EVALUATION OF SITE-SPECIFIC WIND CONDITIONS

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Table of Contents

1 Foreword

MEASNET is a network of measurement institutes, which have been established to harmonise wind energy-related measurement procedures. The institutes of MEASNET are all actively performing wind energy related measurements and evaluations. Each institute has to document the skills and quality of measurements and evaluations, to apply agreed "MEASNET procedures" and to participate as required 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 to be internationally 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 but also as clear and brief as possible, applicable regulations are referred to, where appropriate, and additional requirements are formulated, where 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 which are relevant for the design and structural integrity of a wind turbine (WT). The meteorological site conditions addressed in this document relate to *wind conditions*, where parameters like air density or air temperature are included as far as they affect the wind flow.

The expression "*site assessment*" is defined, according to the common use in wind energy context, as acronym for "assessment of site specific (wind) conditions".

The results of the "Evaluation of site-specific wind conditions" carried out 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 have an influence on the installation, operation and maintenance (O&M), loading and durability as well as the performance and energy yield of wind turbines (WT), that are to be installed at the site.

According to IEC 61400-1 the site-specific conditions can broken down into wind conditions, other environmental conditions, soil conditions and electrical conditions. Furthermore, each condition can be subdivided into normal and extreme condition [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 encloses 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 scheme illustrates the main components of the evaluation process as described within this guideline.

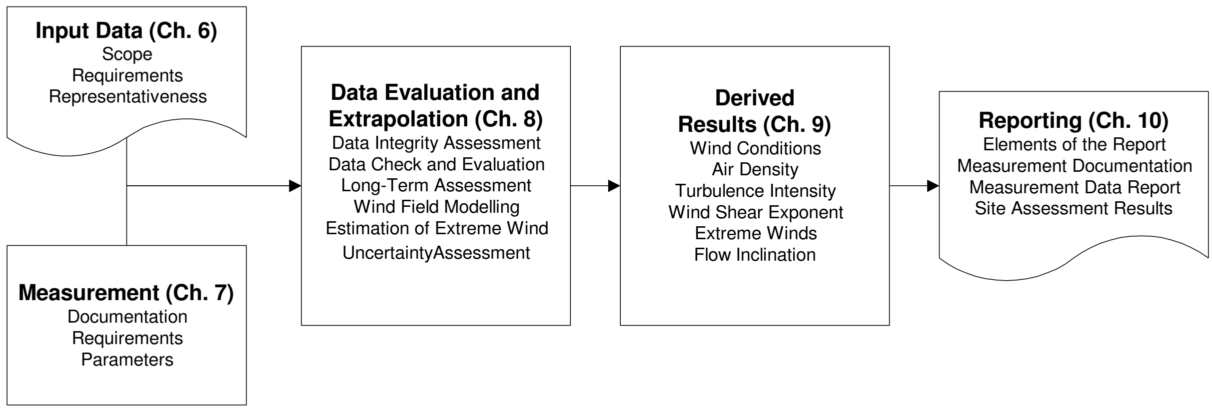

Figure 1: Evaluation process of site-specific wind conditions. In parentheses the chapter where the topic is handled is given.

The above process may require considerable time to be completed, and its evolution needs to 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 one of the above phases of the site assessment procedure can be performed and reported separately provided that:

- All requirements of the current document which are relevant to the specific phase 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 requirement on the data are highlighted in the respective chapters and in the reporting chapter what the documentation concerns.

4 Normative References

Throughout this document the following referenced documents shall be complied with:

- IEC 61400-1 Wind turbine generator systems - Part 1: Safety Requirements, 2nd Ed., 1998 [1].
- IEC 61400-1 Wind turbines - Part 1: Design Requirements, 3rd Ed., 2005 [2].
- IEC 61400-12-1 Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 1st Ed., 2005 [4].
- ISO 2533: 1975-05, Standard Atmosphere [7]
- VDI 3786 Part 2 : 2000: Environmental meteorology - Meteorological measurements concerning questions of air pollution [9]
- ISO/IEC Guide 98:1995 - Guide to the Expression of uncertainty in measurement [12]

5 Handling of Deviations to the Guideline

The guideline provides the definition of methodology and requirements for a site assessment procedure, which will lead to well-founded results according to advanced state of the art. In practise application, the case might occur where not all requirements on input data or methods can be met, so that deviations to the guideline arise.

The general rule is, to identify such deviations and describe them clearly within the site assessment report. However, as the impact of certain deviations on the uncertainties or significance of the derived results can be difficult to assess, some rules for handling of deviations are defined, with the 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 with a reference to the chapter “Deviations to the MEASNET Guideline ‘Evaluation of Site Specific Wind Conditions’” and a short commenting on the significance of each deviation is included in the summary of the site assessment report.
- Each deviation to the guideline shall be considered for the uncertainty assessment of the site assessment. If no possibly for 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*”, “*shall*” or adequate describe *mandatory requirements*, which have to be handled as deviation when not completely fulfilled. Formulations using “should”, “recommended”, “preferably” or adequate describe recommended requirements, which are not to be handled as deviation when not fulfilled.

6 Input Data

The evaluation of site specific wind conditions bases 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 be able to properly assess site conditions a prompt site visit shall be carried out. 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 an appropriate measurement campaign and layout of the measurement system, as well as for the evaluation steps described in Section 8.

6.2 Topographic Data

As basis for the assessment of the site and the flow modelling to be performed, a comprehensive and actual 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 of the site showing the orography and roughness conditions
- possibly satellite 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 models. 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, which form the input for calculation procedures to extrapolate these to the relevant positions and heights. According to the list of parameters to be assessed, 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, those parameters which are marked with asterisk (*) form 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 further parameters are recommended to measure also site specifically, but they can also be derived from available non-site specific data or from estimations. The requirements on this are also described in the subsequent chapters.

6.4 Representativeness of Wind Measurements

The proper design of a measurement campaign – such that the required data basis 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 to define a measurement campaign (met mast type, height 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 third party,

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

The height of the top wind speed measurement level shall be at least 2/3 of the planned hub height. Higher measurement heights 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 measurement masts the assumption is made, that the wind conditions measured at a mast 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, which is called "*representativeness radius*". All wind turbines shall be located in the representativeness radius of at least one mast.

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 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 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 shown classes. For even more complex, mountainous sites, smaller values for the representativeness radius have to 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 proximate surroundings – which create the risk that the mast measurements are influenced by a surface roughness value different than that observed by the wind turbine – the representativeness radius may not be applicable in all directions and a site-specific analysis concerning an appropriate measurement layout shall be carried out.

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 understood in 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 understood in this guideline. Such as site is characterized by orographic features with terrain slopes greater than 0.3 (approx. 17°), which have a dominant influence on wind conditions.

7 Measurement

The basis of the site assessment as described in this guideline are 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, which makes 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 base for assessment of the measurement equipment and evaluation of the 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 uncertainties of the measurement, which will be described and considered within the data evaluation process.

The documentation shall enclose all main aspects as summarized in the following, and which are described in detail in Appendix A:

- Location of the measurement
    - Exact position of the mast.
    - Documentation of the immediate surroundings of the mast.
    - Specification of distance, main properties and dimensions of nearby obstacles.
- Measurement equipment
    - Specification of the type and dimensions of the mast.
    - Specification of the height, dimensions and orientation of the booms.
    - Specification of the used measurement sensors.
    - Description of disturbances on the measurement sensors.
    - Description of the data logging.
    - Information on sensor heating, if relevant.
- Measurement history
    - Specification of date and time of relevant incidents.
    - Documentation of changes of sensors.
    - List of special incidents observed.
- Measurement data
    - Specification calibration factors and any other applied modifications which were applied and which must be applied on the data.
    - Specification of sampling rate, averaging period and further properties.
    - Unambiguous assignment of the data channels to the sensors.
    - Provision of the complete measurement data.
    - Complete description of the measurement data format.

7.2 Wind Speed

On-site measurement of wind speed shall be carried out 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.

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 outside of the prevailing wind direction. In order to minimise flow distortion effects a distance from the anemometer of at least 50 times the diameter of the lightning arrestor shall be kept. The exact dimensions and position shall be reported.

The highest measurement level of wind speed shall be at least 2/3 of the planned hub height (see Section 6.4). In order to assess the wind shear and determine the wind profile at the site, at least one additional anemometer at a significantly lower height (at least 20 m lower) 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.

Mounting of these additional anemometer(s) shall be on separate boom(s) as per IEC 61400-12-1 [4] as well as the recommendations 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, this should be a 45° offset from the prevailing wind direction for tubular masts or 90° from the prevailing wind direction for lattice masts. No other instrument should 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 record also the minima and maxima.

The measurement period shall cover at least 12 complete and consecutive months for at least one mast at the site, to be able to assess seasonal variations. If data from more than one mast are available, correlation between the different masts should be performed 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 no one of the masts at the site covers at least 12 consecutive months.
- The availability of the filtered raw data, where data either from the relevant sensor or its backup sensor installed according IEC 61400-12-1 is available, is less is than 90%.
- The availability of the data filled by MCP methods on base of further measurement data measured at the site data is less than 95%

If a measurement is considered incomplete, this must be clearly stated as deviation to the guideline, in the presentation of the results and it must be taken into account for 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 the re-calibration shows that results deviate significantly, comparative evaluations might be carried out (in situ comparisons with further anemometers) with the aim to determine the time when the deviations began to become significant, 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.

If a re-calibration is not performed, as alternative it shall be tested and documented that the cup anemometer maintains its calibration over the duration of the measurement period. The so called in-situ verification 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.

For extrapolation of the wind measurement to other heights, remote sensing can be used in addition to an anemometer measurement, taking the uncertainty related to these techniques into account. Recommendations concerning calibration, mounting, configuration and testing (see Annex B) shall be taken into account.

7.3 Wind Direction

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

In order to assess the wind shear 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 carried out during installation thereof 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 months for at least one mast at the site to be able to assess seasonal variations. If data of more than one mast are available, correlation between the different masts should be performed 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 no one of the masts at the site covers at least 12 consecutive months.
- The availability of the filtered raw data, where data either from the relevant sensor or a backup wind vane which is installed maximum 30 m lower is available, is less is than 90%.
- The availability of the data filled by MCP methods on base of further measurement data measured at the site data is less than 95%

If a measurement is considered incomplete, this must be clearly stated as deviation to the guideline, in the presentation of the results and it must be taken into account for 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 components of the flow, in order to derive the flow inclination for the measurement position.

7.5 Temperature

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

Mounting of sensors should be 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 be able to assess seasonal variations. Accurate shielding is mandatory in order to minimise uncertainties due to radiation.

In complex terrain or at sites where distinct stratification influence in the wind profiles are expected, two or more temperature sensors at different heights are recommended.

7.6 Pressure

It is recommended to measure 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 carried out 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 and sites with extraordinary climate conditions. The humidity sensor should be mounted within the upper 10 m of the measurement mast.

Extrapolation of humidity should be carried out provided that appropriate long-term data are available in order to derive the long-term mean air pressure 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 on these steps are described in this paragraph.

8.1 Assessment of Data Integrity

As the results of the site assessment depend to 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 to 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 a substitute value is defined which shall be taken into account.

The following classes of measurement data integrity and corresponding uncertainty substitute values have been defined. If the case of deviating situations (Class C and following) arise, this deviation have to be described according to chapter 5, and the respective uncertainty substitute values have to be taken into account as additional measurement uncertainty component for each measurement quantity. This uncertainty substitute value is seen as fully dependent from the measurement uncertainty of the respective sensor, i.e. the uncertainty substitute value must be added to the measurement uncertainty of the respective quantity.

Classes and Characterisations of different Situations of Measurement Data Integrity			
Class	Characterisation	Description	uncertainty subst. value
A	Data integrity ensured (no deviation)	The MEASNET body is the only one which processes the data, what means that the complete measurement installation, operation and data evaluation is performed by the MEASNET body. Hence the MEASNET body can ensure the integrity of the data.	0 %
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. 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 considerable deviations to the standard shall occur, especially that the handling and mounting of the sensors are carried out by the accredited party only, and that a calibration of the whole measurement system traceable back to official standards is performed.	0-1 %
C	Data integrity protected (deviation)	The data integrity is ensured to high degree by protective measures. This can be that the 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. This can be realized also by encryption of the logger data, check-sum proofing or by password protection, so that the data are not manipulable, in combination with a on-site check by the Measnet body.	1-2 %
D	Data integrity verified (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 binary files or can be proven by a detailed documentation.	2-5 %
E	Data integrity insecure (deviation)	The data are obtained by the Measnet body as files with physical values only. To be 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), the data integrity is insecure. This fact shall be mentioned by the Measnet body and considered for the uncertainty assessment.	minimum 5%

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 maxim possible error of measurement data in situations where the data processing is unclear or not traceable, and the measurement data can not be verified. Hence, the proposed uncertainty substitute values can not be seen as maximum error, which could arise.

Furthermore, the definition of uncertainty substitute values do not release the MEASNET body from the duty to perform verifications and plausibilisations of the input data as far as possible, and to reject data which are not traceable and not plausible. In any site assessment campaign, classified according to the above table as Class C, D, or E, where severe deviations in the performance and/or documentation of the measurement campaign are identified, the following remark shall be stated in the corresponding report:

"The requirements of the present procedure were applied solely concerning the data analysis methods and procedures. Severe deviations in the performance and/or the documentation of the measurement campaign were identified. The integrity of the measurement data can not be verified."

8.2 Data Evaluation

8.2.1 Data Quality Assessment and Filtering

The first step of data evaluation consists of the quality assessment and possibly filtering of the data. This data quality assessment and filtering step is quality critical and intrinsically tied to the data evaluation process. Exceptionally a data evaluation might be performed on base of data, which have already been quality checked and filtered by another party, if the requirements on accreditation of this party are fulfilled completely (measurement data integrity class A or B, see Section 8.1), and if 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" or the way to handle these is not general and can depend on the way of evaluation and subsequent steps to be 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" might have impacts on the uncertainty assessment of the measurement, might raise questions which may be possible to clarify, or even might lead to the rejection of the investigated data for the purpose of the site assessment.

The quality assessment of measurement data is a process which requires a profound knowledge of measurement technology and a broad experience with measurement data. Hence is would go far beyond the scope of the document in hand to provide a description of an adequate data quality assessment procedure. Nevertheless, in Annex B 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. These hints are summarized in the following.

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, which are described more detailed in Annex B:

- Check for error values/substitutes
- Visual check
- Check for completeness
- Range test
- Constant value test
- Test for Trends and inconsistencies
- Related parameter test
- Correlation test

The main consequence from the data quality assessment procedure will consist of the rejection of certain data sets (filtering), which will lead to gaps in the data. Furthermore, 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 the filtered data.
- List of the main periods which were filtered (possibly per sensor).
- Evaluation of distribution of filtered data (e.g. seasonal accumulation)
- Considerations on uncertainties coming from the filtering
- Conclusions regarding usability or uncertainty of the data (of specific sensors)

The data quality assessment and filtering provides the base data for the further evaluation and might 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 arisen 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 at specific and not necessarily typical meteorological or climatologic situations (e.g. winter time). Hence the aim of the evaluation shall be, to fill data gaps of the relevant sensors as much as possible by reconstruction of the missing data from measurement values of other sensors, to increase the availability of the data of the relevant sensors.
Relevant sensors are wind speed and wind direction sensors, and possibly further meteorological measurements like temperature or pressure. The data filling will concentrate on the mean values, but might also relate to properties like standard deviation or maximum of these quantities, dependent on the meaning of the data for the further evaluation.

For data filling, *Measure-Correlate-Predict (MCP)* procedures are applied, similar as for long term assessment, which are described in detail in Section 8.3.2. The MCP procedures are preferably applied on base of data which are very similar, e.g. on the data of two anemometers at the same mast with only small deviations of the measurement height, so 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 assessment, 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, some evaluations shall be performed and the documentation of the data filling shall enclose 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 on uncertainties coming from the filling
- Conclusions regarding usability or uncertainty of the filled data (of specific sensors)

8.3 Long-term Assessment

Generally the results of a wind measurement campaign at a wind farm site are valid for the measurement period only. 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 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 assessment is required to project the measured data to long term wind conditions which are considered to be representative for typical mean wind conditions.

The approach bases on the general assumption that a *stable long term mean value* of the wind conditions exists and can be derived from historic data, and that this mean value represents the best estimation for the *future* wind conditions. So the derived results can not take into account future changes like systematic climate change. It is assumed that according to the actual state of the art possible systematic trends or long term oscillations of the wind conditions can not be determined and modelled in a way, which would allow a prediction of the future wind conditions with better accuracy.

8.3.1 Overview

The subject of a long term assessment procedure is to determine and resolve 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 from different aspects like meteorological and topographic situation and the time scale of the performed assessment. For typical wind energy relevant situations the consideration of wind speed and wind direction are considered as necessary, possibly further meteorological parameters like temperature should be taken into account.

The parallel data are analysed in dependency of the relevant parameters, and appropriate models to describe the relationship are established. Defining the type of relationship it must be taken into account, what 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 this, the analysed data should have a high temporal resolution (10 minutes or hourly time series).

The application of a 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, validated and an assessment of the uncertainty of the procedure by means of performed verifications shall be done.

In the following different long term assessment procedures and their specific requirements are described (Section 8.3.2). General requirements on the reference data respectively period are described subsequently (Sections 8.3.3 and 8.3.4).

8.3.2 Methods for Long-term Assessment and Specific Requirements

To determine the long term wind conditions on base of a limited measurement, a *Measure-Correlate-Predict (MCP)* or a kind of *long term scaling method* shall be applied. These methods take into account the measurement data *(site data)* and parallel long term data *(reference data)*, which enclose 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 those 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 to extrapolate them to long term period.

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 be applied also on data with lower resolution (e.g. monthly values).

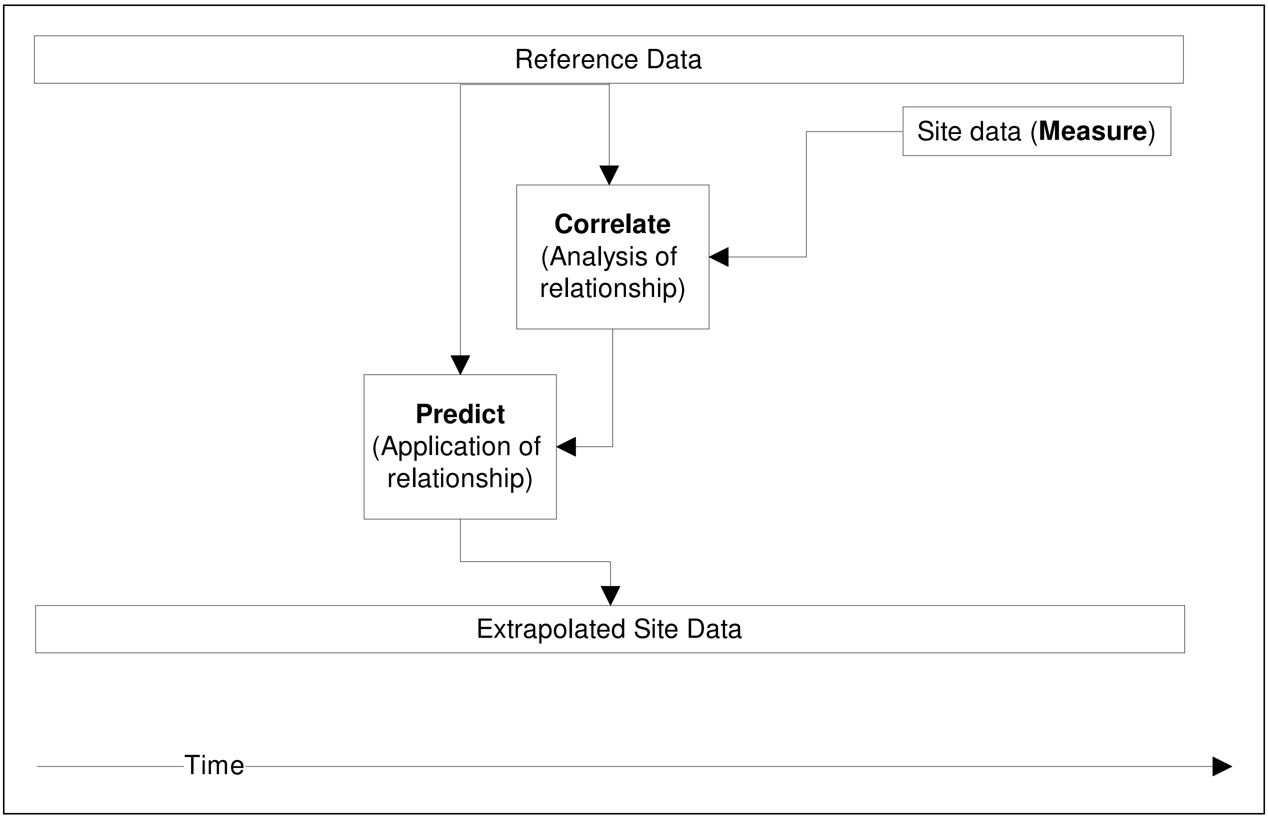

Figure 4: Scheme of the measure-correlate-predict (MCP) procedure

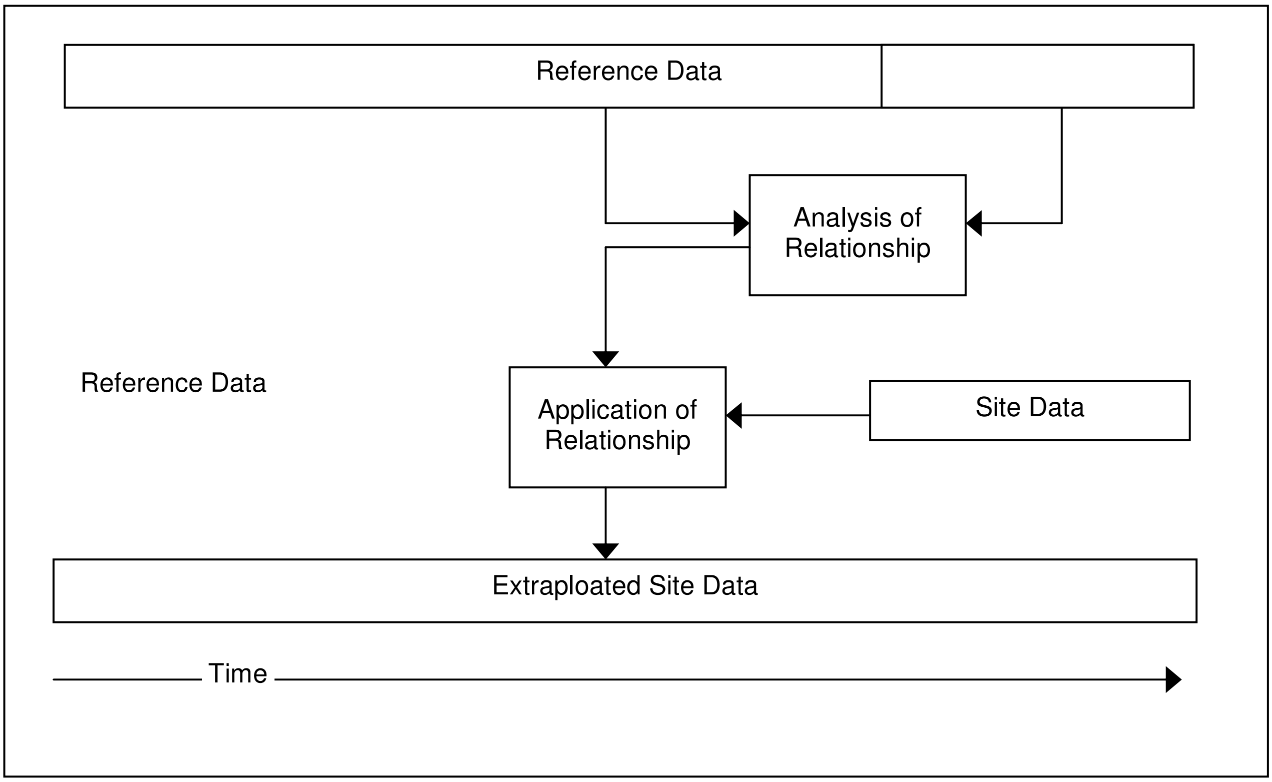

Figure 5: Scheme of long term scaling procedure

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

MCP Methods

- Sectoral Regression MCP

  The concurrent data are analysed in different wind direction sectors regarding a linear or non-linear relationship between them (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 [10]).

  A prerequisite for the sectoral regression MCP is, that clear relationships between the data exist in the chosen sectors. The relationship 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. Furthermore it must be verified if the range of occurring wind speed is sufficient to perform the regression in each sector. This is even more 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), and for each bin the deviation or the relation between the wind speed and direction of the reference data and the site data are determined. For the elements of the matrix, which are not occurring with significant frequency, the respective values need to be interpolated or extrapolated with appropriate methods. All elements of the matrix might be fitted with a surface function, if this function reproduces the determined significant matrix elements to high degree.

  A prerequisite for the matrix MCP is, that a high correlation between the data exists, and 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 as derived from the measurement data as well as applied shall be shown. Furthermore it must be verified if the range of occurring matrix elements covers the occurring wind speed and wind direction ranges sufficiently. 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

  Further methods to analyse the relationship between site and reference data may be used. The requirement is, that these are 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 the results and the assessment of an sufficient data coverage is even more important 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 temporal resolution of the values considered shall be monthly values.

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

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

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

- Distribution Scaling Method

  For this kind of long term correction methods the long term correction are applied on the wind distribution parameters (sectoral Weibull A- and k-parameters and frequency distribution). The correction factors are derived either from a comparison of the wind distribution parameters of the site and reference data, from 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 does not operate on time series data, but only on the wind distributions, the causality of wind distribution changes can not be derived. In these cases an adjustment of the distribution parameters shall only be performed on the *wind speed* distributions. The distribution scaling method has the meaning of 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 which represent the variation of the wind distribution shall evaluated on base of a temporal resolution of at least 6 hours.

If the long term correlation and extrapolation is performed for a special purpose (e.g. extreme wind assessment), then additional requirements are relevant and have to be considered.

8.3.3 Correlation Period

To allow a reasonable extrapolation of the short term wind conditions, the correlation period (period for the determination of the correlation parameters) should include all important typical meteorological situations and allow determining the important relationship between the data. The better and the more detailed the extrapolation procedure is able to resolve the relationship between the data, the better a prediction on base of a short correlation period is possible. Therefore, the minimum period needed is dependent on the specific wind conditions and situations as well as the capabilities of the applied extrapolation procedure.

To be independent from seasonal variations, the concurrent period should enclose minimum one year, especially if the extrapolation can not be performed on time series basis and if the differences between short term and reference mast are large, what differences in measured wind speed conditions, the spatial distance and the difference in measurement height concerns.

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

8.3.4 Requirements on Reference Data

From experience with meteorological long term data it is known that the measured wind conditions often show trends or steps, which seem to be not realistic. 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 possibly by changes in the measurement installation or missing long-term stability of the measuring sensors. Often the question whether the long term is realistic for the region or caused by disturbing effects can not clearly answered without having access to further information regarding the long term measurement station and to further independent long term data.

Therefore an important prerequisite to perform a reliable long term extrapolation is to assess the reliability and consistency of the long term data. An inspection of the long term station and gathering information regarding the history of the meteorological station can provide valuable information for this assessment. The performance a comparative analysis of long term data from different sources is often required to detect trends and inconsistencies in the long term data at issue and to determine an appropriate data period with consistent data. The quality of the reference data needs to be taken into account in the uncertainty assessment of the long-term wind conditions.

To length of the reference data period should be chosen as long as possible with the aim to represent typical, mean wind conditions. From the meteorological point of view the period of about 30 years is considered as being representative. Actually the utilisable period will be limited by data availability and the mentioned considerations to the reliability and consistency of the data. Taking these limits into account, the period of 10 years is generally considered as good compromise between long term representativeness and data reliability.

The length of the reference period should be determined site specific after performing an analysis of the reliability and consistency of the available data. The reference period as well as the criterions 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 needs to 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 on base of 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 base on different modelling approaches. As the physically correct description of atmospheric wind flow is arbitrarily complex and can not be done exactly, each model approach applies simplifications or 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 validation

  The applied model shall be validated 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 significantly to 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, which 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, which 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 for specific cases the conclusion can be drawn, that the entirety of occurring wind speeds can not 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 is, 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 verification

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

  Furthermore, previous verifications of the model against measurement data for 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 on 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.

For determination of extreme wind speeds, usually no measurement data with sufficiently long period are available. Even if they were available, they do not relate to the wind farm site, but to a meteorological station with distinctly different wind conditions. 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 those tasks, different approaches are available and no universal, preferred method can be proposed. Instead, in the following an overview of different methodologies is given and general recommendations are given to come to most reliable results.

For estimation of extreme wind speeds two different methodologies are possible:

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

Both methodologies base on statistical considerations on distribution of extreme values [13], but are entirely different in application. The particularities and application recommendations for both methods are described in the following.

Extrapolation of measured extreme wind speeds in time

This methodology requires a measured wind speed time series which includes measurements of relevant storms events, i.e. measured wind speed values on required heights and with relevant averaging period. Appropriate methods might 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 to a given long term period (e.g. 50 years). Different approaches exist for this task [14].

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

- Significance of the time series which is analysed for long term conditions. This includes considerations on the length of the analysed time series, for which the common recommendations on the minimum required length vary between 4 and 7 years, and also considerations about the dependence of the selected method from the maximum measured during the analysed period.
- Method for recalculation 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 different assumptions on conditions in boundary layer, allows to estimate the probability of occurrence of high wind speeds from the measured (long term) Weibull wind distribution [15].

This methodology bases on certain simplifications and the results depend distinctly on the Weibull parameters and hence the way how to determine these. Furthermore, the outcome of the method is a *distribution* of extreme values, where a exceedance level must be defined 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 shall be justified:

- Derivation of the extreme value from the calculated extreme value distribution. The modal value shall be addresses as extreme value, but also at least the P75 and P90 confidence level shall be given.
- The way of doing 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 the variation of results and sensitivity of the methodologies into account.
- 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 verifications of 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” [12] 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 and 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 linear summation of the individual uncertainty components.

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

Topic	**Uncertainty Component**

Measurement	Wind Speed
	    General anemometer quality
	    Anemometer classification according to IEC 61400-12-1 [4]
	    Anemometer calibration
	    Measurement set-up (mast influences)
	    Data Logger (resolution)
	    Documentation
	    Quality of correction method applied
	Wind Direction
	    Direction sensor quality
	    Measurement set-up (mast influences)
	    Quality of correction method applied
	Remote Sensing
	    „Black Box“-instrument or „open source“
	    Availability of raw data
	    Signal-to-Noise Ratio
	    Fixed echoes
	    Length and season of measurement period
	    Completeness of days
	    Correspondence with measurement mast data

Data Integrity	Uncertainty substitution value (chapter 8.1)
Data Analysis	Uncertainties coming from the data filtering Uncertainties coming from the data filling

Derived parameters	Air density
	    Uncertainty of measured air pressure and temperature acc. [2]
	Turbulence Intensity
	    Number of counts on which I is based
	    Temporal resolution of input data
	    Completeness of data base
	Extreme Winds
	    Comparative analysis of different methods
	    Sensitivity analysis (different time periods, independency criteria etc.)
	    Length of input time series

Correlation and Long term extrapolation	Overlapping period Correlation between site and reference data Consistency of reference station Consistency of scaling factor Length of past period Future Period Used Method
Flow Modelling	Vertical Extrapolation Horizontal Extrapolation Sensitivity on Wind Direction Limitations of Model Atmospheric Stratification

Topic	Uncertainty Component
Wake Modelling	Limitations of used model Atmospheric stratification Size of wind farm
Power Curve	Measurement Uncertainty Deviations from Guidelines Assumptions for calculated power curves

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 instrument as provided from the manufacturer shall be considered as minimal possible uncertainty for that measurement. For wind speed measurements, the findings from the anemometer classification according [16] 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 (chapter 8.1) has to be considered as fully dependent from the measurement uncertainty and hence has to be added to the measurement uncertainty.

Correlation and Long term extrapolation

For the filling of data gaps and long-term correction 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 data 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 below 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.

In case a long-term scaling has been applied, it should be shown that the extrapolation procedure was generally validated also for short periods, that significant correlation relations can be found between the data, that wind directional effects can be resolved reasonable and that 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 reflect as well 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 additional uncertainty component.

Wake models
As the current wake models are verified 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 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 wind turbine power curve is relevant for the results of the assessment, the following requirements at the handling of the uncertainties apply. If a measurement report or an excerpt of a measurement report regarding a power curve measurement according IEC 61400-12 [3] or IEC 61400-12-1 [4] is available, the measured power curve and the respective wind speed dependent uncertainties are applied. Deviations to the standards in the power curve measurement should be considered in uncertainty, if possible.

If only a calculated power curve is available or must be used for the assessment, 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 a measured power curve is available for the relevant wind turbine type (“verification power curve”), the power curve values and the measurement uncertainty of the verification power curve should be taken into account for the uncertainty assessment of the calculated power curve.

9 Derived 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 Positions

The wind conditions are derived from the data evaluation and calculations for the turbine position and hub height of each wind turbine. Additionally, as measure of significance of the results, the percentage uncertainty for the derived wind speed values are specified, or the exceedance probability for the relevant wind speed design limits.

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 air temperature and air pressure is carried out, these parameters can be derived using readings from representative proximate meteorological long-term station, 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 done 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 determined according to Equation 1:

$$I = \sigma_v / v_{mean} * 100 \qquad \text{(Equation 1)}$$

where:

I	=	turbulence intensity [%]
σ_v	=	measured standard deviation of the wind speed within 10-min. interval [m/s]
v_{mean}	=	measured mean wind speed within 10-min. interval [m/s]

For this calculation, the wind speed in hub height is derived from the wind field modelling on base of 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 base on the available measurement.

The derived turbulence intensity is calculated for the measurement positions in measurement height and for the wind turbine positions in hub height. The turbulence intensity values have to be specified for each 30 degree wind direction sector and wind speed dependent in bins of 1 m/s width for each bin, where a significant number of underlying measurement values are available.

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

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

If characteristic or the 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 can be applied for calculating parameters such as the representative turbulence standard deviation (IEC 61400-1 Ed.3, Chapter 6.3.1.3 Equation 11) or the site-specific turbulence standard deviation using the site-specific wind data (IEC 61400-1 Ed.3, Chapter 11.9, Equation 34) [1].

9.4 Wind Shear Exponent

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

$$\alpha = \ln (v_{Z1} / v_{Z2}) / \ln (z_1 / z_2) \qquad \text{(Equation 2)}$$

where:

α	=	wind shear exponent
v_{Z1}	=	wind speed measured at measurement height 1 [m/s]
v_{Z2}	=	wind speed measured at measurement height 2 [m/s]
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 over the rotor-swept area, i.e. from lower blade tip to upper blade tip height, and for each WT position. Hence, the wind shear exponent α shall be derived for each wind turbine position from the wind flow modelling results based on the existing wind measurements.

The wind shear exponent α for the met mast 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 α from measurement values, the mast shading and further disturbing effects shall be corrected as far as possible, or the disturbed sector(s) shall be excluded from the evaluation. If more than two measurement heights are available, α 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 α, measurement heights shall be close to 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 Reporting

The following chapter specifies the requirements for the reporting of the performed work and derived results for the site assessment. After an overview of included parts is given, the important parts of the document are described in detail. As in principle the scope of the work can include the performance of the measurement, but not necessarily must include it, a differentiation regarding the scope of the work and the performed tasks has to be done.

10.1 Elements of the Report

The report shall include at least the following elements, describing at least the following topics.

1) Description of the assigned tasks
   a. Specification 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 *or* Summary of Measurement Documentation according to chapter 10.2 or 10.3
4) Measurement Data Report according to chapter 10.4
5) Site Assessment Results according to chapter 10.5
6) 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.

If the complete scope is included, the reporting can be divided into two documents, where one document ("Wind Measurement Report") contains the items 1), 2), 3) 4) and 6), and the other document ("Site Assessment Report") contains the items 1), 2), 5) and 6).

10.2 Measurement Documentation

If the scope of the work includes the performance of the measurement, a measurement documentation shall be provided according to the requirements stated in this chapter

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 mast(s) 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;
   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 method how to maintain the anemometer calibration over the duration of the measurement period and documentation of results that show that the calibration is maintained.

3) A description of the measurement procedure
   a. documentation of the procedural steps, test conditions, 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.

10.3 Summary of Measurement Documentation

If the scope of the work does not include the performance of the measurement, alternatively to the above chapter a summary of an available measurement documentation shall be provided according to the requirements stated in this chapter. As in this case the work bases on documentation delivered by third party, the following aspects need to be summarized, checked and assessed regarding its completeness and suitability:

In general the reporting format for 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 mast(s) 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;
   b. description or check 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. description of the of the arrangement of the sensors at the mast including principle dimensions of the tower and booms;
   d. description of method how to maintain the anemometer calibration over the duration of the measurement period and documentation of results that show that the calibration is maintained.

3) A description of the measurement procedure
   a. documentation of the procedural steps, test conditions, sampling rate, averaging time, measurement period;

b. description of scope, suitability and main findings regarding available information on important events during the measurement period, including 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 clauses.

10.4 Measurement Data Report

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 met mast 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 m/s and sector-width of 30° or less, the first centred around 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 case 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 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 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 relative humidity for the complete measurement period and for each month shall be presented in tabular form.

10.5 Site Assessment Results

Wind data
Sectoral Weibull A & k-parameters and the frequency distribution for sectors with the width of 30 degree or less, the first centered 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 m/s and sector-width of 30° or less, the first centred around geographic north, for the wind turbine positions in 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, and - for complex sites with large height differences - also the mean air density at hub height for each wind turbine position - shall be stated in the report. as well as min-, max- -values of air density for the complete measurement period and for each month and 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] for each wind speed BIN using a BIN-width of 1 m/s 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 as well as min- and max-values of wind shear exponents (α) shall be presented using the method of BINs with BIN-width of 1 m/s 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 is documented as mean flow inclination for each wind turbine position for each hub height.

Long-term Assessment
The reporting of the long term assessment should include the following:

- Description of the procedure and applied simplifications or observed particularities
- Reporting of the influence of the applied long term adjustment. This should preferably be done by reporting of the arising long term wind distribution.
- Judgement of the significance and uncertainty of the performed long term assessment. 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 the 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:
- 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 revision of the existing literature about the model should be carried out; especial attention will 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 verifications.

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

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

Further Measured Quantities (e.g. Pressure, Humidity)
Mean values of the used quantities have to be stated.

References

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

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[5] MEASNET: *Cup Anemometer Calibration Procedure*, Version 1, September 1997

[6] IEA: *IEA Recommendation 11: Wind Speed Measurement and Use of Cup Anemometry*, 1st Ed., 1999.

[7] ISO 2533: 1975-05, Standard Atmosphere

[8] ISO/IEC 17025:2005 - General requirements for the competence of testing and calibration laboratories

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[11] I. Troen, E.L. Petersen: *European Wind Atlas*. Risø National Laboratory, Roskilde, Denmark, 1990.

[12] ISO/IEC Guide 98:1995 - Guide to the Expression of uncertainty in measurement, Geneva, Switzerland.

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[14] J.P. Palutikof, B.B. Brabson, D.H. Lister and S.T. Adcock: A review of methods to calculate extreme wind speeds. Meteorol. Appl. 6, 119–132 (1999)

[15] H. Bergström: Distribution of Extreme Wind Speed. Wind Energy Report WE 92:2, Department of Meteorology, Uppsala University, 1992

[16] T.F. Pedersen, J.-Å. Dahlberg, Peter Busche: ACCUWIND - Classification of Five Cup Anemometers According to IEC61400-12-1. Report Risø-R-1556(EN), Risø National Laboratory, Roskilde, Denmark, May 2006.

Annex A

(normative)

Requirements on the Documentation of Wind Measurements

As basis for assessment of measurements which are used as input for the described site assessment procedure, and required for evaluation of the belonging 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 uncertainties of the measurement, which will be described and considered within the data evaluation process.

The documentation shall enclose the following aspects:

- Location of the measurement
  - Exact position of the mast in terms of specification of coordinates and belonging coordinate system.
  - Photo documentation and description of the immediate surroundings of the mast.
  - If relevant, specification of distance, main properties and dimensions of nearby obstacles.
- Measurement equipment
  - Specification of the type and dimensions of the mast. The mast shall be documented by at least photos showing the entire mast and the mast top in detail.
  - 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 geographic resp. magnetic 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.
  - Description of the orientation of the north mark of the wind direction sensors, including information whether given degrees refer to geographic or magnetic north.
  - Description of disturbances on the measurements like lighting arrestor in terms of specification of dimensions, distance and other relevant information.
  - 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 taken measures to calibrate the data logging system.

    - Information on sensor heating, if relevant, and underlying power supply system.

- 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 for mast installation, changes, maintenance other work on sensors or other quality relevant aspects other parties than the MEASNET accredited measurement institute 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 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. Description of particularities like reductions of accuracy or resolution, north-gap and others.
    - 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 with measurement data. Hence it would go far beyond the scope of the document in 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

The data verification should include:

- **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 evalutions tools.
- **Visual check:** With a visual check of the data it is possible to detect invalid data such as peaks. 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 strange variations in time.
- **Related parameter test:** Comparison based on the expected values for the physical relationships between the different parameters (e.g. $V_{min} \leq V_{mean} \leq V_{max}$). If one data value is assessed as erroneous all related quantities are also 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 invalid.

- **Correlation test:** Use of scatter plots to assess whether the correlation between different sensors, for example two different anemometers, is plausible.

Major erroneous data periods are to be reported. Temperature, pressure, rain and humidity sensors installed on the met mast can 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

(informative)

Alternative Wind Measurement Procedure

Objective

Referring to the 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. In addition to cup anemometer measurement remote sensing techniques like LIDAR and SODAR as well as 3D-sensors can be utilized taking into account the uncertainty related to these techniques. The objective of this annex is to give recommendation concerning calibration, mounting, configuration and testing for measurement campaigns with theses sensors.

I Measurement Procedure with Sodar Systems

Site Inspection and Assessment

With the help of maps and/or photos the measurement site has to be pre-evaluated in order to pre-select potential measurement sites. The site should be visited ideally before the SODAR-System is sited and installed. At the site visit obstacles or already nearby existing WT must be documented and their influence on the measurement must be checked. Very important is to proof the sound level of the surroundings for e.g. neighbouring wind farms, airports etc. and the negative effects for the acoustic working SODAR. The access route to the site and the measuring site for the system must be examined as well. To determine a possible measurement site the energy supply has an influence on the positioning of the system. In case of a stand-alone system with a generator it will be necessary to increase the cable length because of the noise level of the generator. In case of a power socket from e. g. nearby houses or WT the cable length also leads to losses which have to be taken into account as a limiting factor for the measuring position. Furthermore the site has to be documented in terms of the structure of the terrain.

Measurement Setup

The system has to be placed in a way that the transmitted noise impulses can be received failure-free (elimination of fixed echoes). The SODAR must, as a minimum, be placed at a distance, from WT or obstacles including trees, which is longer than the total height (in case of WT hub height plus blade length). It must be secured that the direct noise signal does not clash together with surrounded obstacles. During the installation the system must be adjusted horizontally (controlled by laser or by a water-level measurements). In dependence on the system that is used the deviation to north direction has to be noticed (compass, bearing binocular, site maps, GPS-Systems) and implemented to the system control. After the measuring setup the SODAR system has to be checked (system test, default parameters, remote control etc.) another time before starting the self-operation modus.

Measurements, which are exceeding a time period of six months, should contain an overhauling of the SODAR system. The speakers should be checked for function and damage.

Configuration and Documentation

The SODAR has to be configured according to the measurement requirements given by the customer or the site-specific conditions (for e. g. measuring height, transmit-frequency, height- and accumulator intervals). All filter limits have to be set like the min. and max. amplitude, min. and max. SNR-ratio etc. (SNR: signal to noise ratio). All modified and default parameters must be documented and checked on plausibility. For further data filtering or rather for increasing the quality of data, meteorological data can be logged (for e. g. rain frequency and quantity, temperature, air pressure etc.) in addition. If the SODAR has to be operated in different modes (e. g. reduced transmitter power or frequency by night), start and ending point of these modes have to be documented.

Testing of Sodar, Proof of Accuracy, Calibration

SODAR systems determine the wind conditions over a measurement volume of significant size. Thus, it is impossible to calibrate SODARS in wind tunnels. Consequently, the accuracy of the individual SODAR should be evaluated by a comparison to cup anemometer and vane measurements before each application of the SODAR. This accuracy test of the SODAR may take place at a different site than the measurement site (e.g. at special test stations for SODAR). The cup anemometer and vane measurements used for the comparison shall fulfil the requirements given in IEC 61400-12-1. The cup anemometers shall be calibrated according to MEASNET. For a test of the accuracy of the vertical wind speed component determined by the SODAR, a 3D sonic anemometer may be applied for the comparison additionally.

The SODAR should be installed as close as possible to the met mast (avoiding fixed echoes), on which the cup anemometers are mounted. The measurement heights of the SODAR should be programmed to the exact mounting heights of the cup anemometers. The data acquisition system applied for recording of the mast mounted instruments shall be well synchronised with the data acquisition system of the SODAR. The accuracy test should be performed in a height range comparable to the height range intended to be covered later by the SODAR measurements.

The SODAR shall be operated with the same parameters during the accuracy test than to be applied during the field application.

The comparison of the SODAR measurements and the mast data shall be based on statistics of 10-minute periods. The measurements of the horizontal wind speed component, the vertical wind speed component and the wind direction shall be compared at least in the wind speed range 4-16 m/s in terms of the horizontal wind speed component. The analysis of the accuracy in terms of the horizontal wind speed component shall be based on a binning of the SODAR measurements against the measurements of the cup anemometer in wind speed bins with a maximum width of 1 m/s.

It is not advisable to derive a calibration for the SODAR measurements of the horizontal wind speed component from the comparison to concurrent cup anemometer measurements, as the deviations between both measurements may be dependent on various meteorological variables, like the atmospheric stability, and other environmental conditions. It is not likely that all of these variables can be captured to such extend by the accuracy test that a calibration in dependence of these variables will be possible. Thus, the accuracy test is intended only to proof the correct functioning of the SODAR, to proof the accuracy of the SODAR measurements and to evaluate the uncertainty of the SODAR measurements.

In terms of the turbulence intensity or the standard deviation of the wind speed within 10-minute periods, it is advised to derive corrections from the comparison of the SODAR measurements and the cup anemometer measurements. Here large and systematic deviations between the two measurements are normal due to the different measurement principles. The deviations between SODAR measurements and cup anemometer measurements in terms of the turbulence intensity are normally dependent on the measurement height. Thus, also the correction shall be derived for different measurement heights.

After the field application, the accuracy test of the individual SODAR shall be repeated. As an alternative, the accuracy of the SODAR shall be proven against data of a met mast at the measurement site at the end of the field application (similar to in-situ testing of different cup anemometers on a mast).

Great care shall apply, when assessing the accuracy of SODAR measurements in complex terrain sites. Additional measurement errors may arise here from the variation of the wind conditions over the measurement volume of the SODAR. These effects may not be covered by the accuracy testing to be performed prior to the field application. The associated uncertainty of the SODAR measurements shall be assessed.

Evaluation of Measured Data

The measured data must be saved according to quality-management standards. The data shall be filtered on implausibility (for e. g. rain or noises) and measurement breakdowns. Further filtering of the data is possible on the basis of internal quality criteria under the obligation of a full documentation. All data reductions or filtering have to be documented and pointed out in the final report.

Reporting of Measurement Failure

The total measurement-failure should be divided at least in the following single major components:

- system failures,
- arrangement and installation failures,
- site depending influences.

All failures of the system shall be reported in the final measurement report. The quantification of the measure-failure can be assessed empirical by measurement experiences, estimations or rather with the involvement of manufacturers' system instructions.

Determination of Measurement Time Period

The measurement period depends on the specific case and cannot be treated generally. Nevertheless it can be assumed that for reliable measurement data the time period should not be smaller than three months, for turbulence or profile information, taking into account related uncertainties of such a short time period. All necessary BINS should be covered during the measurement period. The particular season and time period have to be taken into account and documented.

Mid- and Long-term Measurements

Regular on-site system checks of the SODAR system are required to assure

- continuous power supply,
- cleaning of antenna,

- no damage to system (e.g. broken met tower etc.)
- unchanged upright position,
- unchanged North direction
- swap and reformat of storage media

Sensitivities and Special Notes

Due to the acoustic measurement principle the SODAR system reacts sensible

- on environmental noise (also on high winds),
- on precipitation (rain and snow),
- on atmospheric layering,
- on acoustic reflections due to nearby obstacles.
- on surrounding objects which are causing or absorbing loud noise.

For comparisons between remote sensing measurements (e.g. SODAR and LIDAR) and conventional cup anemometer measurements the different measurement locations as well as the different measurement principles (volume averaging versus punctual measurement) shall be considered for the interpretation of the measurement results.

Recommended Practices for Extrapolating Mast Data at Higher Heights using SODAR

SODAR units can provide wind speed measurements at heights practically unachievable by meteorological masts (eg: 150m, 200m). In general, SODAR measurements are short period campaigns of some months, aiming at collecting data from the main wind direction of a site. At the present time, due to the lack of SODAR calibration procedure, it is required that simultaneous data exist from a pair of cup anemometer-wind vane at a common height.

The following steps should be followed when correlating-extrapolating Mast data based on the SODAR's data.

- Assure clock synchronization and common reference of the file time-stamp (beginning or end of 10min averaging period)
- Set one of the SODAR measuring heights equal to a height of the Mast cup's anemometer, preferably that of the top.
- Create the database with the concurrent SODAR and Cup anemometer data, where data from wind directions "shadowed" by the Mast should be excluded or corrected.
- Verify the linearity of the concurrent mast and SODAR data (either binned in ranges of 1m/s or using the ensemble of the valid data above 4m/s) at the common height. Goodness of fit values R^2 should be superior to 0.98. This should be done for both wind speed and wind direction.
- Calculate the mean, max and gust values, per wind direction sector, for all SODAR heights.
- Provide the detailed Speed-up tables (wind speed ratios, ie: U100m/U80m) for the SODAR's measuring heights, per wind direction sector and per wind speed bin. Actually, these tables are among the main results of the SODAR measurement campaign.

Depending on the SODAR unit, additional information can be extracted using the signal-to-noise ratio (SNR). The SNR describes the ratio between the strength of the reflected signal and the noise. If the SNR is not greater than the specified minimum, the data are not considered valid and are not used in the average.

When applying SODAR for extrapolating mast data at higher heights, special consideration must be given to the question of representativeness of the SODAR measurement period, especially if due to the SODAR data availability influences of seasonal or daily changes of the wind profile are expected. Such influences should be investigated and an assessment of the representativeness of the SODAR data for mean conditions shall be done.

II Measurement Procedure with Lidar Systems

Site Inspection and Assessment

With the help of maps and/or photos the measurement site has to be pre-evaluated in order to pre-select potential measurement sites. It may be necessary to visit the site prior to the installation of the LIDAR-system in order to find the best possible location. At the site visit obstacles or already nearby existing wind turbines, met masts or trees/forests have to be documented and any possible influence on the LIDAR measurement needs to be checked by geometrical means.

Any moving part in the range of the LIDAR's laser cone need to be avoided, such as rotating wind turbine blades, loose guy wires or branches of trees, since those may disturb or influence the measurements.

Single fixed (not moving) obstacles, e.g. the lattice structure of a nearby met mast, intersecting with the laser cone do represent a negligible disturbance if they cover only a small angle range (e.g. 5 ° of 360° circle). In case of using such met mast based wind speed measurements as a reference to the LIDAR (e.g. on a lower height level) the proximity of the LIDAR to the mast may even increase the correlation on the reference height and hence the confidence.

Since most LIDAR systems can be powered either by low voltage DC or high voltage AC a power supply solution needs to be found suiting the conditions at the site, best. In case of a self-contained DC supply any system from solar and/or wind power to small fuel generators will do.

Due to the attractiveness of a LIDAR to men as well as to e.g. cattle certain theft, damage and vandalism pre-cautions such as barbed fences or shields are recommendable

Furthermore the site has to be documented due to the structure of the terrain.

Measurement Setup

The LIDAR system has to be placed in as sufficiently large distance to any moving obstacle – like turbine blades, guy wires tree branches (or similar) – in order to avoid any intersection between such obstacles and the laser cone. The necessary distance to those moving obstacles can be calculated by simple geometrical means. Fixed obstacles in the view of the LIDAR may be neglected if only a few.

The upright erection of the LIDAR needs to be checked using a bubble gauge or similar and the given reference surface of the device.

The LIDAR system should be positioned such that the device’s North direction is identical to actual North. Otherwise, the deviation from actual North needs to be determined (compass, bearing binocular, site maps, handheld GPS receiver) in order to be compensated for by software settings or post processing. All site specific and direction settings shall be documented.

To supply the wash and wipe system with water a reservoir (canister) needs to be provided and put close to the system. To avoid freezing of the wash and wipe fluid anti-freeze should be added.

The following checks need to be performed after installation

- stable position and upright standing of the device
- north direction or deviation
- power supply
- check/test wash and wipe system

After each check the results shall be reported.

Configuration and Documentation

The LIDAR will be configured according to the measurement requirements given by the customer or the site-specific conditions (for e. g. measuring height).

All operating parameters of the LIDAR shall be reported. Such can be for example: measurement heights, speed of rotation of laser beam on cone, cone angle, number of azimuth angles on cone, parameters of focussing, length of laser pulse or length of time window for analysing the reflected laser beam, parameters of Fourier analysis, parameters of automatic data rejection

For further data filtering or rather for increasing the quality of data the meteorological data (for e. g. rain frequency and quantity, temperature, air pressure etc.) can be logged in addition. If the LIDAR is operated in different modes (e. g. different measurement heights, cloud correction ON/OFF etc.), start and ending point of these modes have to be documented.

Testing of Lidar, Proof of Accuracy, Calibration

LIDAR systems determine the wind conditions over a measurement volume of significant size. Thus, it is impossible to calibrate LIDARs in wind tunnels. Consequently, the accuracy of the individual LIDAR should be evaluated by a comparison to cup anemometer and vane measurements before each application of the LIDAR. This accuracy test of the LIDAR may take place at a different site than the measurement site (e.g. at special test stations for LIDARs). The cup anemometer and vane measurements used for the comparison shall fulfil the requirements given in IEC 61400-12-1 [4]. The cup anemometers shall be calibrated according to MEASNET. For a test of the accuracy of the vertical wind speed component determined by the LIDAR, a 3D sonic anemometer may be applied for the comparison additionally.

The LIDAR should be installed as close as possible to the met mast, on which the cup anemometers are mounted. The measurement heights of the LIDAR should be programmed to the exact mounting heights of the cup anemometers. The data acquisition system applied for recording the mast mounted instruments shall be well synchronised with the data acquisition system of the LIDAR. The accuracy test should be performed in a height range comparable to the height range intended to be covered later by the LIDAR measurements.

The LIDAR shall be operated with the same parameters during the accuracy than to be applied during the field application.

The comparison of the LIDAR measurements and the mast data shall be based on statistics of 10-minute periods. The measurements of the horizontal wind speed component, the vertical wind speed component and the wind direction shall be compared at least in the wind speed range 4-16 m/s in terms of the horizontal wind speed component. The analysis of the accuracy in terms of the horizontal wind speed component shall be based on a binning of the LIDAR measurements against the measurements of the cup anemometer in wind speed bins with a maximum width of 1 m/s.

It is not advisable to derive a calibration for the LIDAR measurements of the horizontal wind speed component from the comparison to concurrent cup anemometer measurements, as the deviations between both measurements may be dependent on the wind speed, the wind direction and in particular cases also on the measurement height and other meteorological variables like the wind shear. It is not likely that all of these variables can be captured to such extend by the accuracy test that a calibration in dependence of these variables will be possible. Thus, the accuracy test is intended only to proof the correct functioning of the LIDAR, to proof the accuracy of the LIDAR measurements and to evaluate the uncertainty of the LIDAR measurements.

In terms of the turbulence intensity or the standard deviation of the wind speed within 10-minute periods, it is advised to derive corrections from the comparison of the LIDAR measurements and the cup anemometer measurements. Here large and systematic deviations between the two measurements are normal due to the different measurement principles. The deviations between LIDAR measurements and cup anemometer measurements in terms of the turbulence intensity are normally dependent on the measurement height. Thus, also the correction shall be derived for different measurement heights.

After the field application, the accuracy test of the individual LIDAR shall be repeated. As an alternative, the accuracy of the LIDAR shall be proven against data of a met mast at the measurement site at the end of the field application (similar to in-situ testing of different cup anemometers on a mast).

Great care shall apply, when assessing the accuracy of LIDAR measurements in complex terrain sites. Additional measurement errors may arise here from the variation of the wind conditions over the averaging volume of the LIDAR. These effects may not be covered by the accuracy testing to be performed prior to the field application. The associated uncertainty of the LIDAR measurements shall be assessed.

Evaluation of Measured Data

The measured data must be saved according to quality-management standards. The data shall be filtered on implausibility's (for e. g. laser failure) and measurement breakdowns. Further filtering of the data is possible on the basis of internal quality criteria under the obligation of a full documentation. All data reductions or filtering have to be documented and pointed out in the final report.

Reporting of Measurement Failure

The total measurement-failure should be divided at least in the following single major components:

- system failures,

- arrangement and installation failures,
- site depending influences.

All failures of the system shall be reported in the final measurement report. The quantification of the measure-failure can be assessed empirical by measurement experiences, estimations or rather with the involvement of manufacturers' system instructions.

Determination of Measurement Time Period Lidar

The measurement period depends on the specific case and cannot be treated generally. Nevertheless it can be assumed that for reliable measurement data the time period should not be smaller than three months, for turbulence or profile information, taking into account related uncertainties of such a short time period. All necessary BINS should be covered during the measurement period. The particular season and time period have to be taken into account and documented.

Mid- and Long-term Measurements

Regular on-site system checks of the LIDAR system are required to assure

- continuous power supply,
- sufficient wash and wipe fluid,
- sufficiently good shape of wiper,
- no damage to system (e.g. broken met tower etc.)
- unchanged upright position,
- unchanged North direction
- swap and reformat of storage media

Regular necessary service activities are

- replacement of wipe fluid, on demand (on site)
- replacement of wiper blade, generally twice a year (on site)

Sensitivities and Special Notes

Due to the laser measurement principle the LIDAR may react sensible

- on heavy precipitation (rain and snow),
- on heavy mist,
- on moving parts in the laser cone's view angle

Since remote sensing measurements (such as LIDAR or SODAR) represent a volume and vector averaging measurement of the wind the difference to the conventional cup anemometry – as a point measurement of the wind speed magnitude – has to be considered for the interpretation of measurement results.

III Measurement Procedure with 3-D Wind Sensors

Wind Measurements by the use of ultrasonic 3 dimensional sensors (3-D sensors) can deliver an inertia-free measurement of the horizontal and vertical components of the wind speed.

Calibration

The wind speed measurement of the horizontal component must be calibrated in a MEASNET conform wind tunnel according to MEASNET "Cup Anemometer Calibration Procedure" [5] guideline. For a 3D sonic anemometer a directional calibration with a 1°resolution is necessary (360° sweep). The vertical wind speed measurement can be verified in a wind tunnel. Within the measurement campaign a second wind sensor shall be available for in situ calibration. During transportation and mounting the beams of the sensors have to be protected to avoid unacceptable deformations.

Mounting

The mounting has to ensure that the measurement is as undisturbed as possible. Prepositioned obstacles must be avoided or kept below an acceptable level. The Mounting instructions for cup anemometers, which are described in the guideline IEC 61400-12-1 [4] shall be taken into account for the mounting of 3-D sensors as well.

Electrical Connection

The installation of the sensor should be designed to reach a high availability of the measurement system (ideally higher than 95%). The following factors must be considered in this context taking the electric properties of ultrasonic wind speed sensors into account:

- lightning protection concept because of the highly sensible electronic components,
- power supply concept because of the high power consumption in comparison with cup anemometers,
- data storage concept because of the higher data stream compared to conventional cup anemometers.

Sensor Applicability, Configuration, Testing and Documentation

The sensor specific maximum vertical elevation angle, which can be measured, must be kept above the maximum elevations, which must be expected at the site. The data transfer parameters (BAUD rate, protocols) must be adjusted according to the requirements of the data logger. The reporting formats have to be selected (polar co-ordinate-or Cartesian-system, units). Before the use of the sensor all edited and default output parameters as well as the output parameters must be checked and documented. The wake correction and temperature compensation parameters should be checked and documented as well.

Recommended Practices for Extrapolating Mast Data at Higher Heights using Lidar

LIDAR units can provide wind speed measurements at heights practically unachievable by meteorological masts (eg: 150m, 200m). In general, LIDAR measurements are short period campaigns of some months, aiming at collecting data from the main wind direction of a site. At the present time, due to the lack of LIDAR calibration procedure, it is required that simultaneous data exist from a pair of cup anemometer-wind vane at a common height.

The following steps should be followed when correlating-extrapolating Mast data based on the LIDAR's data.

- Assure clock synchronization and common reference of the file time-stamp (beginning or end of 10min averaging period)
- Set one of the LIDAR measuring heights equal to a height of the Mast cup's anemometer, preferably that of the top.
- Create the database with the concurrent LIDAR and Cup anemometer data, excluding data from wind directions "shadowed" by the Mast.
- Verify the linearity of the concurrent mast and LIDAR data (either binned in ranges of 1m/s or using the ensemble of the valid data above 4m/s) at the common height. Goodness of fit values R^2 should be superior to 0.98. This should be done for both wind speed and wind direction.
- Calculate the mean, max and gust values, per wind direction sector, for all LIDAR heights.
- Provide the detailed Speed-up tables (wind speed ratios, ie: U100m/U80m) for the LIDAR's measuring heights, per wind direction sector and per wind speed bin. Actually, these tables are among the main results of the LIDAR measurement campaign.

Depending on the LIDAR unit, additional information can be extracted using the 3sec time-series (ZephIR unit). This includes the distribution of the vertical wind speed component, per wind speed bins and the fast (3sec) wind direction changes between two successive heights.