at least 12 consecutive months
- The availability of the filtered data from the primary sensor in combination with its backup sensor installed according to IEC 61400-12-1, is less than 90%
- The availability of the data filled by MCP methods based on further measurement data measured at the site is less than 95%

If a measurement is considered incomplete, this must be clearly stated as a deviation to the guideline, in the presentation of the results and must be taken into account in the uncertainty assessment.

Re-calibration of the anemometers should be performed after 12 months and following the end of the measurement period via wind tunnel calibration by a MEASNET accredited institution. If a re-calibration is not performed, it shall be alternatively tested and documented that the cup anemometer maintains its calibration over the duration of the measurement period. The so-called in-situ comparison procedure shall be used, which consists of a comparison of the primary anemometer to a control anemometer installed close to it and the evaluation of significant temporal changes of the relations.

If the re-calibration shows that results deviate significantly, comparative evaluations may be performed (in-situ comparisons with further anemometers) with the aim to determine the time when the deviations began to become significant compared to measurement uncertainty and to shorten the evaluated data to a time period during which the anemometer performance lies within an acceptable range of uncertainty.

In case the calibration differences appear to be too high, the analysis of the calibration differences and data rejection due to calibration differences shall be reported. Alternatively, suspicious data can be retained and the uncertainty increased accordingly.

When ultrasonic anemometers are used these shall be calibrated by a MEASNET accredited institution according to the MEASNET guideline [5] with respect to the directional sensitivity of those sensors. It is also necessary that the settings/configuration of these devices are well documented (e.g. measuring range, units, polar coordinates or Cartesian system, BAUD rate, protocols etc.). Note that during transportation and mounting the sensors have to be protected to avoid unacceptable deformations.

## 7.3 Wind Direction

On-site measurement of the wind direction shall be performed according to IEC 61400-12-1 [4]. Wind vane(s) shall be mounted on separate boom(s) according to IEC 61400-12-1 [4], and as per the recommendations in the IEA guidelines [6] concerning boom orientation and length. The aim is to minimise flow distortion effects with respect to the complete 360°-sector. The flow distortion in the wake of the mast must be considered within the estimation of uncertainties.

In order to assess the wind veer at the site and to have an increased availability, at least one additional wind vane at a significantly lower height (at least 20 m lower) should be used. When choosing measurement heights, it should be kept in mind that the most important heights are those which lie within the rotor-swept area.

Accurate alignment of the wind vane shall be performed during its installation in order to allow for wind direction offset correction of the data.

Wind direction data shall be measured as 10–min. averages, preferably with a sampling rate of 1 Hz or faster. The data acquisition system shall record and save the averages and the standard deviations.

The measurement period shall cover at least 12 complete and consecutive months for at least one mast at the site to appropriately assess seasonal variations. If data from more than one mast are available, correlation between the different masts should be performed, in order to extend the measurement period for each mast and to fill in data gaps. The uncertainty related to the correlation procedure shall be taken into account.

The measurement is considered incomplete, if one or more of the following conditions are fulfilled:

- The measurement period of none of the masts at the site covers at least 12 consecutive months
- The availability of the filtered data, where data from the relevant sensor in combination with a backup wind vane (installed no more than 20 m lower) is less is than 90%.
- The availability of the data filled by MCP methods based on of further measurement data measured at the site is less than 95%

If a measurement is considered incomplete, this must be stated as deviation to the guideline, in the presentation of the results and must be taken into account in the uncertainty assessment.

## 7.4 Flow Inclination

The occurrence of significant flow inclination (i.e. a significant vertical component of the flow) is strongly linked to the slope of the surrounding terrain. Therefore, for complex sites appropriate sensors should be used to measure the three directional flow components, in order to derive the flow inclination for the measurement position.

## 7.5 Temperature and Atmospheric Stability

On-site measurement of air temperature is generally recommended especially for sites where extreme temperature ranges are expected. The measurement should be performed according to IEC 61400-12-1 [4].

One sensor should be mounted within the upper 10 m of the measurement mast. The sensors should be calibrated. The measurement period shall cover at least 12 complete months in order to appropriately assess seasonal variations. Adequate shielding is mandatory in order to minimise biases and uncertainties due to solar radiation.

At sites where non-neutral stability conditions are predominant for situations relevant for wind energy purposes, it is recommended to explicitly measure stability, preferably by heat flux measured explicitly using an ultrasonic anemometer. Alternatively, stability can be estimated by use of two or more temperature sensors, preferably differential, at different heights.

Extrapolation of temperature should be performed, provided that appropriate long-term data are available in order to derive the long-term mean temperature for the site.

## 7.6 Pressure

It is recommended to measure barometric air pressure on site and preferably close to hub height. If the air pressure sensor is not mounted close to the hub height, air pressure measurements shall be corrected to hub height according to ISO 2533 [7].

Extrapolation of air pressure should be performed provided that appropriate long-term data are available in order to derive the long-term mean air pressure for the site.

## 7.7 Humidity

On-site measurement of relative humidity is recommended at sites with high temperatures or extraordinary climate conditions. The humidity sensor should be mounted within the upper 10 m of the measurement mast.

Extrapolation of humidity should be performed provided that appropriate long-term data are available in order to derive the long-term mean humidity for the site.

# 8 Data Evaluation and Extrapolation

Within the site assessment procedure, the measured data must be assessed, evaluated and extrapolated to significant long term periods, as well as to the positions of the wind turbines. The methodologies and requirements of these steps are described in this chapter.

## 8.1 Assessment of Data Integrity

As the results of the site assessment depend to a high degree on the measurement data used as input, considerations on the integrity of the input data shall be made. These are especially relevant, if – deviating from the requirements formulated in this guideline – the measurement is not traceable according to ISO/IEC 17025.

The integrity of the measurement data can be difficult to verify if the measurement procedure does not show a clear, reproducible and complete chain of processing steps. If the party performing the data evaluation and the site assessment (hereafter referred to as "MEASNET body") is the only one processing the data, this party can ensure the integrity of the data. If this is not the case, different requirements should be fulfilled to ensure or verify the integrity of the data to the greatest degree possible.

Dependent on the scope of possible checks and verifications, a classification of different situations regarding data integrity is made in the following. According to the rule that deviations to the guideline procedure shall be considered with substitute values for additional uncertainty components for each case such a value shall be defined

The following classes of measurement data integrity have been defined. If a deviating situation (Class D - E) arises, this deviation has to be described according to Chapter 5, and an uncertainty substitute value has to be taken into account as an additional measurement uncertainty component.

| Characterisations of different Data Integrity classes | | |
|---|---|---|
| Class | Characterisation | Description |
| A | Data integrity ensured (no deviation) | The MEASNET body undertakes or supervises the installation and maintenance of the measurement at the site. The monitoring and data evaluation is performed by the MEASNET body. Hence the MEASNET body can ensure the integrity of the data. |
| B | Data integrity ensured (no deviation) | The measurement is performed according to a quality management system, which ensures the integrity and reproducibility of the measurement.<br>A measurement accredited according to the ISO/IEC 17025 [8] meets these requirements if the ISO/IEC 17025 is being strictly applied. This means that no significant deviation from the standard shall occur, especially that the handling and mounting of the sensors are carried out or supervised by the accredited party only, and that a calibration of the whole measurement system, traceable back to official standards, is performed.<br>A remark shall be stated in the corresponding report that the measurement was not carried out completely by the MEASNET body. |
| C | Data integrity protected (no deviation) | The data integrity is ensured to a high degree by protective measures.<br>This can be achieved when a MEASNET body checks the logger configuration and sensor details during a site inspection, and has direct remote access to the data logger, to do at least random download and checks of the data.<br>It can also be realised by proving the authenticity and integrity of the complete data chain by sufficient encryption and authentication measures, so that the data cannot be manipulated, in combination with an on-site check by the MEASNET body.<br>A remark shall be stated in the corresponding report that the measurement installation and the data analysis were not carried out completely by the MEASNET body. |
| D | Data integrity assessed by documentation (deviation) | The data are obtained by the MEASNET body in logger file format, preferably binary file format. The applied calibration factors are either included in the data files or can be demonstrated by detailed documentation.<br>A remark shall be stated in the corresponding report that the integrity of the measurement data can only be ensured to a small degree. |
| E | Data integrity insecure (deviation) | The data are obtained by the MEASNET body as files with physical values only.<br>To be also applied for all measurements for which it is not possible to verify whether the values are correct (e.g. if the calibration parameters have been applied correctly, poor documentation), the data integrity is insecure. This fact shall be mentioned by the MEASNET body and considered for the uncertainty assessment.<br>A remark shall be stated in the corresponding report, that the integrity of the measurement data is not ensured, protected or assessed by documentation. |

Table 2: Definition of classes and characterisations of different situations of measurement data integrity.

It has to be emphasized that it is not possible to assess the uncertainty or the maximum possible error of measurement data in situations where the data processing is unclear or not traceable and the measurement data cannot be verified. Hence, an assumption of an uncertainty substitute value cannot be seen as the maximum error, which could arise.

Furthermore, the assumption of an uncertainty substitute value does not release the MEASNET body from the duty to perform verifications and plausibility checks of the input data as far as possible, and to reject data which are not traceable or not plausible.

In any site assessment campaign, classified according to the above table as Class D or E, in which significant deviations in the performance and/or documentation of the measurement campaign are identified, this shall be stated in the corresponding report.

## 8.2 Data Evaluation

### 8.2.1 Data Quality Assessment and Filtering

The first step of data evaluation consists of the quality assessment and, if necessary, filtering of the data. This data quality assessment and filtering step is quality-critical and intrinsically tied to the data evaluation process. In special cases, a data evaluation might be performed based on data, which have already been quality-checked and filtered by another party, on the condition that the accreditation requirements are fulfilled (measurement data integrity Class A or B, see Section 8.1), and that the scope of responsibility of the involved parties is clearly described.

The objective of the data quality check is to detect and eliminate as many significant errors from the data as possible, and to come to an overall assessment of the data quality. The definition of "erroneous data" and the correct method of handling such data cannot be generally prescribed, as it may depend on the evaluation methods and subsequent steps applied. For example, an anemometer measurement subject to mast shading could be assessed as measurement error and eliminated for specific purposes, however for other purposes such data might be retained, especially if a correction of the mast effect is performed.

The objective "overall assessment of the data quality" may impact the uncertainty assessment of the measurement, raise questions to be clarified, or even lead to the rejection of the investigated data for the purpose of the site assessment.

The quality assessment of measurement data requires a profound knowledge of measurement technology and a broad experience with measurement data. Hence a full discussion of this topic or definition of an adequate data quality procedure extends far beyond the scope of this document. Nevertheless, in Annex B some aspects of data quality assessment are described, these may be seen as hints and recommendations to be taken into account, when developing the individual data assessment procedure. These hints are summarised in the following.

For quality assessment, the data of the relevant sensors should be evaluated individually, but also in comparison to the data from other sensors and possibly further masts at the site. The checks applied to the data or appropriate auxiliary quantities (like relations or deviations) should consist of different evaluations, which are described more detailed in Annex B:

- Check for error values/substitutes
- Visual inspection
- Check for completeness
- Range test
- Constant value test

- Test for trends and inconsistencies
- Related parameter test
- Correlation test

The main consequence of the data quality assessment procedure will be the rejection of certain data sets/values (filtering), which will lead to gaps in the data. Additionally, some general findings might be drawn. The documentation of the data filtering process shall cover the following aspects:

- Specification of the overall number or percentage of rejected data
- List of the main periods which were filtered (possibly per sensor)
- Evaluation of distribution of filtered data (e.g. seasonal accumulation)
- Considerations of uncertainties resulting from the filtering
- Conclusions regarding usability or uncertainty of the data (from specific sensors)

The data quality assessment and filtering provides the base data for the further evaluation and may provide additional information on the usability or uncertainty of the measurement, which must be taken into account for the subsequent evaluation and uncertainty assessment steps.

### 8.2.2 Filling of Data

Data gaps, including those arising from the quality assessment and filtering, can introduce systematic errors in the measurement, especially if the gaps are not randomly distributed, but occur with accumulation in specific and not necessarily typical meteorological or climatologic situations (e.g. winter time). Hence, data gaps of the relevant sensors should be filled by reconstruction of the missing data from measurement values of other sensors, in order to increase the data availability from the relevant sensors.
Relevant sensors include wind speed and wind direction sensors, and possibly further meteorological measurements, such as temperature or pressure. Data filling may not be limited to mean values, but might also relate to properties like standard deviation or maximum of these quantities, depending on the purpose of the data for the further evaluation.

For data filling, usually *Measure-Correlate-Predict (MCP)* procedures are applied in a similar manner as with long-term extrapolation, which is described in detail in Section 8.3.2. The MCP procedures are preferably applied based on very similar data sets e.g. data from two anemometers on the same mast with only small deviations of the measurement height, such that the scatter of the analysed data, and hence the uncertainties of the MCP application, are as small as possible. Generally, the requirements for the methodology and the application are comparable to those for the long-term extrapolation, so the description of Section 8.3.2 can be applied accordingly.

The result of the data filling process will consist of the filled time series of measurement data. To allow a critical assessment of the uncertainties introduced by the data filling process, certain evaluations shall be performed and the documentation of the data filling shall include the following:

- Specification of the overall number or percentage of the filled data
- List of the main periods which were filled (possibly per sensor)
- Evaluation of distribution of filled data (e.g. seasonal accumulation)
- Evaluation of the influence of the data filling on mean values and distributions of the relevant quantities

- Considerations of uncertainties resulting from the filling
- Conclusions regarding usability or uncertainty of the filled data (of specific sensors)

## 8.3 Long-term Extrapolation

Generally, the results of a wind measurement campaign at a wind farm site are valid only for the measurement period. Usually this is a short term period of one or only a few years. Due to the fact that wind speed and wind direction distributions can show distinct inter-annual and seasonal variations, a database of many years is required in order to perform a reliable determination of the typical mean wind conditions, and hence for the determination of wind-speed related site parameters or long-term annual energy yields. Thus a long-term extrapolation is required in order to project the measured data to long-term wind conditions which are considered to be representative for typical mean wind conditions.

This approach is based on the general assumption that a *stable long term mean value* of the wind conditions exist and can be derived from historic data, and that this mean value represents the best estimation for the *future* wind conditions. Thus, the derived results cannot take into account future changes like systematic climate change. It is assumed that according to state-of-the-art methods, systematic trends or long-term oscillations of the wind conditions cannot be determined and modelled in such a way, which would lead to the prediction of the future wind conditions with higher accuracy.

### 8.3.1 Overview

The aim of a long-term extrapolation procedure is to determine the relationship between concurrent site and reference wind data and to apply the relationship for long-term extrapolation of the site data. The set of relevant parameters depend on different aspects such as the meteorological and topographic situation and the time scale of the performed assessment. For typical wind energy related situations, the long-term extrapolation of wind speed and wind direction is necessary. Further meteorological parameters, like air temperature, should possibly be taken into account.

The concurrent data are analysed with respect to the relevant parameters, and appropriate models to describe the relationship are established. When defining the type of relationship it must be taken into account, which properties of the wind distribution need to be modelled, as not only the mean wind speed, but also the shape of the wind speed distribution is relevant. It might be required to consider a non-linear relationship between the data. If the quality of the reference station allows, the analysed data should have a high temporal resolution (10 minutes or hourly time series).

The application of an extrapolation procedure shall include an assessment of the significance and quality of extrapolation as well as a plausibility test of the derived correlation parameters. The applied method to determine the relationship must be well-defined and validated and an assessment of the procedure’s uncertainty by means of performed verifications shall be done.

In the following section different long-term extrapolation procedures and their specific requirements are described (Section 8.3.2). Subsequently, the general requirements on the reference data and correlation period respectively are described (Sections 8.3.3 and 8.3.4).

### 8.3.2 Methods and Specific Requirements for Long-term Extrapolation

To determine the long-term wind conditions based on a limited measurement, a *Measure-Correlate-Predict (MCP)* or a type of *long term scaling method* shall be applied. These methods take into account the measurement data *(site data)* and concurrent long-term data *(reference data)*, which include at least a significant part of the period of the site data *(concurrent period)*.

A Measure-Correlate-Predict procedure consists of a comparison of the short-term site data with the reference data during the concurrent period and the analysis of the relationship ("correlation") between the data. The prediction consists of the application of the determined relations on the long-term reference data to extrapolate the short-term data to the long-term period (Figure 4).

A long-term scaling method consists of the analysis of the reference data with respect to the relation of wind conditions during the long term period to the conditions during the concurrent period. These relationships are applied to the concurrent site data in order to extrapolate them to a long-term period (**Figure 5**).

Whereas the MCP methods require a statistical data basis for determination of the relationships, and hence usually a high-resolution time-series of wind speed and wind direction, the long-term scaling methods can also be applied to data with lower resolution (e.g. monthly values).

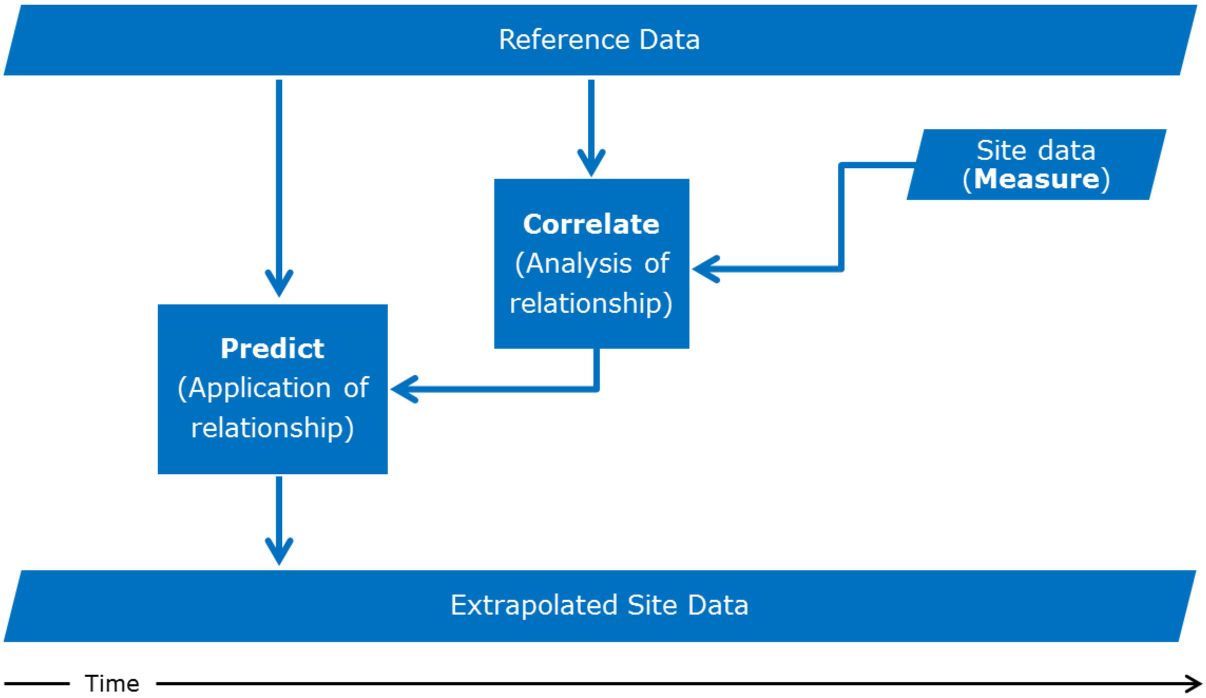

Figure 4: Scheme of the measure-correlate-predict (MCP) procedure.

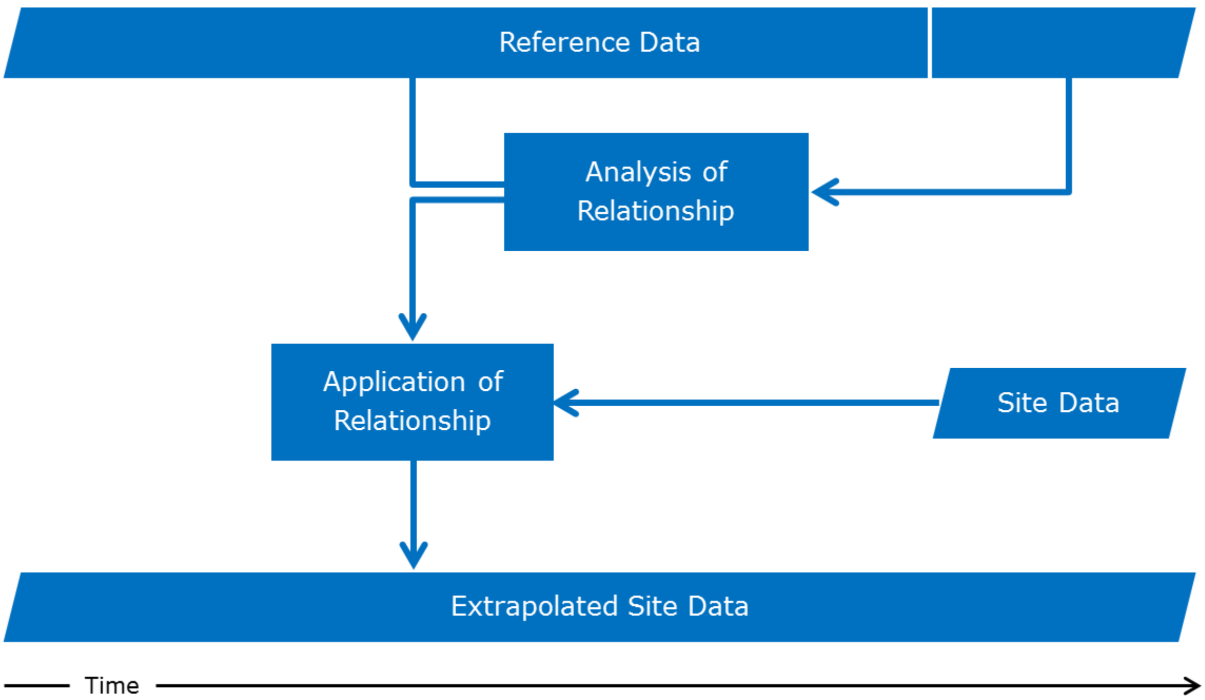

Figure 5: Scheme of long-term scaling procedure.

Dependent on the properties of the data and the site, different methodologies can be applied and different specific requirements must be taken into account.

**MCP methods**

- Sectoral Regression MCP

  The concurrent data are analysed in different wind direction sectors with respect to a linear or non-linear relationship (regression analysis). The wind direction deviation between the data is handled independently or implicitly. The definition of the sectors can be organized in flexible way, and the way of determining the relationship between the data can be oriented at the deviation of the wind distributions (e.g. Chi-Square Test [9]).

  A prerequisite for the sectoral regression MCP is that precise relationships between the data exist in the chosen sectors. The relationships shall be evaluated and documented at least in form of the correlation coefficient ($R$) or coefficient of determination ($R^2$) of the wind speed values for each considered sector. Additionally it must be verified that the range of occurring wind speeds is sufficient to perform the regression in each sector. This is especially important, if non-linear regressions are performed. The correlation coefficient of the data and the grade of coverage of the relevant wind speed ranges shall be taken into account for the uncertainty assessment of the results.

- Matrix MCP

  The concurrent data are classified regarding the wind speed and wind direction (bin analysis matrix). For each bin the deviation/relation between the wind speed/direction of the reference data and the site data are determined. For the elements of the matrix, which do not occur with significant frequency, the respective values shall be interpolated or extrapolated with appropriate methods. All elements of the matrix may be fitted with a surface function, if this function reproduces the determined significant matrix elements to a high degree.

  A prerequisite for the matrix MCP is that a high correlation exists between the data, and that a systematic relationship can be found which leads to a smooth pattern of the matrix elements. The relationship shall be evaluated and documented at least in form of the coefficient of determination ($R^2$) of the wind speed values for different wind direction sectors. The pattern of the matrix elements derived from the measurement data as well as the applied function shall be documented. Additionally, it must be verified that the range of occurring matrix elements sufficiently covers the occurring wind speed and wind direction ranges. The coefficients of determination of the data and the grade of coverage of the relevant wind speed ranges shall be taken into account for the uncertainty assessment of the results.

- Other MCP methods

  Additional methods to analyse the relationship between site and reference data may be used. That requires well-defined and validated methods, which are oriented at the empirically determined relationship between the data. Similar considerations regarding significant relationship and sufficient coverage as described above shall be made. For methods with higher degree of freedom the verification of results and the assessment of sufficient data coverage are especially important in order to avoid artefacts.

**Long-Term Scaling Methods**

- Wind Index (or Energy Index) Method

  From the reference data an index value is derived which represents the wind speed or energy yield variation at the site with sufficient quality. The minimum acceptable temporal resolution shall be monthly values.

  The calculation of the index value may be based on empirically determined relationships (correlation of wind speed or energy yield values) or based on calculation models (to determine the wind speed or energy yield at the site based on the reference data).

  The appropriateness of the index values for the site shall be validated. As a minimum, the coefficient of determination ($R^2$) between the index value and the relevant value based on the site measurement during the concurrent period must be determined and disclosed.

  The basis for scaling is usually the wind distribution measured during the short-term period at the site; consequently the influences of varying wind direction and wind speed shape parameters are not handled. Hence for this method it must be verified, that the wind direction distribution and the Weibull shape parameters during the short-term measurement are not atypical for long-term conditions.

- Distribution Scaling Method

  For this type of long-term extrapolation method the long-term extrapolations are applied to the wind distribution parameters (sectoral Weibull *A*- and *k*-parameters and frequency distribution). The long-term extrapolation factors are derived from either: a comparison of the wind distribution parameters of the site and reference data; a comparison of the wind distribution parameters at the reference station during short-term and long-term period; or from a comparative analysis of the time-series of the site and reference data. The precondition for applying the distribution scaling method is that the actual wind speed conditions can be well described by the assumed frequency distribution function (Weibull distribution). By applying distribution scaling methods the influence of varying wind speed or direction distribution may be possible to describe.

  However, if the distribution scaling method uses only wind distributions (i.e. not time-series data), the causality of wind distribution changes cannot be derived. In these cases an adjustment of the distribution parameters shall only be performed on the *wind speed* distributions. The distribution scaling method functions as a wind index scaling method in this case and shall follow the requirements specified above for that method.

  If the distribution scaling method is based on an analysis of time-series data, then a set of parameters representing the variation of the wind distribution shall be evaluated based on a temporal resolution of at least six hours.

If the long-term correlation and extrapolation is performed for a special purpose (e.g. extreme wind assessment), additional requirements may become relevant and must be considered.

### 8.3.3 Correlation Period

In order to allow a reasonable extrapolation of the short-term wind conditions, the correlation period (i.e. period for the determination of the correlation parameters) should include all important typical meteorological situations and allow the determination of the important relationships between the data. The better the extrapolation procedure is able to resolve the relationship between the data, the better the possibility of an accurate prediction based on a short correlation period. Therefore, the minimum period needed depends on the specific wind conditions and situations as well as the capabilities of the applied extrapolation procedure.

In order to ensure independence from seasonal variations, the concurrent period should include at least one year, especially if the extrapolation cannot be performed on a time-series basis and if the differences between the short-term and reference mast are large, with respect to measured wind speed conditions, the spatial distance and the difference in measurement height.

If the reference data are of high quality, have been measured at similar height and undergone a time-series based extrapolation including wind direction effects, then shorter measurement periods are possible. In this case, it should be shown that the extrapolation procedure was also validated for short periods, that significant correlation relations can be found between the data, that wind directional effects can be resolved acceptably and that seasonal effects can be assumed to be limited. These considerations must be taken into account for the estimation of the uncertainty of the long-term extrapolation.

#### 8.3.4 Requirements to Reference Data

From experience with meteorological long-term data it is known that the measured wind conditions often show trends or steps, which seem unrealistic. Often a decreasing trend in long-term data is caused by changes in the surroundings of the measurement (new buildings, growing of trees, etc.), and steps and inconsistencies in the data can often be due to changes in the measurement installation or missing long-term stability of the measuring sensors. Often the question of whether the long-term data is realistic for the region cannot be clearly answered without access to further information regarding the long-term measurement station and availability of additional independent long-term data.

Therefore, an important prerequisite for performing a reliable long-term extrapolation is an assessment of the reliability and consistency of the long-term data. An inspection of the long-term station and evaluation of information regarding its history can provide valuable information for this assessment. A comparative analysis of long-term data from different sources is often required in order to detect trends and inconsistencies in the long-term data in question and to determine an appropriate period with consistent data. The quality of the reference data must be taken into account in the uncertainty assessment of the long-term wind conditions.

The length of the reference data period should be as long as possible with the aim to represent the typical, mean wind conditions. From the climatological point of view the period of approximately 30 years is considered to be representative. The utilisable period will, however, be limited by data availability and by the aforementioned considerations to the data reliability and consistency. Taking these limits into account, a period of ten years is generally considered as a reasonable compromise between long-term representativeness and data reliability.

The length of the reference period should be determined specifically for the site after performing an analysis of the reliability and consistency of the available data. The reference period as well as the criteria and the data base for determining it should be disclosed and explained. The reference period should be assessed regarding its representativeness for long-term wind conditions, and this representativeness must be taken into account in the uncertainty assessment of the long-term wind conditions.

## 8.4 Wind Field Modelling

For spatial extrapolation of the wind data measured at specific points at the wind farm area ("measurement points") to the position and hub heights of the prospected wind turbines ("target points"), a modelling of the wind field is required. The wind field modelling consists of the application of appropriate flow modelling methods based on the measured wind data and a topographic description of the site as well as a sufficient surrounding area.

For this task, various methodologies and models exist, which are based on different modelling approaches. As the physically correct description of atmospheric wind flow is arbitrarily complex and cannot be done exactly, each model approach applies simplifications or has limitations. As it is not possible within the scope of this guideline to assess or select the wind field modelling methodologies, certain general requirements on the modelling are described, which shall be fulfilled independently from the model approach applied.

- Model verification

  The applied model shall be verified for the application case, i.e. it shall be generally capable to describe the relevant effects and it shall be proven to work according to the specifications. Basic properties like the production of physically reasonable and plausible results, the reproducibility of the results and the correct self-prediction of the input data (correct reproduction of the wind conditions at the measurement points) shall be given.

- Appropriateness of model simplifications

  The appropriateness of the inherent model simplifications or limitations has to be considered and assessed for the respective application. For example, it can be assessed as appropriate to ignore atmospheric heat and moisture processes, when it can be expected with high probability or it is known, that such processes do not significantly contribute to the relationship of the wind conditions between the measurement points and the target points of the calculation.

- Model input data

  The model shall make use of those input data which are available and which are known to significantly influence the wind conditions. These are usually at least the description of elevation and roughness length or vegetation type of the area, but can be supplemented by obstacle descriptions or further atmospheric parameters like description of temperature stratification.

- Flow field resolution

  For models that reduce the input data and the flow field to discrete values (grid), the resolution of the input data and the calculated flow field shall be selected appropriately with regards to the scale of the effects expected or known to be relevant. This implies that the description of the terrain and flow field around the measurement points must be of high resolution, which resolves also small scale effects which influence the measured wind conditions.

- Flow variable resolution

  For models that reduce the entirety of the possible sets of flow variables, i.e. all possible flow situations, to a set of discrete situations, the resolution of the discretisation must be appropriate for the scale of flow effects, and the way of evaluation (inter- and extrapolation of situations) must be appropriate for the nature of the effects. From this, for specific cases the conclusion may be drawn, that the entirety of occurring wind speeds cannot be described by a single representative per sector and the assumption of linearity, or that the description of the wind distribution via Weibull fit might be questioned.

Another impact from this may be that in complex terrain the calculation of orographic effects on the wind speed must be done with a resolution in wind direction, which resolves sufficiently the orographic variation at the site, and hence which is much finer than 30 degrees.

- Model validation

  The model shall be validated against the available measurement data as far as possible for each application case, to validate the applicability and to derive estimations for uncertainty assessment. This can be done by the cross-prediction and comparison of the wind conditions based on different measurement points. The significance of possible deviations of the validation results for the produced results shall be assessed and taken into account for the uncertainty assessment.

  Furthermore, previous validations of the model against measurement data for an exemplary case which are comparable to the application case, and which relate to relevant properties of the modelling, shall be available, cited in the site assessment report and taken into account for the uncertainty assessment.

- Model sensitivity analysis

  The sensitivity of the model to small changes of the input data or the model configuration should be investigated exemplarily for comparable cases and for the specific application case. The implications of the sensitivity analysis should be taken into account for the assessment of applicability of the respective model and the uncertainty assessment.

Generally, the flow modelling approach shall consider all site-specific measurement data, which are available and which help to reduce the uncertainty of the results. If the wind field modelling provides results also for the standard deviation of wind speed or turbulence intensity, also these results should be based on all available site-specific measurements of these quantities.

## 8.5 Extreme Winds

Extreme wind speeds are related to atmospheric phenomena that take place at different scales. Depending on the latitude, the sources of extreme winds (storm mechanism) can be different; while in tropical areas hurricanes and tropical storms are the main events generating extremes; in mid latitudes, low-pressure systems and mesoscale phenomena (storms) are normally the driving factors for extremes.

Frequently, measurement data with a sufficiently long period length to determine extreme wind speeds are not available. In such cases where this information is available, it is usually only for a meteorological station with distinctly different wind conditions than the site of interest. Hence, methods are required to estimate extreme wind speeds from a limited measurement data time series, and/or to transfer long-term time series measured at a meteorological station to the wind farm site.

For these tasks, several approaches are available and no universal, preferred method can be proposed. Instead, an overview of various methodologies is provided below and general recommendations are given in order to produce the most reliable results.
For the estimation of extreme wind speeds, two different methodologies are possible:

- Extrapolation of measured extreme wind speeds in time
- Derivation of extreme value probability distribution function from the long-term wind distribution

Both methodologies are based on statistical considerations related to the distribution of extreme values [12], but are entirely different in application. The particularities and application recommendations for both methods are described in the following section.

**Extrapolation of measured extreme wind speeds in time**

This methodology requires a measured wind speed time-series which includes measurements of relevant storm events, i.e. measured wind speed values at required heights and with relevant averaging period. Appropriate methods may be applied to recalculate the measured wind speed values to the required height and averaging period.

By analysis of the time-series for storm events, and appropriate application of statistical methods on those events, the measured storm events can be extrapolated from the limited measurement period (e.g. 10 years) to a given long term period (e.g. 50 years). Several approaches exist for accomplishing this task [13].

When applying this method, the following aspects shall be taken into account, addressed in the site assessment report and the respective approach justified:

- Significance of the time-series which is analysed for long-term conditions. This includes considerations regarding the length of the analysed time-series, for which the common recommendations on the minimum required length is about seven years, and also considerations about the dependence of the selected method on the maximum measured during the analysed period.
- Method for extrapolation of storm events to different heights and positions in the wind farm. The selected method shall be explained and justified.
- Method for recalculation of storm events to the relevant averaging period. The selected method shall be explained and justified.
- If relevant, considerations on directional effects or handling of multiple storm mechanism.

**Derivation of extreme value probability from the long-term wind distribution**

The extreme value theory in combination with various assumptions on conditions in the boundary layer, allows one to estimate the probability of occurrence of high wind speeds from the measured (long-term) Weibull wind distribution [14].

This methodology is based on certain simplifications and the results depend distinctly on the Weibull parameters and hence the way in which these are determined. Furthermore, the outcome of the method is a *distribution* of extreme values, where an exceedance level must be defined in order to derive a scalar value for the extreme value. Hence, when applying this method, the following aspects shall be taken into account, addressed in the site assessment report and the respective approach justified:

- Derivation of the extreme value from the calculated extreme value distribution. The modal value shall be addressed as the extreme value, and the consideration of further exceedance levels may be relevant for specific purposes.
- The way of performing the Weibull fit to measurement data shall be described and justified. Special consideration of the fitting routine to high wind speeds shall be given, and the dependence of the results for different fitting routines shall be shown at least exemplarily.

- The applied method for recalculation of the wind conditions from the measurement position to the wind turbine positions, especially the influence of this procedure on the Weibull shape parameter, shall be described and justified.
- The applied method for long-term assessment of the measured wind distribution, especially the influence of the long-term assessment procedure on the Weibull shape parameter, and/or the consideration of high wind speed events in any applied MCP procedure, shall be described and justified.

To come to more reliable results when doing extreme value estimation, it is recommended to apply both described methods for each application. For the overall result, the following aspects shall be taken into account and addressed in the site assessment report:

- Comments on uncertainty and significance of the derived extreme value estimation, taking into account the variation of results and sensitivity of the methodologies.
- Comments on relevance of the wind speed uncertainty for the derived extreme values. If a quantitative consideration is not feasible, this shall be handled qualitatively.
- Results of exemplary or site-specific validations or plausibility checks of the methodology.

## 8.6 Uncertainty

Obligatory for a site assessment is the estimation of the uncertainty associated with the input data, applied procedures and models and the determined results. If the results refer to other measures than the input (e.g. input: wind speed, result: energy) a sensitivity factor has to be applied for transferring the uncertainty of the input data to the result.

The uncertainty analysis shall be carried out considering the ISO information publication "Guide to the expression of uncertainty in measurement" [11] and the IEC 61400-12-1 Annex D and E [4].

Table 3 provides a list of uncertainty parameters that shall be included in the uncertainty analysis.

The overall uncertainty is assessed by a combination of its individual components. The selected method for combining uncertainty components should account for their independence or interdependence.

If the uncertainty components are independent from each other, the combined standard uncertainty is the square root of the summed squares of the uncertainty components. Alternatively, the uncertainty components can be fully correlated, leading to a summation of the individual uncertainty components.

Known systematic deviations between measured and true value must not be included within the uncertainty assessment, but have to be considered separately as systematic losses or bias.

| Topic | Uncertainty Component |
|---|---|
| Measurement | Wind speed<br>Anemometer classification according to IEC 61400-12-1 [4]<br>Anemometer calibration<br>Measurement set-up (mast influences)<br>Data logger (resolution)<br>Quality of correction method applied<br>Wind direction<br>Direction sensor characteristics<br>Measurement set-up (mast influences, accuracy of north gap orientation, in-situ comparison)<br>Quality of correction method applied<br>Remote sensing<br>Verification test<br>Sensitivity on environmental conditions<br>Variation of wind conditions across probe volume or uncertainty of respective corrections<br>Alignment of RSD<br>Control mast deviations / 2$^{nd}$ verification test<br>Availability of raw data<br>Data quality (signal to noise ratio, possible fixed echoes (SODAR))<br>Representativeness of measurement period: duration and availability with respect to seasonal and diurnal variation |
| Data Integrity | Uncertainty substitute value (Section 8.1) |
| Data Analysis | Uncertainties coming from the data filtering<br>Uncertainties coming from the data filling |
| Derived parameters | Air density<br>Uncertainty of measured air pressure and temperature<br>Turbulence intensity<br>Number of counts on which turbulence intensity is based<br>Temporal resolution of input data<br>Completeness of data base<br>Extreme winds<br>Comparative analysis of different methods<br>Sensitivity analysis (different time periods, independency criteria etc.)<br>Length of input time series |
| Correlation and long-term extrapolation | Overlapping period<br>Correlation between site and reference data<br>Consistency of reference station<br>Consistency of scaling factor<br>Length of past period<br>Future period<br>Used method<br>Inter-annual variability |

| Topic | Uncertainty Component |
|---|---|
| Flow modelling | Vertical extrapolation<br>Horizontal extrapolation<br>Sensitivity on wind direction<br>Limitations of models<br>Topographical descriptions (land cover, elevation, obstacles)<br>Atmospheric stratification |
| Wake modelling | Limitations of used model<br>Atmospheric stratification<br>Size and layout of wind farm |
| Power curve | Uncertainties and possible deviations of power curve measurement<br>Assumptions for calculated power curves |
| Systematic operational losses | Uncertainty assessment of relevant systematic operational losses (cf. Section 10.3) |

Table 3: Components to be considered in uncertainty analysis (all listed uncertainties belong to category B).

**Measurements**

Regarding all measurements, the uncertainty range of the used instruments, as provided by the manufacturer, shall be considered as minimal possible uncertainty for that measurement. For wind speed measurements, the findings from the anemometer classification according to [15] have to be taken into account and determine the minimum uncertainty for the specific terrain classes. Further uncertainties (e.g. influence of mast set-up or mounting uncertainties) will be added to this minimum uncertainty.

The uncertainty substitution value as derived from the assessment of the data integrity (Section 8.1) has to be considered as fully independent from the measurement uncertainty and hence has to be added to the measurement uncertainty.

In the case that the measurement includes RSD application please refer to Annex C (especially C5 to C10) for further specification of relevant uncertainties.

**Correlation and long-term extrapolation**

For the filling of data gaps and long-term extrapolation using MCP-extrapolation methods, the coefficients of determination of the data and the grade of coverage of the relevant wind speed ranges shall be taken into account for the uncertainty assessment of the results. Furthermore, the share of correlated to measured data strongly influences the final uncertainty of the extrapolation. The quality of the applied MCP extrapolation and the validity of the MCP result shall be tested by performing a self-consistency test.

If the period of the site measurement is less than one year, the uncertainty of the extrapolation is significantly increased. This is especially true for larger differences in measurement height between the site and the reference station due to possible seasonal variations of the vertical stratification of the atmosphere.

When long-term scaling has been applied, it should be shown that: the extrapolation procedure was generally validated also for short periods; significant correlation relations can be found between the data; wind directional effects can be resolved reasonably and seasonal effects can be assumed to be limited. These considerations need to be taken into account for the estimation of the uncertainty of the extrapolation.

**Flow modelling**

The uncertainties for the flow modelling shall be given depending on the topographic and meteorological complexity of the site with respect to the horizontal and vertical distance to the measurement position, and the representativeness of the measurement mast position for the wind turbine positions. The uncertainties shall also reflect the limitations of the applied model regarding the site characteristics.

In complex terrain with distinct directional structure and/or special uncertainties of the correctness of the wind direction measurement, the sensitivity of the results on wind direction deviations shall be investigated and taken into account as an additional uncertainty component.

**Wake models**

As the current wake models are validated and adjusted mainly to small wind farms, they have significant uncertainties for large wind farms. Furthermore, they are adjusted to near-neutral stratification conditions, and have larger deviations if the site conditions are different to neutral stratification. Furthermore, the calculated wind farm losses depend strongly on the measured wind direction, so that the determination of the sensitivity on a wind direction deviation is strongly recommended.

**Power curves**

If a measured power curve according to IEC 61400-12 [3] or IEC 61400-12-1 [4] is used for the energy yield assessment, the uncertainty should be assessed on basis of the stated measurement uncertainties, possibly in combination with evaluation of further power curve measurements or data. Deviations to the standards in the power curve measurement should be considered in uncertainty, if possible.

For assessment of the uncertainties of a calculated power curve, assumptions for the uncertainty of the calculated power curve have to be taken, considering the wind speed dependence of the power curve uncertainty. If additionally one or more power curve measurements are available for the relevant wind turbine type, the power curve values and relating measurement uncertainties should be taken into account for the uncertainty assessment of the calculated power curve.

**Systematic operational losses**

An uncertainty assessment of the relevant systematic operational losses (cf. Section 10.3) shall be performed, taking the magnitude of the estimated losses into account, as well as the data basis and methodology applied for assessment.

# 9 Site Assessment Results

From the results of the data evaluation and calculations as described above, the following results are derived and assumed as relevant for the assessment of the site-specific wind conditions.

## 9.1 Wind Conditions at the Turbine Sites

The wind conditions are derived from the data evaluation and calculations for the turbine position and hub height of each wind turbine. Additionally, as a measure of significance of the results, the percentage uncertainty for the derived mean wind speed values should be specified.

## 9.2 Air Density

Based on on-site measurement of air temperature and atmospheric pressure (see Sections 7.5 and 7.6), the site-specific air density is derived. If no on-site measurement of the air temperature and the air pressure is carried out, these parameters can be derived using readings from a representative meteorological long-term station nearby, corrected by at least the influence of deviating elevation. An extrapolation of measured temperature and pressure should be carried out provided that appropriate long-term data are available in order to derive the long-term mean temperature for the site.

Calculation of air density shall be performed according to IEC 61400-12-1 [4]. At high temperatures, it is also recommended that relative humidity be measured and corrected for. The correction for the density effect of the air humidity can be performed according to IEC 61400-12-1 Annex F [Equation F.1] [4].

## 9.3 Turbulence Intensity

Turbulence intensity ($I$) is defined according to Equation 1:

$$I = \frac{\sigma_v}{V_{\mathrm{mean}}} \cdot 100 \qquad \text{(Equation 1)}$$

Where:

$I$ = turbulence intensity [%]

$\sigma_v$ = measured standard deviation of the wind speed within 10-min. interval [$ms^{-1}$]

$V_{\mathrm{mean}}$ = measured mean wind speed within 10-min. interval [$ms^{-1}$]

For this calculation, the wind speed at hub height is derived from the wind field modelling based on the available measurement data. The standard deviation is calculated from the measured standard deviation and the variation of standard deviation over the height and wind farm area, which is either assumed constant, or which is derived from modelling results which is based on the available measurement data.

The derived turbulence intensity is calculated for the measurement positions at measurement height and for the wind turbine positions at hub height. The turbulence intensity values have to be specified for each 30 degree wind direction sector and wind speed bins of 1 $ms^{-1}$ width, where a significant number of underlying measurement values are available.

As long as the measurement period covers 12 complete months, long-term extrapolation of the measured data is not necessary for the determination of the turbulence intensity.

Depending on the measurement averaging period and sample rate, a correction of the measured turbulence to ideal conditions (de-trending and correction for sampling rate) can be recommendable.

If the characteristic or representative turbulence is calculated, the applied method shall be documented while ensuring that the specifications and criteria of the method are followed. IEC 61400-1 Ed.3 [1] can be applied for calculating parameters such as the representative turbulence standard deviation (IEC 61400-1 Ed.3, Section 6.3.1.3 Equation 11) or the site-specific turbulence standard deviation using the site-specific wind data (IEC 61400-1 Ed.3, Section 11.9, Equation 34).

## 9.4 Wind Shear Exponent

The magnitude of the wind shear exponent $\alpha$ between two given heights shall be calculated according to Equation 2:

$$\alpha = \frac{\ln\left(\frac{V_1}{V_2}\right)}{\ln\left(\frac{z_1}{z_2}\right)} \qquad \text{(Equation 2)}$$

Where:

$\alpha$ = wind shear exponent
$V_1$ = wind speed measured at measurement height $z_1$ [ms$^{-1}$]
$V_2$ = wind speed measured at measurement height $z_2$ [ms$^{-1}$]
$z_1$ = measurement height 1 above ground level [m]
$z_2$ = measurement height 2 above ground level [m]

The IEC 61400-1 [1] requires the wind shear exponent be calculated over the rotor-swept area, i.e. from lower blade tip to upper blade tip height, and for each wind turbine position. Hence, the wind shear exponent $\alpha$ shall be derived for each wind turbine position from the wind flow modelling results based on the existing wind measurements.

The wind shear exponent $\alpha$ for the measurement position(s) as derived from the measurements shall always be given as reference, while indicating the measurement heights used for its determination. The measured wind shear exponents should be considered to assess the uncertainty and significance the wind shear exponents calculated for the wind turbine positions.

Generally, for derivation of the wind shear exponent $\alpha$ from measurement values, the mast shading and further disturbing effects shall be corrected for, as far as possible, or the disturbed sector(s) shall be excluded from the evaluation. If more than two measurement heights are available, $\alpha$ can be derived by using a fit through all the measurement heights, respectively the wind shear exponents for different height intervals and possibly findings about height dependence can be derived. For the most accurate determination of $\alpha$, measurement heights should be close to upper blade tip or hub height and to the lower blade tip. As long as the measurement period covers twelve complete months with sufficient data availability, long-term extrapolation of the measured data is not necessary for the determination of wind shear.

## 9.5 Extreme Winds

From the results of the extreme value estimation methodologies, as described in Section 8.5, performed on base of data evaluation and wind field modelling with special considerations of the requirements described in Section 8.5, the extreme values for a recurrence period of 50 years for 10 minutes average ($V_{ref}$) and the gust value for 3 seconds averaging period ($V_{e50}$) shall be derived.

According to the requirements described in Section 8.5, the considerations on uncertainties are seen as part of the results, from which hints for the significance of the estimated extreme values shall be derived.

## 9.6 Flow Inclination

If a measurement of the flow inclination is not performed, or cannot be transferred from the mast position to the wind turbine positions, the flow inclination at hub height at the respective turbine positions shall be estimated as proposed in the IEC 61400-1 Ed. 3 [1]. This means that an estimation of the flow inclination at the hub height of the wind turbines can be made either by evaluating the results of appropriate three-dimensional flow simulations, or by applying the procedure described in IEC 61400-1 Ed. 3, Sections 11.2 and 11.9, i.e. fitting a plane to the topographic variations around the site.

# 10 Energy Yield Assessment

Within this chapter the assessment of the energy yield of a planned wind farm is described, based on representative high-quality site wind observations and related evaluations as described in the preceding chapters. After a careful wind data analysis and extrapolation of the site wind conditions to long-term, a site wind climate usable as input for flow modelling can be derived. The application of a suitable flow model results in a characterisation of the wind conditions at the wind turbine positions and at hub height. Connecting these wind conditions with the power production characteristics of the wind turbine leads to the gross energy yield for the wind turbine(s) and wind farm. To derive the wind farm net energy yield, the wind farm wake losses and systematic operational losses have to be assessed. The net energy yield is often given in terms of exceedance probability ($P_x$) values, which represent the resulting energy yields for given yield uncertainty and for different risk levels.

Figure 6 describes these main steps in the energy yield assessment process.

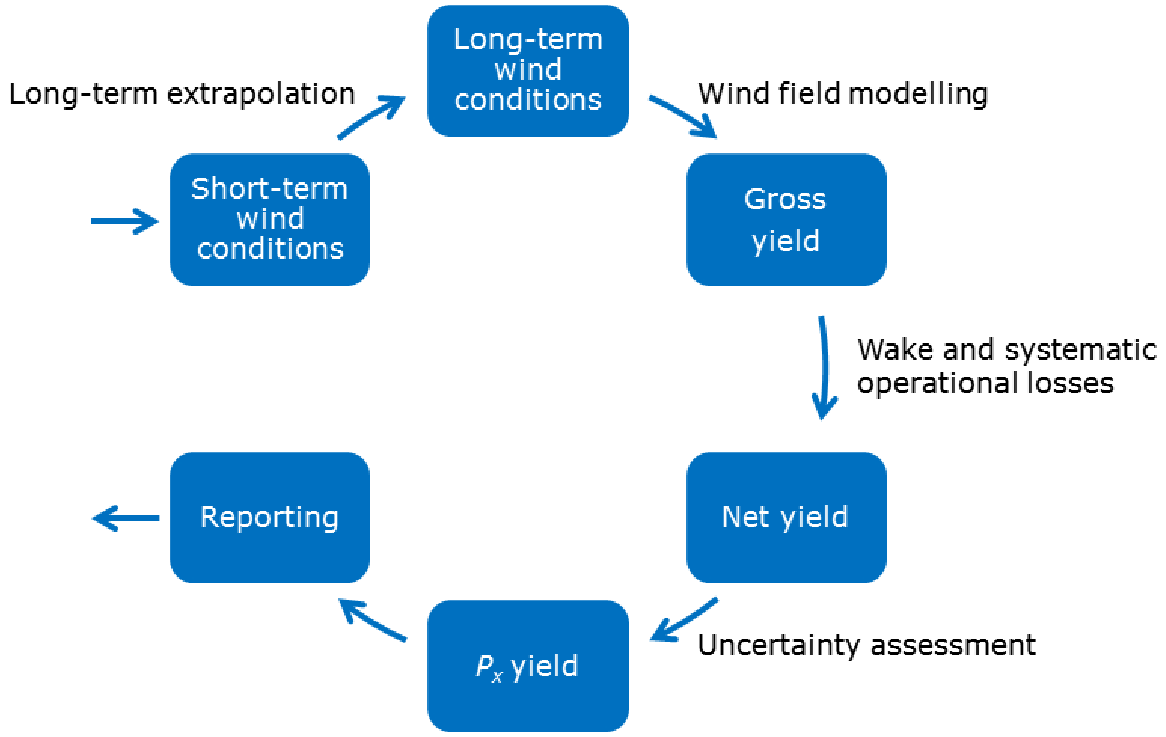


Figure 6: Main steps in the Energy Yield Assessment process.

## 10.1 Technical inputs for energy yield assessment

There are three main inputs needed for an energy yield assessment: the wind turbine power curve, the wind speed conditions at hub height and the air density at hub height.

Wind turbine power curves are provided by the manufacturers and can be calculated and/or measured power curves.

Calculated power curves are based on numerical models, possibly in combination with different power curve measurements for the respective wind turbine. The power curves may be calculated for different air density and further meteorological conditions (like turbulence and wind shear). In addition, the wind turbine manufacturers deliver their calculated power curves with corresponding $c_t$-curves, which are the basis for the calculation of the wake losses (see Section 10.3.1). They depend on the rotor blade geometry and the control of the wind turbine; therefore only such type-specific $c_t$-curves shall be used for the determination of the wake losses.

Measured power curves used for energy yield assessment shall be determined following the IEC standard 61400-12-1 (2005) [4] and measured independently by accredited institutes.

In the case that the considered power curve cannot be evaluated as adequate for the specific site conditions (turbulence, wind profile, wind flow angle, etc.), this can lead to losses (or gains) in the performance, and to higher uncertainties.

The average annual wind conditions at the turbine positions at hub height are the basis for calculating the energy yield. The wind speed and direction can be given in form of the time series, predicted frequency distribution or fitting of analytical distributions to the predicted frequency distributions (e.g. [10]). If a fit of analytical distributions is applied, this shall be done wind direction specifically, and the accuracy of the applied fit shall be assessed at least in terms of mean wind speed and the mean power density, but preferably in terms of turbine energy yield.

Based on the hub height wind conditions, the power output is calculated by referring to the power curve, and performing an air density correction to account for any difference between the air density present at the site and that for which the power curve is valid. This air density correction is performed according to the recommendations of the IEC standard 61400-12-1 (2005) [4].

## 10.2 Gross Energy Yield

The gross energy yield ($AEP_{gross}$) is the annual output of a wind farm without wake or other systematic operational losses.

The $AEP_{gross}$ is defined according to Equation 3:

$$AEP_{\text{gross}} = \sum_i P(v_i) \cdot H_i \qquad \text{(Equation 3)}$$

Where:

$P(v_i)$ = power output for each wind speed interval $i$

$H_i$ = the number of hours in a year for each wind speed interval ($H_i = f_i \times 8766$, with $f_i$ the relative frequency of each wind speed interval).

For the calculation of the $AEP_{gross}$, the wind speed frequency distribution may be described by a fit (e.g. sector-wise Weibull fit). Then the accuracy of the fitted data for the purpose of the energy assessment shall be assessed. The $AEP_{gross}$ can also be calculated using the wind data time series (applying the power curve on the wind data time series).

The $AEP_{gross}$ value shall be calculated individually for the relevant wind turbines (positions and hub heights), and may be calculated for the measurement positions at measurement and hub height for comparison purposes.

The overall wind farm $AEP_{gross}$ shall be calculated as the sum of the $AEP_{gross}$ of each wind turbine.

## 10.3 Net Energy Yield

In the previous sections, the gross energy yield of a wind farm is defined. It is based on power curve characteristics and calculated wind conditions within the wind farm, but it does not take into account reductions in the energy yield caused by wake effects or systematic operational losses occurring during the normal operation of a wind farm (one power plant). By considering wake and systematic operational losses, the net energy yield ($AEP_{net}$) is derived.

The $AEP_{net}$ is defined according to Equation 4:

$$AEP_{\text{net}} = AEP_{\text{gross}} \cdot \eta_{\text{total}} \qquad \text{(Equation 4)}$$

Where:

$\eta_{\text{total}}$ = overall loss factor (see 10.3.7)

The most important losses are described in the following.

### 10.3.1 Wake losses

The wake losses are the reduction of the estimated energy yield of a wind turbine or wind farm, caused by the presence of other nearby wind turbines. The wake effects are often modelled separately by using a wake model, e.g. [17], [18] and [19], but the wake modelling can also be an integral part of the general flow modelling of the terrain. The wake model used should be validated for the size, layout and spacing of the wind farm(s) in question, as well as the general flow conditions present.

For the calculation of the wake losses, all wind turbines located within at least 20 rotor diameters (referring to the biggest rotor size) of the wind turbine of interest should be taken into account. For large neighbouring wind farms onshore and offshore, and other demanding conditions, this modelling radius of 20 rotor diameters should be extended.

Losses in a wind farm are specified here as a percentage or loss factor in relation to the gross energy yield. The wake losses shall be given for each wind turbine and for the entire wind farm. The calculated wake losses may be stated separately for internal, external and future wake effects (assumed future scenarios).

### 10.3.2 Availability

Wind turbine non-availability due to exceptional faults, component failures and related service, as well as downtime due to planned wind turbine maintenance, is usually contractually limited. A simplified approach for estimating the turbine availability losses may be based on the assumption that the contractual limits are utilized, and that downtimes occur during mean energy production periods, i.e. percentage temporal losses are identical to percentage energetic losses. A more detailed and specific approach will take relevant operational experience and an analysis of the correlation of non-availability with wind speed into account.

The balance of plant losses describe losses due to downtime in components between the turbine main circuit breaker to and including project substation transformer as well as project-specific transmission line. Losses due to downtime of power grid external to the wind power facility are considered as grid availability losses. Both figures may be estimated based on experience values.

Limited site access may be necessary to be considered in the analysis of the non-availability losses.

### 10.3.3 Losses due to turbine performance

During operation, losses can occur due to non-ideal wind turbine performance. This can include losses due to the turbine not producing to its reference power curve within test specifications and losses due to differences between turbine power curve test conditions and actual conditions at the site (e.g. turbulence, inclined flow, off-yaw axis winds, wind shear, wind veer). Such losses may be estimated or calculated site specifically on basis of determined sensitivities according to methodologies defined in IEC 61400-12-1 [20]. High wind hysteresis losses should be assessed based on the site wind conditions and information on the turbine cut-out strategy. Losses due to operational issues like yaw misalignment, wind turbine instrumentation errors or blade pitch inaccuracies may be assessed based on operational experiences.

### 10.3.4 Electrical losses

Electrical losses cover the losses to the point of revenue metering, including, as applicable, transformers, collection wiring, substation, transmission and losses due to parasitic consumption (heaters, transformer no-load losses, etc.) within the facility. The electrical losses depend on the project-specific design of the grid connection and the involved components, and could be derived project specifically on basis of a detailed calculation, or may be based on estimations. The self-consumption of wind farms is often seen as an operation cost factor rather than an efficiency figure, and considered in the operation and maintenance (O&M) budget rather than as energy loss.

### 10.3.5 Environmental losses

Over the lifetime, wind turbines will face environmental impacts which affect the power output. For example, it can be expected that the rotor blades do not keep their ideal aerodynamic profile, due to dirt, insects, rime as well as aging of the rotor blade material. Such limited impacts can mostly be assessed only on basis of rough estimations.

The icing losses (due to temporary ice accumulation or ice induced shutdown) should be estimated site specifically or on basis of relevant experience values. Losses due to ambient temperatures outside the turbine’s design specifications can usually be estimated based on the temperature distribution derived for the site.

### 10.3.6 Curtailments

Special operating modes should be calculated according to the specific requirements of the wind farm project. Such curtailment may enclose losses due to shutdowns or altered operations to reduce noise and shadow impacts, and for bird or bat mitigation.

Losses due to shut down or special operation modes implemented to reduce physical loads on the turbines should be calculated on basis of the site specific wind conditions and specification of the applied operation strategy, requested at the turbine supplier.

Temporary or ongoing limitations of the external grid could cause grid curtailment losses, which should be calculated on basis of the distribution or times series of wind farm energy output.

### 10.3.7 Summary of losses

The systematic operational losses shall be given in a tabular form and be summarized as overall loss factors. The origin of the values used shall be specified.

When combining different loss factors, the interdependencies should be considered. Certain loss factors may occur simultaneously or exclusively, so loss factors can mutually affect each other. After the treatment of interdependencies, the percentage losses should be transformed into efficiency η and combined by multiplication of the remaining efficiencies $\eta_1, \eta_2, \eta_3, \ldots, \eta_i$.

$$\eta_{\text{total}} = \eta_1 \cdot \eta_2 \cdot \eta_3 \cdot \ldots \cdot \eta_i \qquad \text{(Equation 5)}$$

Where:

$\eta_i$ = 1 − $\text{loss}_i$ , expressed as a fraction

## 10.4 Energy Yield Exceedance Level

The calculated values for AEP represent the most probable results, considering the uncertainties of the calculation. The uncertainties are usually assumed to follow a normal distribution. From this distribution the values *Px* which are exceeded with a given probability *x* can be derived. The probability for exceeding the most probable result is 50%, so the calculated value for AEP is also called “P50”-value.

Several *Px*-values are normally used as input for the project planning, in particular for the financing of the wind farm. Based on the determined overall result uncertainty, interpreted usually as standard deviation, at least the $AEP_{net}$ values for further exceedance levels shall be specified, so that at least the exceedance levels P75, P90 and P95 are covered.

# 11 Reporting

The following chapter specifies the requirements for the reporting of the performed work and derived results for the site assessment and/or energy yield assessment.

## 11.1 Elements of the Report

The report shall include at least the following elements, describing at least the following topics. As the purpose of the report can cover either the site assessment or the energy yield assessment (or both), the chapters on the respective site assessment and energy yield results are optional.

1) Description of the assigned tasks
   a. Name and address of the client
   b. Specification of the scope of assigned work
2) Summary of the document and the results
   a. Overview of the assigned work;
   b. Summary of the derived results and findings;
   c. Highlighting of the particularities and critical issues with reference to the respective chapters;
   d. Complete list of deviations to the guideline with reference to the chapter "Deviations to the MEASNET Guideline 'Evaluation of Site-Specific Wind Conditions'".
   e. Overall assessment of the significance of the results with reference to the uncertainties and/or the deviations to the guideline.
3) Measurement Documentation
   according to Section 11.2
4) Measurement Data Report
   according to Section 11.3
5) Site Assessment Results (if relevant)
   according to Section 11.4
6) Energy Yield Results (if relevant)
   according to Section 11.5
7) Chapter "Deviations to the MEASNET Guideline 'Evaluation of Site-Specific Wind Conditions'":
   a. Complete list of deviations to the guideline with commenting and reference to the uncertainty assessment;
   b. Overall assessment of the impact of the deviations on the significance of the results.

The reporting may be divided into two documents, where one document ("Wind Measurement Report") would contain the items: 1), 2), 3), 4), 7). The other document ("Site Assessment/-Energy Yield Assessment Report") would contain the items: 1), 2), 5) and/or 6), 7).

## 11.2 Measurement Documentation

If the scope of the work includes the performance of the measurement, measurement documentation shall be provided according to the requirements stated in this section. If the scope of the work does not include the performance of the measurement, a summary of the available measurement documentation shall be provided according to the requirements stated in this section. As in this case the work is based on documentation delivered by a third party, the documentation needs to be checked and assessed regarding completeness and suitability.

In general, the reporting format for the measurement documentation shall be according to IEC 61400-12-1 [4] and contain at least

1) A description of the site including:
   a. Photographs of the complete 360°-sector taken from the measurement position(s)
   b. Topographical maps of the site indicating the mast position
2) A description of the measurement system including:
   a. identification of the sensors and data acquisition system, including documentation of calibrations for the sensors respectively sensitivity test and verification test of the RSD;
   b. description of the arrangement of cup anemometers and others sensors on the meteorological mast, following the requirements and descriptions in IEC 61400-12-1 [4] and IEA [6];
   c. sketch of the arrangement of the meteorological mast showing principle dimensions of the tower and instrument mounting fixtures;
   d. description of the method how to maintain the anemometer calibration over the duration of the measurement period and documentation of results that shows that the calibration is maintained respectively the method to monitor the stability of the RSD (with a mast measurement or with a second verification test after the measurement).
3) A description of the measurement procedure
   a. documentation of the procedural steps, sampling rate, averaging time, measurement period;
   b. a log book that records all important events during the measurement period; including a listing of all maintenance activities that occurred during the measurement period;
   c. identification of any data rejection criteria that were applied during data analysis and determination of results.

Reporting format and results to be derived for each site-specific condition are described in more detail in the following sections.

## 11.3 Measurement Data Report

This report contains the results of the measured quantities as described in Chapter 7.

**Wind Speed and Direction Data**
Mean as well as max / min and standard deviation values of the wind speed for the complete measurement period and for each month shall be presented in tabular format.

Sectoral Weibull *A* & *k*-parameters and the frequency distribution for sectors with the width of 30 degree or less, the first centred around geographic north, shall be specified in tabular form for the measurement device position(s). In addition, a wind direction distribution shall be plotted. A detailed frequency distribution shall be presented using the method of BINs with BIN-width of 1 $ms^{-1}$ and sector-width of 30° or less, the first sector centred on geographic north, for the mast position(s) in tabular format.

The daily and the seasonal pattern of the average wind speed shall be presented in tabular form.

**Flow Inclination**
In the case that the flow inclination is measured, mean- as well as max-values of the flow inclination for each wind direction sector and wind speed bin should be presented in tabular form.

**Temperature**
Mean as well as min- and max-values of the air temperature for the complete measurement period and for each month shall be presented in tabular form.

**Pressure**
Mean as well as min- and max-values of the barometric air pressure for the complete measurement period and for each month shall be presented in tabular form.

**Humidity**
Mean as well as min- and max-values of the relative humidity for the complete measurement period and for each month shall be presented in tabular form.

## 11.4 Site Assessment Results

This report contains the derived results as described in Chapter 9

**Wind data**
Sectoral Weibull *A* and *k*-parameters and the frequency distribution for sectors with the width of 30 degree or less, the first centred around geographic north, shall be specified in tabular form for the wind turbine positions in hub height. Alternatively, a detailed frequency distribution shall be presented using the method of BINs with BIN-width of 1 $ms^{-1}$ and sector-width of 30° or less, the first centred on geographic north, for the wind turbine positions at hub height in tabular form.

**Air Density**
The mean value of the air density at hub height for a representative position of the wind farm shall be stated in the report. Moreover, if the site is complex and significant elevation differences (i.e.: ±500 m) exist within the wind farm, the mean air density at hub height for each wind turbine position shall be presented in tabular format.

**Turbulence**
Turbulence intensity as well as the characteristic/representative turbulence intensity according to IEC 61400-1 ed. 2/ed. 3 [1] respectively [2] for each wind speed BIN using a BIN-width of 1 $ms^{-1}$ or less and wind direction BIN using a BIN-width of 30° or less at hub height at the mast position shall be presented in tabular format.

**Wind Shear Exponent**
Mean wind shear exponents ($\alpha$) shall be presented using the method of BINs with BIN-width of 1 $ms^{-1}$ and sector-width of 30° or less for mast position(s) in tabular format.

For the turbine positions the mean wind shear exponents derived from the wind field calculation shall be given.

**Flow Inclination**
The estimated flow inclination (see Chapter 9.6  is documented as mean flow inclination for each wind turbine position for each hub height.

**Long-term Extrapolation**
The reporting of the long-term extrapolation should include the following:

- Description of the procedure and applied simplifications or observed particularities
- Reporting of the influence of the applied long-term extrapolation. This should preferably be done by reporting of the arising long-term wind distribution and statistics.

- Judgement of the significance and uncertainty of the performed long-term extrapolation. This should be done by critical analysis of performed consistency tests and by comparison of the influence of different long term data sources and periods.

**Extreme Winds**
The results of the $V_{ref}$ calculation have to be reported, including all the relevant details in order to ensure traceability. The documentation has to include:

- Description of the methodology:
    - Statistical or physical basis.
    - Existing references.
    - Limitations of the method.
    - Uncertainty calculation for the selected method (if available).
- Description of the data available to calculate $V_{ref}$:
    - Anemometer type.
    - Averaging period, frequency of data.
    - Available period.
    - Applied filtering criteria.
- Verification of the selected method
    - Comparisons with other calculation methods

**Vertical / Horizontal Flow Modelling Procedure**
Concerning the used model the following aspects should be reported:

- General description; including software name and version
- Simplifications, assumptions and their consequences.
- Limitations of the model:
- Limitations to calculate in complex terrain (i.e. maximum slopes or thermal effects).
- Input data limitations (i.e. number of measurement points).
- Calculation limitations (i.e. number of grid points).
- Other limitations.
- Literature. A review of existing literature about the model should be carried out; special attention should be paid to papers describing model results in similar environments to the one to be studied.

Concerning the modelling procedure itself the following aspects should be reported:

- Selected configuration of the flow model.
- Used input data.
- Performed site validations.

Concerning the model output the following points have to be reported:

- Calculated variables
- Grid resolution. This parameter has to be specified according to the model capabilities to simulate and according to the available input data
- Spatial domain size

Concerning the specific model validation, the methodology used for the validation has to be described and reported jointly with the results.

## 11.5 Energy Yield Results

This report contains the derived results as described in Chapter 10.

**Gross energy yield**

The $AEP_{gross}$ value shall be presented for the wind turbine positions at hub height. The overall wind farm AEP shall be calculated as the sum of the AEP of each wind turbine position.

**Wake losses**

The wake losses shall be given for each turbine in the wind farm and for the entire wind farm. The wake model used including software version and the wake decay constant or other parameter settings, shall be presented.

**Systematic operational loss factors**

A complete list of systematic operational losses used shall be given in tabular format. The table shall include the loss factors and loss assumption used.

**Net Energy yield**

The net energy yield value ($AEP_{net}$) of the entire wind farm as well as the corresponding exceedance levels of net energy yield at 75%, 90% and 95% shall be given.

# References


[1] IEC: IEC61400-1 Wind turbine generator systems - Part 1: Safety Requirements, 2nd Ed., 1998.

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[20] IEC: IEC61400-12-1 Ed. 2 Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2nd Ed., CDV July 2015.

[21] IEA: IEA Recommended Practices 15: Ground-based vertically profiling remote sensing for wind resource assessment, 1st Ed., 2013.

# Annex A

(normative)

## Requirements for the Documentation of Wind Measurements

As a basis for assessment of measurements which are used as input for the described site assessment procedure, and required for evaluation of the associated measured data, a complete documentation of the measurement equipment and the measurement location shall be available.

Generally, gaps in the documentation of the measurement will lead to increased measurement uncertainties, which will be described and considered within the data evaluation process.

The documentation shall include the following aspects:

- Location of the measurement
    - Position of the measurements in terms of specification of coordinates and associated coordinate system (projection and datum) including accuracy of position.
    - Photo documentation (including camera position and bearing) and description of the immediate surroundings of the measurement.
    - If relevant, specification of distance, main properties and dimensions of nearby obstacles.
    - Magnetic declination
- Measurement equipment
    - Specification of the type and dimensions of the measurement. The mast shall be documented by at least photos showing the entire mast and the mast top in detail. The RSD shall also be documented by photos.
    - Specification of the height, dimensions and orientation of the booms. The mounting of each wind-related sensor shall be documented additionally by sketches and photos. At least, for all the wind-related sensors the sensor levels relatively to the ground, the orientation of booms or sensors relatively to geographic north and the distances of the sensors to the mast structure must be possible to derive from the documentation.
    - Specification of the used measurement sensors including serial number, information on calibration and measurement uncertainty, position at mast, orientation (if relevant). For anemometers, the calibration information shall consist of calibration certificates from MEASNET approved institutes.
    - In the case that an RSD is used a sensitivity test report and a validation test report is required.
    - Description of the orientation of the north mark of the measurement devices in geographic north.
    - Description of disturbances on the mast measurements like lighting arrestor in terms of specification of dimensions, distance and other relevant information.
    - Description of disturbances on the RSD like trees or other obstacles in terms of specification of dimensions, distance and other relevant information

    - For mast measurements: description of the data logging system including specification of data logger type, version, software release and description of power supply, data transfer, sensor wiring including possible lightning protection, description of measures taken to calibrate the data logging system.
    - For RSD measurements: description of the manufacturer, type, specification of the settings, software version, description of power supply and data transfer.
    - Information on sensor heating, if relevant, and the power supply system for it.
- Measurement history
    - Specification of date and time of installation, dismantling, possible changes and maintenance at the measurement.
    - In case of changes of sensors, complete documentation of performed work, changes in equipment and resulting changes of calibration values.
    - If other parties than the MEASNET accredited measurement institute for measurement installation, changes, maintenance, other work on sensors or other quality relevant aspects were involved, a description of the respective work, involved parties and measures taken for supervision and control of the work has to be provided.
    - List of special incidents observed, like defects, power supply problems, icing periods and other relevant issues.
- Measurement data
    - Specification of applied calibration factors and any other applied modifications of the data. Unambiguous documentation of these aspects by dumps of logger parameters or logger, respectively RSD, software and compilation of further relevant information like further software involved.
    - Specification of calibration factors or any other modifications of the data which still must be applied on the data.
    - Specification of sampling rate, averaging period and relevant properties of further statistical evaluations performed in the data logger, respectively RSD. Description of particularities like reductions of accuracy or resolution, dead bands and others.
    - For mast measurements: unambiguous assignment of the data channels to the sensors.
    - Complete description of the measurement data format and possible particularities like error codes or others.

# Annex B

(informative)

# Measurement Data Quality Assessment and Filtering

**Objective**

The quality assessment of measurement data is a process which requires a profound knowledge of measurement technology and a broad experience in processing measurement data. Hence it would go far beyond the scope of the document at hand to provide a description of an adequate data quality assessment procedure. In fact, each experienced measurement institute will have developed methodologies and tools to perform such data quality assessment and filtering procedure.

Nevertheless, in the following some aspects of data quality assessment are described, which can be seen as hints and recommendations to be taken into account, when developing the individual data assessment procedure.

For quality assessment, the data of the relevant sensors should be evaluated apart, but also in comparison to the data from other sensors and possibly further masts at the site. The checks applied on the data or appropriate auxiliary quantities (like relations or deviations) should consist of different evaluations, including

- **Check for error values/substitutes:** Error values/substitutes (like ‘999’ or "NaN") would disturb statistical evaluations and need to be filtered out or handled appropriately by the evaluation tools.
- **Visual check:** With a visual inspection of the data it is possible to detect invalid data such as spikes or sudden drops. This visual check must include a comparison with the data measured at different heights.
- **Check for completeness:** Check whether the number of records and their sequence is correct (identification of gaps, check for repetition).
- **Range test:** Check whether the data of each sensor lie within the measurement range of that sensor.
- **Constant value test:** Repetitions of consecutive wind data (speed and direction) with the same value.
- **Test for trends and inconsistencies:** Detection of implausible variations or patterns in time.
- **Related parameter test:** Comparison based on the expected values for the physical relationships between the different parameters (e.g. $V_{\mathrm{min}} \leq V_{\mathrm{mean}} \leq V_{\mathrm{max}}$). If one data value is assessed as erroneous all related quantities have to be rejected. For example, if the mean wind speed value is deemed invalid, the wind speed standard deviation as well as maximum and minimum are also to be considered as invalid.
- **Correlation test:** Use of scatter plots to assess whether the correlation between different sensors is plausible, for example two different anemometers.

Major erroneous data periods are to be reported. Temperature, pressure, precipitation and humidity sensors installed on the measurement mast may be used to identify erroneous wind data periods.

Raw data series are consequently filtered; only correct values are retained. The main aim of this exercise is to obtain a correct (albeit incomplete) data series from the former raw data series.

This stage is considered essential since sensor malfunctions can lead to a poor estimation of the available wind resource.

# Annex C

(normative)

# Wind Measurement using Remote Sensing Devices

## C1. Objective

Referring to IEC 61400-12-1 [4] the state of the art technique to measure wind speed and direction is to mount cup anemometers and wind vanes on a meteorological mast. Remote sensing techniques like LIDAR and SODAR have reached a stage, where they can be considered as supplement or as alternative to mast measurements in many cases. The objective of this Annex is to define necessary preparations and conditions for the utilization of remote sensing devices (RSD's) and possible applications of these systems.

## C2. Requirements on RSD

Two different report types must be available at the time of preparing the site assessment, besides further requirements described below.

- A verification test report acc. to IEC [20] or IEA [21]

The measurement of the RSD is traced back to national standards by means of a comparison to measurements of calibrated reference sensors on a met mast. The verification test has to be performed for each individual RSD unit. An application-specific differentiation for the requirements on verification tests is given below. In the case of significant and systematic deviations of the measurements of the RSD and the reference sensors, possible reasons for deviations shall be investigated. If the RSD works basically correct, the transfer functions as derived from the comparison of the reference sensors to RSD measurements should be applied, and the evaluation of the verification test shall be repeated with the corrected data of the RSD.

- A device type specific classification test report acc. to IEC [20].

Type specific means that there is no need to perform a classification test for each individual device, but it is valid for one production series as long as the device and its operating software is not changed with regards to measurement-relevant parts, i.e. not to modem or GPS parts. It includes an analysis of the sensitivity of the measurements of the RSD on environmental variables like e.g. wind shear and turbulence intensity. This sensitivity analysis considers that influencing environmental variables may be different at the verification test site and at the later application of the RSD at the investigated site. Thus, a classification test is needed for all applications, for which the verification test is not performed over the entire measurement period of the application.

These tests should be prepared by independent companies having extensive experience in wind measurements, RSD and with the performance of such tests.

For all types of RSD measurements, verification tests are needed. In the case that the measurements are performed for the determination of the absolute wind speed, the verification test must be performed in simple terrain, i.e. terrain meeting the requirements of Annex B of IEC 61400-12-1, Ed. 2 [20].

Application specific information regarding verification test requirements is given in Annex C6.

## C3. Monitoring of RSD Measurements

Apart of the verification test and classification tests, the IEC 61400-12-1, Ed. 2 [20] requires a monitoring of the RSD measurements with a control mast with a minimum height of 40 m or the lower tip height of the considered type of wind turbine. The purpose is to check the data for consistency, caused e.g., by a drift or outliers in the data of the RSD or systematic effects because of unavailability times. A monitoring can be substituted by performing a second verification test after the measurement campaign, as described in Annex C8.

## C4. Application of RSD in Complex Terrain

The IEC 61400-12-1, Ed. 2 [20] restricts the application of RSD to simple terrain (simple terrain according to Annex B of [20]). Background of this restriction is that most RSD's measure different wind speed components in spatially separated probe volumes under the assumption of equal wind conditions across the different probe volumes. This assumption can be violated in non-simple terrain and can lead there to significant measurement errors. Nevertheless, there are different possibilities to control or correct such errors:

- The measurement error due to flow inhomogeneity across the probe volumes can be evaluated with the help of three-dimensional flow models. In addition, IEC 61400-12-1, Ed. 2 [20] includes a simple procedure to estimate this measurement error. Based on such assessments, the position or beam orientation of the RSD can often be chosen such that the respective measurement error remains acceptably low.
- The error assessment by means of the application of three-dimensional flow models can be applied for deriving corrections of the measurement of the RSD.
- There are RSDs with automatic detection of complex flow regimes and internal corrections of the measurement error due to the flow complexity.

Contrary to [20], the application of remote sensing is acceptable in non-simple terrain if at least one measurement mast exists on the site. RSDs give additional information about the flow conditions on the site and such can be used as a validation of the flow model, and so reduce modelling uncertainties. See also a more detailed description in Annex C9. In this case following conditions shall be considered.

- If no correction of the measurement of the RSD is performed, the respective measurement error due to inhomogeneous airflow as assessed by means of a three-dimensional flow model or by other means shall be calculated and added as standard uncertainty. The total combined uncertainties of the measurement of the RSD must be acceptably low for the required application.
- If a correction of the measurement of the RSD is performed on the basis of a three-dimensional flow model or an internal correction, at least half of the correction shall be applied as an additional standard uncertainty of the correction (weighted with wind rose). For relative wind speed applications (wind shear) the *difference* of the correction at the relevant heights used shall be considered.
- If a three-dimensional flow model is used to assess a correction or to estimate the measurement error due to inhomogeneous airflow, the model shall be applied with a resolution in terms of the wind direction of at least 10°. Furthermore, the spatial resolution of the model shall be appropriate in horizontal and vertical direction such that differences of the airflow covered by the different probe volumes can be

evaluated. For usually regarded measurement heights and devices a reasonable mesh resolution would be in the order of 10 m for the horizontal resolution.

- Both uncorrected and corrected wind speed time series must be available to allow the determination of the magnitude of the internal correction and plausibility checks.

Correction methods have to be validated and the general correction principle must be transparent.

# C5. Further Requirements on RSD Measurements

IEC 61400-12-1, Ed. 2 [20] as well as the IEA-guideline [21] further contain requirements on the realisation of measurements with RSD’s, which shall be fulfilled and which in the end also influence the accuracy of the measurement. These requirements cover for instance the positioning of the RSD relative to wind turbines and other objects (forests, buildings and sound sources), the parameterisation of the RSD, the alignment of the RSD and the synchronisation of the RSD with concurrent mast measurements or other measurements. The uncertainty of the measurement of the RSD shall be evaluated according to [20], i.e. the following uncertainties shall be considered:

- Uncertainty resulting from the verification test
- Uncertainty resulting from the sensitivity of the RSD on environmental conditions
- Uncertainty due to the assumption of equal wind conditions across the probe volumes. If the respective measurement value is corrected, the uncertainty of the correction shall be applied; otherwise the full measurement error shall be treated as uncertainty. This uncertainty shall also be assessed in case of simple terrain according to the definition in Annex B of [20].
- Uncertainty due to possible misalignment of the RSD (levelling and directional orientation)
- Uncertainty due to an unexpected result of the monitoring of the RSD with a control met mast according to Annex L of [20], possibly combined with rejection of data analogous to chapter 7.2. If a second verification test is performed instead of the application of a control mast, the second verification test shall be treated for the assessment of a possible additional uncertainty like a measurement with a control mast according to Annex L of [20].

The verification test, the sensitivity analysis and the uncertainty analysis according to IEC 61400-12-1, Ed. 2 [20] shall be performed at least in terms of the 10-minute mean value of the horizontal component of the wind speed. In addition, it should be performed for all other measurement variables of the RSD as needed for the specific application. These can be:

- Wind speed ratio at two height levels, e.g. wind speed at hub height divided by wind speed at highest measurement height of an adjacent measurement mast
- Rotor equivalent wind speed according [20]
- Wind shear
- Wind veer
- Wind direction
- Standard deviation of horizontal wind speed component

- Turbulence intensity
- Vertical wind speed component
- Standard deviation of vertical wind speed component
- Vertical flow inclination
- Extreme wind speed within 10-minute period

In the case that an RSD is applied for turbulence measurements, at least the verification test shall be performed also for the turbulence intensity, and the results shall prove the capability of the instrument for such measurements.

It is pointed out that the accuracy of an RSD can be dependent on the measurement height, so the requirements of the IEC 61400-12-1, Ed. 2 [20] regarding heights used for the verification test shall be applied.

## C6. Application of RSD's for Absolute Wind Speeds

Generally, for absolute wind speed measurements, the same requirements with respect to the measurement period and measurement height as described in chapter 7.2 and 7.3 apply.

This remains valid also for the case that a measurement mast is used only as control mast for the RSD, but all data evaluation is done only on the basis of the measurements of the RSD. In these cases, besides what has been mentioned in Annex C2, the uncertainties of the RSD in terms of the

- measurement of the horizontal wind speed component and
- wind direction at the target measurement heights

are relevant regarding the wind resource. In the case of large turbines, it is recommended to cover the entire height range of the turbine rotor in order to evaluate the wind shear, rotor equivalent wind speed and wind veer over the rotor height range apart of the wind conditions at hub height. Wind measurements with RSD's can be subject to data gaps of other nature than in the case of the application of measurement masts. These can arise from e.g.:

- Precipitation (especially SODAR data is mostly invalid or inaccurate at rain). For vertical wind speed measurements also LIDAR devices are affected.
- Fog (LIDAR can often not measure in fog)
- Decreasing data availability with measurement height
- Internal data filters
- Atmospheric stability (the availability of SODAR data often decreases at neutral atmosphere due to lacking air temperature gradient)
- Too low aerosol content (can appear at LIDAR measurements, e.g. at clear weather at high altitudes)
- Too high ambient noise or fixed echoes in the case of SODAR measurements
- Outage of power supply

Periods with doubtful measurements must be excluded from the data evaluation. However, care shall be taken if data gaps always tend to appear at similar meteorological conditions and if these conditions are then not well represented in the valid database anymore. In such cases, relations to long-term data can be biased, what can result in significant errors of the long-term adjustments of the measurements.

## C7. RSD with Control Mast

One verification test according to IEC 61400-12-1, Ed. 2 [20] or IEA [21] is required. The verification test can be performed at a special test site before the application at the investigated site. As an alternative, the verification test can also take place at the investigated site provided that the control mast meets the requirements for verification test masts according to Annex L of [20] and the terrain at the test site meets the terrain requirements of Annex B of [21]. The control measurement mast shall be used to monitor the performance of the RSD as described in [20] over the entire measurement period. This includes in-situ testing of the RSD at the end of the measurement period. A particular case exists if the verification test is performed with the control measurement mast over the entire measurement period. Then, no classification test is needed, because the uncertainty of the RSD measurements due to sensitivities on environmental conditions is zero. While the verification test has to be performed in flat terrain, the RSD can be applied and the in-situ comparison of the RSD can be performed in complex terrain.

## C8. Stand-Alone Application of RSD

If the on-site measurements are performed only with an RSD, a verification test must be performed before and after the application at the investigated site. The verification test after the application at the investigated site serves as a substitute of a control measurement mast at the investigated site for ensuring the consistency of the RSD measurements over the measurement period. The difference of the verification test results shall be evaluated as in the case of applying a control mast according to Annex L of [20]. The verification tests must be performed in flat terrain The RSD can be used as stand-alone device in flat terrain, but shall not be the only measurement device in a complex site.

Verification tests must be repeated at latest two years after the start of the first application following the former verification test in the case of continuous operation of the RSD at one site.

## C9. Wind Measurements Aiming for a Better Spatial Coverage of a Wind Farm Area

Wind measurements with RSD’s in addition to mast measurements often aim to provide a better spatial coverage of the considered wind farm area by the measurements. For this application, an RSD can be used successively at different positions, while the position of the measurement mast remains fixed. Then the wind conditions at the positions of the RSD are re-constructed for the full measurement period of the mast using MCP-methods, see chapter 8.3.2.

It is essential for this application that for each measurement position of the RSD the wind conditions cover all main wind directions and all main wind speeds occurring in the different wind direction sectors. This is often reached after a measurement period of 3 to 6 months per position. Measurement periods below 3 months per position should be avoided.

Furthermore, the wind conditions at the position of the RSD and the mast are influenced by daily and seasonal variations. Thus, a sufficient coverage of stability and typical weather conditions in the commonly covered measurement period per measurement position is essential. This may require a longer measurement period, especially for situations in which stability has a significant impact (e.g. coastal or offshore sites).

For the above described application, the uncertainty of the wind resource measurement contains the following uncertainty components, besides what is mentioned in Annex C5:

- Uncertainty of the wind measurement of the RSD
- Uncertainty of the applied relation of the measurement of the RSD and the measurements of the measurement mast
- Uncertainty due to limited representativeness of the measurement period with regard to wind conditions and seasonal variations

## C10. Wind Shear Measurements for Vertical Extrapolation of Mast Measurements

For the purpose of vertical extrapolation of mast measurements, the RSD measurement is used in combination with a reasonably tall measurement mast for vertical extrapolation and is located in a distance to a measurement mast, which ensures at the same time minimal disturbances by mast & surrounding and most identical wind conditions at both mast and RSD location. Then the same requirements as for the above described case of an RSD for measurements of the absolute wind speed with a co-located measurement mast apply, except that the on-site verification test during the entire measurement period and the in-situ comparison can also be performed in complex terrain. The RSD needs to cover at least part of the height range of the mast measurements and the following uncertainties are relevant in terms of the wind resource, besides what has been mentioned in Annex C5:

- Uncertainty of the wind measurement with the measurement mast at the considered measurement height
- Uncertainty of RSD regarding the wind shear measurement or regarding the determination of the ratio of wind speeds at the target height and the considered mast measurement height
- Uncertainty of the applied relation of the measurements of the RSD and the measurements of the measurement mast.

Different techniques can be applied for the transfer of the mast measurements to larger heights on the basis of RSD measurements, depending on the commonly covered measurement period:

**C.10.1. The mast measurement and the RSD measurement cover exactly the same period:**

If the measurement mast and the RSD have one common measurement height and if in addition the RSD covers exactly the target height, the principle of the relative wind speed measurement according to IEC 61400-12-1, Ed. 2 [20] shall be applied. In [20], the wind speed measured by the RSD in the target height is divided by the wind speed measured by the RSD in the common measurement height for each 10-minute period in order to eliminate the part of the systematic measurement error of the RSD, which is equal at the two height levels. This wind speed ratio is multiplied with the wind speed measured by the measurement mast in the common measurement height in order to evaluate the wind speed at the target height. If the measurement height of the measurement mast with the most precise measurement (usually the measurement at top of the mast) is not exactly matched by the RSD, or if the target height is not exactly matched by the RSD, a shear exponent shall be calculated from the RSD measurements at the height closest to the referring mast measurement height and the target height for each 10-minute period, and this shear exponent shall then be applied in order to extrapolate the mast measurement to the target height. In these cases the uncertainty of the evaluated wind speed at the target height results from the measurement uncertainty of the mast measurement and from the uncertainty of the relative wind speed measurement or shear measurement of the RSD.

**C10.2. The RSD measurement covers a shorter period than the mast measurement:**

Great care shall be taken in this case for a proper representation of the shear conditions in the measurement period covered by the mast and by the shear measurements of the RSD. The wind shear is strongly influenced by the atmospheric stability, and in short measurement periods of the RSD, special stability conditions can prevail. Thus, a sufficient representation of stability and weather conditions in the measurement period of the RSD is essential for this application, similar to the case described in Annex C9. This is often reached after a common measurement period of about 3 to 6 months when both measurements are fully available in this period. Situations where stability has a significant impact (e.g. coastal or offshore sites) require a critical assessment whether the chosen measurement period is sufficient to cover representative conditions. Common measurement periods below 3 months should be avoided.

There are different techniques available to limit the impact of a lack of representation of mean shear conditions by the measurement period of the RSD, like correlations of the wind shear in the height range covered by the mast and in the height range covered by the RSD exceeding the mast height instead of direct correlations of the wind speed measured at the mast and the wind speed measured by the RSD at the target height or the classification of the wind shear according to the atmospheric stability. If possible, the determined relation of the RSD measurements and the mast measurement shall be tested on the basis of the measured data, e.g. by dividing the common measurement period in sub sets and testing the relations on each sub set. A direct evaluation of a relation of the wind speed measured by the RSD at the target height and the wind speed measured by the mast should be avoided, because then the full measurement uncertainty of the RSD in the target height would become relevant. Furthermore, the measurement masts shall be high enough in order to avoid a too strong decoupling of the wind conditions in the height range covered by the mast and in the target height. The mast shall at least allow a comparison of mast based shear measurements and RSD based shear measurements in the same height range, i.e. both measurements shall cover at least a common height range of 20 m sufficiently above surrounding wind obstacles. If two common heights are not available, it is possible to derive the seasonal wind shear variation solely from the mast measurements, taking additional uncertainties into account.

**C.10.3. The RSD measurement does not overlap with the measurement period of the measurement mast:**

In this case a wind direction dependent relation of the wind speed measured by the RSD at the height range covered by the mast and the target height may be derived. Similar to the case covered in C.10.2, the measurement of the RSD shall cover a sufficiently representative period and the height of the mast shall be large enough to compare shear measurements with the mast and with the RSD in a common height range. As the verification of the shear relations requires a time series of the mast and RSD measurements for which shear conditions are assumed to be comparable, an extended measurement period compared to the case treated in C.10.2 must be expected.