

# European Wind Turbine Standards II

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# EUROPEAN WIND TURBINE STANDARDS II

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This book contains results of the "European Wind Turbine Standards - II" project carried out within the JOULE-III RD programme of the European Commission, contract nr. JOR3-CT95-0064.

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## PREFACE

*The number of installed wind turbines, world wide as well as in Europe, is increasing rapidly. At the end of 1997, the total amount of wind power had reached 7600 MW, almost 4800 MW was found in Europe<sup>1</sup>. Wind energy has realized a substantial improvement in system reliability as well as a considerable reduction in costs over the recent years. The electricity production in regions with high average wind speeds is now competitive with conventional production methods<sup>2</sup>.*

*The increase in industrial activity in wind energy in turn generates a demand for standardized methods of design, testing and certification of wind turbines. This demand is partly covered by the activities of standardization bodies (CEN/CEGELEC, IEC), however a number of bottle-necks in knowledge and technical harmonization still exists. It was the objective of the European Wind Turbine Standards project (EWTS), the predecessor of the current project, to remove some of the constraints and bottle-necks and contribute to the harmonization. EWTS was completed in the beginning of 1996, but during its execution a number of technical items evolved that still required further investigation. Therefore, a continuation of the project was defined: EWTS-II, to address items that could not be completed. These items were:*

- 1. load spectra and extreme wind conditions;*
- 2. quantification of failure probabilities;*
- 3. integration of blade tests in design;*
- 4. power performance in complex terrain;*
- 5. site evaluation..*

*This report presents the results of these investigations.*

*Furthermore, the previous EWTS project started to establish an organisation of qualified measurement institutes in the field of wind energy, the MEASNET organisation. MEASNET unifies measurement procedures of the participating institutes and guarantees qualified measurements and mutual acceptance among its members. MEASNET was formally established during EWTS-II. A summary on its results is included in the executive summary. More details on the structure of MEASNET, its in house measurement procedures and the rules for acceptance are presented in a separate report<sup>3</sup>.*

*We want to express our gratitude to the European Commission and to the national governments for sponsoring this project and we hope that it has brought the work on wind turbine standardisation a step further.*

*Jos Dekker and Jan Pierik,  
June 1998,  
Petten, The Netherlands*

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<sup>1</sup> International Wind Energy Development: World Market Update 1997. BTM Consult

<sup>2</sup> Inaugural speech of Prof. dr. ir. G.A.M. van Kuik, June 1998, Delft

<sup>3</sup> Implementation of the Network of European Measurement Institutes, MEASNET



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# EXECUTIVE SUMMARY

## 1. LOAD SPECTRA AND EXTREME WIND CONDITIONS

### 1.1 Introduction

The subproject Load Spectra and Extreme Wind Conditions will generate technical background information to facilitate the development and improvement of the European Wind Turbine Standards in the framework of CENELEC.

The objective of this subproject is to provide guidelines for:

- description of the wind condition in wind farms,
- description of the wind condition in complex terrain
- investigation and evaluation of extreme wind conditions.

All the investigations were performed with reference to the IEC-1400-1 standard.

The turbine classifications in IEC-1400-1 are defined in terms of mean wind speeds, turbulence intensities, and a procedure to determine the extremes. The IEC-1400-1 defines four standard classes I, II, III, IV and an S class. In the S-class, all the wind field parameters have to be specified by the manufacturer. The mean wind speeds in class I to IV are 10m/s, 8.5m/s, 7.5m/s and 6m/s, respectively. The wind speed is assumed to be Raleigh distributed. In addition the standard classes are divided into a high and low turbulence class A and B.

The turbulence classes are defined to cover an extended range of wind turbine operation, including operation in wind farms and complex terrain. Even so, the standard states, that the modified turbulence structure in complex terrain and wake effects must be taken into account in the fatigue analysis of the wind turbines. However no commonly accepted procedures or guidelines exist for the estimation of the relevant turbulence parameter for the two above mentioned types of wind turbine operation. Based on the knowledge of the ambient wind and turbulence distribution, and assumptions of the wind farm configuration, the presented subproject “Load Spectra and Extreme Wind Conditions” provides guidelines for estimation of the wake turbulence for wind farm operation. In the same way, the fatigue relevant turbulence characteristics for complex terrain are investigated. The extreme wind conditions given in the IEC 1400-1 are evaluated from a theoretical and practical point of view. Guidelines are given how to estimate the extreme wind conditions from the actual wind distribution and the turbulence intensity level.

### 1.2 Wind farms-Wind field and turbine loading

When operating under wake conditions, an increase in fatigue consumption of wind turbines has been observed. The changes in the load patterns originate both from modifications in the mean wind field and from modifications in the turbulence field. By means of a parameter study, the significant wind field parameters, in relation to the increased wind turbine fatigue consumption in wakes, are identified. The analysis is based on a large number of aeroelastic simulations for five significantly different wind turbine concepts. The effect on selected equivalent loads, originating from realistic perturbations in the selected parameters, is determined by means of a two level factorial method.

It has been demonstrated that the deterministic wake deficit as well as the modified turbulence characteristics (turbulence length scale, turbulence intensity, and coherence decay) all are of primary importance in relation to fatigue loading in wake conditions. Furthermore the effects of each of the above parameters appeared to be approximately additive in a fatigue life consumption sense.

Finally a set of simple models has been investigated and subsequently proposed for the quantification of the identified key parameters. The result is that the wind farm effects are easily included in the IEC 1400-1 by including wake load cases simply defined by suitable modifications in the parameters presently used in definition of the conventional load cases.

### 1.2.1 Conclusions

A procedure for wake load predictions, and its possible inclusion in the IEC-code framework is established. The overall philosophy is to preserve the existing division in four wind turbine classes, and simply supplement the existing load specifications with quantitative wake load specifications.

This procedure is limited to single wake situations, but it is supposed to apply also for multiple wake situations. A detailed investigation has been performed to quantify the wake load situation. The investigation falls into three phases: a crude identification of key wake wind field parameters, a quantification of the identified key parameters and finally a detailed key parameter identification based on predicted wake characteristics.

Applying a two level-factorial method it has been demonstrated that, in the present analysis, 10-minutes simulation time series are a sufficient representation of the individual load situations to yield significant results.

The main findings from the investigation are:

- All four investigated parameters representing the wake wind field, wake deficit, wake turbulence, length scale, and wake coherence—were demonstrated to be significant in relation to increased fatigue life consumption in wakes compared to ambient conditions.
- It is possible to quantify the relevant wake parameters by use of simple models.
- The fatigue contributions, caused by the investigated four parameters, are shown to behave additively. This implies, that a simple approximate method, involving only a very limited number of aeroelastic calculations, can be applied for fatigue estimates taking into account the detailed wind farm topology and the particular wind turbine concept.
- The effect due to increased turbulence intensity is crucial and usually dominates the fatigue effects caused by the other investigated parameters with a factor of 2 to 3.
- The different turbine concepts and different load types act differently with respect to parameter sensitivity. This fact demonstrates the appropriateness of a detailed wake load estimation based on the philosophy applied here, compared to the “all factors in one parameter” approach previously used.

## 1.3 Complex terrain and fatigue loading

The aims of this subtask are:

- to investigate the effect of the terrain complexity on the wind field properties that drive the fatigue loading of wind turbines (like wind shear, Reynolds stresses, etc.).
- to investigate and quantify the impact of the above properties on fatigue loading for machines of different size and design philosophy.

The first goal is met by analysing the available experimental complex terrain wind databases, as well as by performing systematic parametric runs for simple, 2-D, configurations including single and tandem hill

layouts. In the latter case, results are presented in terms of speed-up and turbulent kinetic energy distributions. The second goal is met through parameter identification (PI) procedures applied on both measurements and computational -aeroelastic- results. “Fatigue influence” matrices are, thus, established for different machine sizes and concepts. Recommendations are made on how to include the present findings into the IEC Standards.

When a turbine is erected at a site which differs significantly from the design conditions of the IEC standard, the fatigue and the extreme loads have to be recalculated. The estimation of the turbulence parameters at a specific site must be part of the site assessment procedure. If a turbine, designed according to the standard classes, is intended to operate at a site with a Weibull shape factor  $k$  lower than 1.8, the fatigue load has to be recalculated using the actual Weibull parameters. The actual extreme wind speed events at the site need to be re-evaluated also.

It is felt that the 16% to 18% turbulence intensity values used in the IEC 1400-1 standard can cover complex terrain operation with turbulent intensities from 13% up to 15% respectively, without additional design calculations. It was estimated that this 3% extra turbulent intensity value can compensate a 20 % increase in fatigue loading due to overall complex terrain effects. When a machine is intended to operate at a complex terrain site with a turbulent intensity larger than 15%, the fatigue loads have to be re-evaluated based on the actual values of the Weibull parameters and turbulence conditions at the site.

The wind shear law used in the standards can be maintained, having in mind that a conservative estimation of complex terrain loading is thus achieved.

Sites with wind inclination more than 20 degrees should be considered within the (S)pecial class context.

A site assessment of a complex terrain site must, as a minimum include the following parameters:

- Weibull scale and shape factors  $C$  and  $k$ ;
- turbulence intensity;
- flow tilt (inclination) angle;

Characteristic values of the remaining wind field parameters can be selected on basis of these values.

## 1.4 Extreme wind climate events

Critical loads result in responses that exceed the limits beyond which structural damage or irreversible change may be expected. Thus the designer is interested in the number of times, or the probability, that large loads and resulting large responses may occur during the life of the system.

In the IEC 1400-1 standard divides the wind regime for load and safety considerations into normal wind conditions which will occur frequently during normal operation of the wind turbine, and extreme wind conditions which are defined as having a 1 year or 50 year recurrence period. The extreme wind conditions are used to determine critical design loads which the turbine must withstand during its lifetime. These extreme conditions include peak wind speeds due to storms and rapid changes in wind speed and direction.

The objective of this part of the project is to review the models for extremes of the IEC 1400-1 standard, in particular to investigate whether the specified values for the extremes correspond to the assigned probability .

To this end a theoretical approach is adopted by using Extreme Value Theory rather than to perform yet another analysis of wind speed time series. Although measurements should ultimately be decisive, it is obviously dangerous to infer statistics of extremes from a necessarily limited set of data.

Using Extreme Value Theory it is shown that, given a certain knowledge of the climatology, it is possible

to derive statistical characteristics of extreme wind conditions which are believed to be important for wind turbine design, e.g. the survival wind speed, extreme gusts and extreme wind direction changes. In the present report the limit distributions of these three extreme wind conditions have been investigated, assuming that the climatology (the Weibull distribution, the annual average turbulence intensity, the turbulence model etc.) is defined by the IEC wind turbine classes I through IV. In addition the sensitivity of the extremes for the shape parameter  $k$  investigated.

With the assumptions given above the derivation of the probability density functions (pdf) and the limit distributions (cdf) for the 10-minute average and 3-second average extreme wind speed is straightforward. It is shown that, given a certain confidence level, the magnitude of the extreme wind speed strongly depends on the shape,  $k$ , and scale parameter,  $C$ , of the parent Weibull distribution. Smaller shape parameters lead to higher extreme values and vice versa. The influence of the shape parameter becomes pronounced when  $k \leq 1.8$ .

Comparison with the IEC values shows that the reference wind speed  $V_{\text{ref}}$  is acceptable for sites with  $k \geq 1.77$ , i.e. for most flat terrain sites in Europe. This is also the case for the extreme 3-second average wind speeds  $V_{e1}$  and  $V_{e50}$  (the so-called ‘survival wind speeds’) given in the IEC extreme wind speed model (EWM). But it should be noted that the annual extreme 3-second average wind speed with a recurrence period of one year,  $V_{e1}$ , has been redefined to the “*annual characteristic largest 3-second average wind speed.*”

If a wind turbine has to be designed for complex terrain ( $1.4 \leq k \leq 1.5$ , say), then it is recommended to increase the ratio of the reference wind speed to the annual wind speed to  $V_{\text{ref}}/V_{\text{ave}} = 6.6$ . In that case, the expressions for  $V_{e50}$  and  $V_{e1}$ , given by the IEC, still hold.

Assuming longitudinal wind speed fluctuations  $u_{T1}$  and  $u_{T2}$  at the same location but at different instants  $t_1$  and  $t_2$  to be jointly normal, the conditional pdf  $f(u_{T2} - u_{T1} | u_{T1})$  is derived and the limit distribution function is computed through numerical integration. For extreme gusts not only a strong dependence on the parameters of the parent Weibull distribution is found, but also on the assumed turbulence model, viz. Von Kármán or Kaimal, which determines the temporal correlation as function of the time lag  $\tau = t_2 - t_1$  and the integral time scale ( $L/U$ ).

The magnitude of the extreme gust is inversely proportional to the shape parameter  $k$  of the parent Weibull distribution. The gust speed increases for increasing time lag  $\tau$  until the time lag is greater than the integral time scale ( $L/U$ ), then the gust speed hardly changes anymore. Given the same confidence level, gust values are greater for a starting wind speed at  $V_{\text{rated}}$  than for a starting wind speed at  $V_{\text{out}}$ .

The values found for the extreme 3-sec average gusts with a confidence level of 98% are much larger than the values specified by the IEC 1400-1 standard. This was to be expected because experience using the IEC standard has shown that the Normal Turbulence Model (NTM) leads in most cases to higher loads than the extreme operating gust, indicating that the extreme operational gust model is too benign with respect to actual external conditions.

New analysis of the extreme operating gust, performed by a working group of the IEC (TC88/WG7), based on measurements from the German lowland and from Californian sites, shows a ratio of gust magnitude,  $V_{\text{gust1}}$ , to standard deviation,  $\sigma_1$ , of about 4.8, indicating that ‘real’ extremes will yield much higher ratio’s, close to values found in the present project, which are estimated to vary between 4.4 for wind turbine class IV and 7 for wind turbine class I. Therefore it must be concluded that acceptance of the new model of the extreme operating gust for the second edition of the IEC standard, proposed by the above mentioned working group, would definitely be an improvement.

The derivation of a probability density function  $f_{\theta}(\theta)$  for the wind direction can be found in the literature. It can be shown that this angular pdf only depends on the reciprocal value of the turbulence intensities and

the non-dimensional ratio of the standard deviation of the u and v component of the wind (a measure of the anisotropy of the fluctuations). Because of the non-Gaussian tail of  $f_{\theta}(\theta)$  it cannot be assumed that the density function  $f_{\theta_1, \theta_2}(\theta_1, \theta_2)$  is jointly normal and it turns out to be impossible to derive, from first principles, this density function in closed form. Numerical integration proved to be too costly.

To circumvent this problem an exponential type density function is fitted to  $f_{\theta}(\theta)$  and the extreme value analysis is performed in much the same way as for the extreme gusts. Given the uncertainties in the present analysis the comparison with the IEC values is very limited. It is clear, however, that the IEC values are too benign. Again the newly proposed formulation for the next edition of the IEC standard will be an improvement.

Finally some attention is given to some rare meteorological phenomena— tornadoes and downbursts— which quite likely will induce extreme wind loads, but which are not included in the extreme climate events of the IEC standard.

To conclude:

- Probability density functions and distribution functions have been derived for extreme wind speeds, extreme gusts and extreme wind direction changes. With these density functions it is not only possible to assign a probability to certain extreme wind conditions, but it is also possible to construct a standard where the model for extreme winds and the model for ‘normal’ turbulence and the site classification are logically related, both mathematically and physically.
- The derived distribution functions have been used to compute the magnitude of extreme wind speeds, extreme gusts and extreme wind direction changes with a confidence level of 98%. Comparison with the values given by the IEC 1400-1 standard confirms the observation that the IEC values for extreme gusts are generally too benign. It is recommended however to re-evaluate the distribution function for the extreme wind direction change.
- Finally a rare meteorological phenomenon, called a downburst, is described, which should be included in the extreme climate events of the IEC standard.

## 2. QUANTIFICATION OF FAILURE PROBABILITIES

Presently, wind turbines are being designed in accordance with deterministic design rules embedded in standards like the IEC 1400-1 and various national standards and certification criteria. These rules concern the design of the load carrying components and the design of safety and control systems.

### 2.1 Target values for structural reliability

For a safe design of load carrying components a margin is introduced between the design value of the strength and the characteristic value of the load. Over the years various methods to define safety margins have been used, but nowadays the concept of the partial safety factors is commonly embodied in the structural design codes. The determination of the magnitude of the partial safety factors can be done empirically. However, a probabilistic approach is preferred, because in this way uncertainties in the load and the strength can be considered in a more rational manner. This probabilistic method has been applied already in other branches of industry like offshore and civil engineering, but is not introduced in the wind energy branch yet. As the concept of probabilistic calibration of partial safety factors is fairly new in the

wind turbine community the principles behind the method were examined as part of the EWTS-I subproject “Calibration of Safety Factors”. To calibrate partial safety factors based on a probabilistic method target values for the structural reliability of load carrying components have to be drawn up. This aspect has been considered in the current subproject by means of a literature study. From this literature study it is concluded that:

- The Scandinavian countries and The Netherlands seem to be leading in the application of structural reliability methods.
- The code which is not local to a country, but shall be applied Europe-wide, is the Eurocode 1.

Therefore, it is recommended to apply the safety level of the Eurocode to wind turbines, which would mean a yearly safety index of 4.7, corresponding to a failure probability of  $10^{-6}$ /year.

## 2.2 Guidelines for data collection and parameter estimation

Generally, the control systems have to keep the wind turbine within its design limits during normal operation and have to ensure that electrical energy is generated and supplied to the grid in an efficient manner. In case of a failure or in case of abnormal external conditions, the control systems in combination with the safety systems also have to keep the turbine within its design envelope to prevent damage or unsafe operation. As a consequence of a failure of a safety system, the wind turbine can run into overspeed and is operating beyond design conditions. This can lead to catastrophic failures like blade rupture. Scenarios, how a wind turbine can run into overspeed or failed operation, are derived by means of a qualitative Probabilistic Safety Assessment (PSA). With a quantitative PSA it is also possible to calculate the frequency of occurrence of for example overspeed. PSA’s for wind turbines have been carried out successfully in various countries. Because it is expected that PSA’s will be used more and more, guidelines or recommended practices were formulated as part of the EWTS-I subproject “Assessment of Wind Turbine Safety; Recommended Practices”.

Because the treatment of data for the quantification was beyond the scope of the EWTS-I project, this aspect has been considered in the current subproject. Guidelines to collect data for quantitative safety and reliability analyses have been formulated, based on a limited benchmark study.

As guidelines for data collection and parameter estimation, it is recommended to use as starting basis:

- the guidelines as outlined in the LW 15/75 and NEWECs-45 studies reports; and
- the recommended practices from the EWTS-I project.

In addition to these reports, the following is recommended:

1. The recommendations set out in the LW15/75 and NEWECs-45 studies can be used for design of specific data collection and parameter estimation. Also, the recommendations of the LW 15/75 study on the use of generic data are still valid.
2. Preferably, use should be made of standard, proven methods as laid down in reliability handbooks. Preferably, computerised versions of (generic) databases and existing software for reliability data analysis should be used.
3. Generic wind turbine data sources can be used if no specific data are available or if there are no time or resources available to collect design specific data.
4. Generic wind turbine data sources can be used to provide data on a high level, e.g., an estimate of blade failure frequency to be used in risk studies, or for frequencies of certain initiating events, e.g., grid loss.
5. If generic data are used to estimate a particular parameter (e.g., a failure rate), the following should be documented clearly for each parameter estimated:
  - *the reference(s) to the source(s) used,*
  - *a discussion why the source is considered valid or why the source is used,*

- *the calculation procedure to arrive at the final estimate if multiple sources are used.*
6. If engineering judgement is used to provide an estimate, the reason for this should be indicated. Engineering judgement should be used to provide an estimate if design specific or generic sources do not provide an adequate answer.

## 2.3 Risks to the public

As mentioned above failure of the safety system might lead to catastrophic failures like blade rupture, which can cause risks to the public. In that way it is of great interest for e.g. authorities, especially in densely populated areas. To judge whether a risk is unacceptable, limits have to be indicated above which the risks become unacceptable (maximum permissible levels).

From a literature study it is concluded that risk criteria related to the risk to the public, applicable for wind turbines are:

- the individual risk and
- the group risk (as defined in the official Dutch premises for risk management).

For these two criteria, the following target values are recommended:

### **Individual risk**

For the use of the individual risk a risk target level of  $10^{-5}$ /year is recommended. The individual risk is independent of the site of the wind turbine (park) and can be calculated without knowing the exact location of the installation. Note that the term 'risk limit' is not used but instead the term 'risk target', because risk limits are not commonly used in all EU countries.

### **Group risk**

The target value for the group risk is that the likelihood of an accident with 10 deaths occurring should not exceed one in every hundred thousand years ( $10^{-5}$ /year). The aim of setting target values for group risk is to prevent social disruption (the death of a group of people all at once). Accidents with even more serious consequences lead to correspondingly greater degrees of disruption. It is therefore assumed that an  $n$ -times larger impact than 10 deaths should correspond with an  $n$ -squared smaller probability of such an accident occurring. The actual group risk is expressed as a so-called Complementary Cumulative Distribution Function (CCDF).

## 2.4 Final recommendations

The main recommendations resulting from this EWTS-II subproject are summarised as follows:

- The guidelines formulated as part of this EWTS-II subproject can be an aid to collect data and to use it wisely for the purpose of safety and reliability studies of wind turbine designs.
- Qualitative safety and reliability studies are recommended very strongly as a minimum, as these studies result often in the identification of design errors (e.g., no or too less redundancy, no defence for certain events). Quantification, even with only the use of generic data sources, often results in a good ranking of the important event sequences, component failure modes, and systems. A combination of generic data and engineering judgement can always be used, although the reliability analyst should be aware of the limitations. In this way, a design can be made (more) balanced.
- Quantitative safety and reliability studies should be used primarily for the 'relative' (qualitative) purposes outlined above. The use of absolute figures and absolute criteria should be avoided.

## 3. INTEGRATION OF BLADE TEST IN DESIGN

### 3.1 Introduction

The objective of this part of the project is to develop a recommended methodology to include full-scale blade tests in the wind turbine design process. Actual test and measurement procedures do not need to be addressed here, especially because they are in development under the co-ordination of a working group of IEC TC-88WG8.

During the performance of the work a continuing discussion has been held whether the general objective, the deliverables and the activities to be performed are in compliance with each other. Full scale blade tests, as performed nowadays, are executed to demonstrate adequate safety margins and to verify design calculations. This means that the performance of mechanical tests on rotor blades is already a fact today, although the tests are usually performed at the end of the design process. Consequently the test results are not used to upgrade the design, unless the experiments showed that the design criteria are not met. So the tests are performed to demonstrate, to a reasonable level of certainty, that specified limit states of the rotor blades are not reached, provided that they are produced according to the specifications. In other words that the rotor blade will survive the design load spectrum. The usefulness of these tests for the designer to improve the design formed the main discussion point within this EWTS II subproject.

Use has been made of the reports and guidelines of the SFAT and IEC-TC88 WG8 documents.

The deliverables of the work as reported, contain information concerning recommended methodologies to include blade tests in the wind turbine design process in order to, demonstrate adequate safety margins and to verify design calculations.

### 3.2 Technical description

#### **General**

The full scale tests as discussed here, are split up in (blade) property tests, i.e. the eigenfrequencies, mass etc. , strength tests, and fatigue tests.

#### **Property tests**

These tests are intended to check whether properties, like mass, centre of gravity, eigenfrequencies and static strength are (almost) equal to the values assumed in the load spectrum calculations. When they differ to much, the loads used to verify the structural design are not valid any more. The actual allowable margin, between measured values and the values assumed in the aeroelastic calculations can easily be determined using calculations in which the most critical parameters are varied some percents up or down. When the most important statistics, such as maximum, minimum and standard deviation, or for example a fatigue equivalent load range, differ a lot, the sensitivity of that parameter is large and consequently the allowable margin is small.

*Mass and centre of gravity* are the most easiest measurements to perform. The values give a very good indication whether the blade has been produced according to the specifications.

*Stiffness* is very important, it indicates whether tower clearance is sufficient and together with the mass distribution it provides the input for the calculation of the natural frequencies. The stiffness distribution is not that easy to determine, especially when the lay-up of the laminates across the cross-section is not symmetric and coupling between deformation modes has to be taken into account.

*Natural vibration tests.* Results are very important to verify whether the aeroelastic calculations have been

performed on an accurate model of the wind turbine (rotor blades). The eigenfrequencies are not that difficult to determine, however the actual mode shape is more difficult to measure. Differences compared with the assumed values should be consistent with the differences between assumed mass and stiffness distribution.

#### **Static tests**

The static test results are used to verify whether the structural design is sufficient. This test can be performed in a number of selected directions.

When it is the intention to go to ultimate load or failure load one has to be very careful which direction is tested first. The most likely direction to fail first should be tested last.

The results, usually strain gauge readings on a number of selected spots give a fair indication whether the structural design is accurate enough to predict the strains/stresses. Strain/stress concentrations are difficult to determine due to the fact that only a limited number of strain gauges will or can be monitored.

When failure occurs at an early stage in the test, a careful examination of the failure and the (test) loading compared to the design loading, has to be made in order to make sure that differences between design and test loading are not the cause of the early failure.

#### **Fatigue tests**

The fatigue test has limited value for the designer, especially when the designer wants to improve the design from the test results.

The main reason is that the test loading differs much from the design loading, due to the fact that a test is made up of only  $3 \cdot 10^6$  to  $10^7$  cycles and the design loading comprises up to  $5 \cdot 10^8$  cycles. For coupon fatigue tests the scatter in allowable number of cycles is almost a factor of 10. When only 1/3 of that scatter is present at a full scale test, the results of two or even more tests are needed to obtain clear conclusions, except when a failure occurs early in the fatigue test.

### **3.3 Conclusions**

For designers the blade property and static test are the most important tests. The design load spectrum and structural integrity can be checked to a large extent. The fatigue test which is of less use for the designer, is however a very valuable test to check all details of design and manufacturing. Errors or design flaws which remain unnoticed easily during the other tests, will show up clearly in a fatigue test. Spots with high strains e.g. in corners where strain gauges can not be applied, will crack and this will indicate that the design requirements are not met.

## **4. POWER PERFORMANCE IN COMPLEX TERRAIN**

### **4.1 Introduction**

It is widely accepted that in spite of the fact that during the last years the wind energy technology and industry attained an outstanding progress, further research is needed on specific technical and non-technical issues. The prominent issues are related to system integration, cost-effectiveness improvement as well as standardisation and certification. All these issues are strongly dependent on the power performance verification and assessment practices. Recently, several EU funded research projects as well as standardisation bodies were concentrated on the different aspects of this issue.

The research, presented within this EWTS II subproject, is intended to clarify the status of power performance verification and assessment in complex terrain, putting emphasis on the following items:

- power performance verification for wind turbines operating in complex terrain,
- assessment of developed, applied and verified tools for WECS power performance in complex terrain.,
- assessment of the available international and national standards.

The major achievements of the project are:

- presentation and assessment of various power performance measurements regarding wind turbines of different size and control strategy,
- presentation and assessment of alternative power performance verification practices
- identification and quantification of the terrain induced effects on the power performance of wind turbines,
- assessment of the existing recommendation and standardisation documents and identification of all inefficiencies that influence the power performance assessment and verification in complex terrain,
- construction of the technical basis for the development of a reliable procedure for power performance measurements in complex terrain.

## 4.2 Technical description

The project scientific and technical description and progress is presented for each task separately, as follows:

### **Inventory of existing information on the issue of power performance measurements in complex terrain.**

The literature research resulted in many topic-related articles and documents, yet it provided a limited readily exploitable information for complex terrain measurements. The survey and the resulting conclusions regarded topography effects, effect of obstacles, site calibration practices, alternative power curve measurement procedures and site dependent wind characteristics effect on power curve.

### **Assessment of power performance measurement campaigns and site calibration techniques. Focus on comparison of different power curve measurements at different sites through annual energy production estimation and uncertainty estimation for power curve and annual energy production.**

Several power performance campaigns have been analysed in order to assess the recommended procedures regarding site calibration, power curve determination and annual energy production uncertainty estimation. The analysed data regarded wind turbines of different size and control strategy operating at different sites, as shown in table 1.1 where an overview of the experimental and analysis work performed within the project is presented.

In the field of site calibration different techniques were assessed, namely a nacelle cup anemometer at a downwind parked turbine and the use of a meteorological mast prior wind turbine erection. Moreover the application of numerical site calibration was judged also.

Table 1.1. Overview of experimental and analytical research within EWTS-II.IV.

Wind turbine	Terrain	Institute	Site calibration technique	AEP estimation	Uncertainty estimation	Parameter identification
WINCON 110XT (110kW, stall)	complex	CRES	nacelle cup on running WT nacelle cup on parked WT rotor disk measurements	Yes	Yes	Yes
VESTAS V27 (225kW, pitch)	complex	CRES	nacelle cup on parked WT	Yes	Yes	Yes
	flat	RISO	reference mast	Yes	Yes	No
	flat	DEWI	reference mast	Yes	Yes	No
	flat	WINDTEST	reference mast	Yes	Yes	No
MADE AE-30	flat	CIEMAT	reference mast	Yes	Yes	Yes
	complex	CIEMAT	reference mast	Yes	Yes	Yes
NORDTANK 500/37 (500kW, stall)	complex	CRES	calibration prior WT erection nacelle cup on parked WT	Yes	Yes	Yes
	flat	RISO	reference mast	Yes	Yes	Yes
	complex	NEL	numerical simulation	Yes	Yes	Yes
	complex	NEL	numerical simulation	Yes	Yes	Yes
	flat	DEWI	reference mast	Yes	Yes	Yes
	flat	WINDTEST	reference mast	Yes	Yes	Yes
NEDWIND 500kW	complex	DEWI	nacelle cup on running WT	Yes	Yes	No
ELKRAFT 1MW	flat	RISO	nacelle cup on running WT	Yes	Yes	No

#### Assessment of power curve evaluation using nacelle anemometers.

The assessment of the nacelle anemometer on running machines was performed on a wide range of wind turbine sizes ranging from 110kW up to 1MW machines (see table 1.1).

The following conclusions were drawn from this research:

- the correct application of the methodology and the transfer of the calibration formula to other wind turbines of the same make and type, presupposes that the wind turbine rotor settings, yaw behaviour, the position on the nacelle anemometer are unchanged as well as that the terrain remains flat.
- the dependency of the calibration formula to wind and wind turbine parameters was found to be limited. On the other hand these effects are expected to be magnified in cases where wind structure and wind turbine response at the calibration site compared with the testing site are quite different.
- lower scatter in the measured power curve as a function of the nacelle wind speed may be obtained.
- the introduction of the nacelle cup calibration formula introduces a statistical error that should be taken into account in the uncertainty estimation.
- The use of nacelle wind speed measurements may decrease the error induced by site calibration significantly in cases where large discrepancies are encountered between the measured and reference wind speed.

#### Parametric analysis of the available power curve measurements for the identification of the site related effects influencing the power performance behaviour.

The parameter identification of wind turbine power performance regarded the quantification of the dependency of power characteristics on wind deterministic and stochastic characteristics, especially mean value and standard deviation.

The following issues were clarified by means of this parameter identification procedure:

- identification and quantification of the wind parameters that affect power performance,
- assessment of the sensitivity of power characteristics for wind turbines of different size and control system,
- assessment of the sensitivity of power characteristics for the same wind turbine type when operated in different sites,
- assessment of causal parameters in relation to complex terrain characteristics
- assessment of a power curve normalising procedure based on parameter identification results .

An analytic method is introduced covering parameter identification tasks in power performance measurements. The developed tool is based on multivariate regression analysis with a backward parameter elimination technique in order to account for the statistically insignificant parameters. The method was applied for the parameter identification of the power performance of wind turbines operating at different sites, both flat and complex. The parameters chosen to comprise the model set describe the deterministic part of the wind, the main turbulent characteristics, the turbulence length scale as well as the wind speed distribution. The examined dependent variables were the mean power output, the standard deviation of the power output and in the case of pitch controlled machine the response of the control system. The effect of the above parameters was identified and quantified. It appeared that except from the mean wind speed other parameters, related to the deterministic as well to the stochastic wind characteristics are affecting the power performance of the turbine and should be considered within power performance assessment procedures. The parameter identification procedure was applied to the following cases: 225kW pitch regulated, 110kW stall regulated, 300kW stall regulated and 500kW stall regulated. Moreover, a separate investigation on the sensitivity of power performance on turbulence, wind shear and atmospheric stability has been performed on a 3MW wind turbine.

**Assessment of existing guidelines and their validity for complex sites. Identification of drawbacks connected to the application of existing guidelines and recommendations for power performance measurements in complex sites.** The assessment was focused on the recommendations of IEC 1400-1 ed.2. Certain inefficiencies, related to site calibration and uncertainty estimation procedures, were identified.

The assessment of the existing standards and recommendations regarded the following issues:

- status of wind turbine power performance assessment and verification (existing standards, EU project results, contractual matters, market needs etc.),
- review of characteristics of complex terrain and their effect to power performance ,
- points that are not adequately described by the present IEC 1400-1 ed.2 document, particularly in relation to complex terrain (site calibration, uncertainty estimation etc.),
- recommendations for performing power performance assessment and verification in complex terrain.

The discussed critical points regarded the following issues:

- test site requirements,
- characterisation of wind speed sensors,
- influence of wind mean and turbulent structure,
- site calibration,
- response system ,
- measurement analysis,
- contractual aspects.

The derived practical recommendations for power performance assessment in complex terrain followed from the identified inefficiencies of the IEC 1400-1 ed.2. and regarded the following issues:

- definition of site complexity,
- selection and characterisation of instrument configuration,
- wind turbine control system response,
- site calibration,
- normalisation procedure,
- uncertainty estimation procedure,
- power curve measurements of wind farms.

**Drafting of a status report providing a comprehensive overview of the up to date available information on power performance in complex terrain and of the proposed solutions and results of the parameter identification.**

The final technical report includes the following items:

- introductory review on project background, objective, working methodology and project scientific and technical performance,
- review on power performance measurements focusing on the effects of terrain orography on wind field, site calibration, alternative methodologies for power measurements and effects of turbulence and shear on power curves,
- presentation of the experimental research and analysis performed by the participants within the project,
- review of the experimental research on alternative power performance methodologies, namely using a nacelle cup anemometer on a running wind turbine or by using the upwind rotor averaged wind speed as reference,
- presentation of the parameter identification procedure background and results. Analysis was performed on all available data bases regarding wind turbines of different size and control strategy,
- review of the assessment of existing guidelines for power performance,
- presentation of practical recommendations and conclusions.

## 5. SITE EVALUATION

Over the ten to fifteen years that commercial wind farm development has been a reality throughout Europe, the term “site assessment” or “site evaluation” has generally tended to be associated with the prediction of the energy yield potential of a site prior to the installation of wind turbines. Hence, historically, the evaluation has usually been restricted to the assessment of the site annual average wind speed and wind speed distribution. However, as the economic and design margins on wind turbines and wind farms become tighter, the need to quantify and minimise all aspects of risk has become more important. The site evaluation is at the core of this risk evaluation process and consequently needs to consider more than just energy yield potential if other aspects such as turbine integrity and safety are to be assessed.

This is addressed in the latest draft edition of the IEC wind turbine safety standard (IEC-1400-1 “Safety of Wind Turbine Systems”, Edition 2) which necessitates a site evaluation. Although IEC 1400-1 (ed2) explicitly states what the scope of the site evaluation must be, it does not give guidance on how to do it. Therefore, the intention of this sub-project has been to provide information and methods which will be of practical use to those involved in the application of the IEC standard.

The approach taken may be summarised as follows:

- a survey of consultants and test organisations offering site assessment/evaluation services in each of the EC countries taking part in the ongoing project was made in order to determine the various methodologies used .
- the survey results were collated in a database and interpreted to identify national or other trends.
- with regard to mean wind speed prediction, which is but one aspect of site evaluation, a detailed review of the results of numerous well documented modelling and measurement based evaluation techniques was carried out and hence guidelines for the application of the techniques were proposed.
- the more promising new or revised modelling based evaluation techniques for mean wind speed determination were implemented using various test cases to assess their repeatability and usefulness.
- a detailed investigation of the background principles and theory relating to “other” site wind parameters was carried out and summarised. Hence a list of instructions for the practical determination of these other parameters was written, including a summary of instrumentation requirements.

## 5.1 Survey of European Consultants

Consultants and test organisations in Denmark, Germany, Greece, Netherlands, Spain and United Kingdom were individually contacted to determine the scope and methods used for site evaluation, with the emphasis on mean wind speed prediction techniques as it was anticipated that this was the most commonly assessed parameter. Consequently 71 responses to the survey were received out of a total of about 100 consultants approached.

## 5.2 Database

The survey results reveal strong national and topographical trends governing the extent and method of site assessment. Countries with generally flat or simple terrain rely mainly on modelling or calculation based techniques whereas the countries with complex terrain primarily use measurement based techniques, sometimes in combination with modelling for short distance spatial extrapolation of wind speed. In certain countries the mean wind speed evaluation is carried out as a legal requirement but primarily with regard to the aspect of energy yield rather than structural integrity. Of the measurement based techniques used, variations on the Measure-Correlate-Predict (MCP) technique are most common whereas the most popular model in use is WASP. Of the other parameters assessed by measurement, turbulence intensity and the mean shear layer characteristic were typically determined.

As a separate exercise a review of the sources and types of input data available commercially within each country for use with modelling or MCP type techniques was carried out. The main specifications of terrain contour maps and long term wind speed data available in each country are summarised.

## 5.3 Mean Wind Speed Prediction

A comprehensive review of the technical status of modelling and measurement based techniques was carried out. As dictated by the results of the survey, specific emphasis was placed on WASP and MCP with a view to proposing guidelines for use.

In the case of WASP the main recommendations for successful implementation are:

- both the reference and predicted sites are subject to the same weather regime
- neutral atmospheric conditions prevail
- the surrounding terrain is sufficiently gentle and smooth to ensure mostly attached flows
- the reference data are reliable
- the description of the background roughness length must be as accurate as possible The MCP technique can be successfully applied where the following conditions can be satisfied:

- validated, long-term and short-term concurrent measured reference wind speed data are available at a reference site within the same climatological zone as the prediction site.
- validated prediction site wind speed measurements are available for a period of at least 8 months and more typically 12 months or more.

## 5.4 Mean Wind Speed Modelling Technique Enhancements

Perhaps the major shortcoming in the commercial use of wind flow models (and MCP) is the difficulty in the quantification of uncertainties. In this report a philosophy for the assessment of uncertainty is proposed which, although not necessarily easy to apply to wind models, does highlight the components of uncertainty of relevance. Derivation of a specific parameter (Ruggedness Index) for categorising terrain has been summarised from recent literature and is proposed as a useful technique for identifying when the limits of applicability of a model may have been exceeded.

## 5.5 Other Parameters

Methods for assessing parameters other than mean wind speed are proposed. In each case, the theoretical background is also presented.

The following parameters have been considered:

- reference wind speed
- characteristic turbulence intensity at 15 m/s
- annual average wind speed distribution
- normal wind profile
- turbulence length scales
- coherence
- standard deviation ratios
- negative gust

Recommendations for instrumentation and measurement requirements are given in each case. As certain parameters require the use of an ultra-sonic anemometer and as this is still a rather specialised instrument a review of important points on the use and interpretation of data arising from this device is presented.

It is believed that the information presented in this report will provide useful guidance to those involved in site evaluations and, especially with regard to the other parameters, collates relevant practical information and knowledge in one convenient document for the first time. However, more practical experience of applying the recommended techniques should be gained to determine if all of the proposals are indeed sufficient.

# 6. IMPLEMENTATION OF EUREC-AGENCY MEASNET

## 6.1 Introduction

More than three years ago the six the European institutes CIEMAT, CRES, DEWI, ECN, NEL, RISØ later joined by WINDTEST, decided to improve their measurement quality jointly in order to avoid any problems of future mutual recognition. Measurements performed by the institutes, even applying the existing IEA, IEC and other standards and recommendations, showed remarkable differences in their results, a situation which is unacceptable in an open international market. To improve this unsatisfactory situation the above mentioned test centres worked together in the projects “European Wind Turbine Standards I and II” co-financed by the European Commission and agreed to form a grouping called: MEASNET, Network of European Measuring Institutes.

During the two projects special attention was given to the anemometer calibration procedure. Due to the third power dependence of power from wind speed, the main emphasis had to be concentrated on a accurate anemometer calibration. Specially the problem of the use of different wind tunnels for anemometer calibration had to be solved. Basis for all performed harmonisation and quality evaluation work were round robin tests and agreed quality evaluation procedures.

Within the two above mentioned projects, the main task of the project team consisted of creating an organisational structure and of establishing rules and requirements which will guarantee that high quality measurements are carried out by the participants. In effect, the objective of this project was to arrive at the situation where the measuring institutes are able to perform measurements of equal quality which are sufficient for the mutual comparison and acceptance.

MEASNET is not restricted to the actual founding members but also open for other institutions as long as they are independent of industry and fulfil the membership requirements set up by MEASNET. All member institutes ensure compliance with the agreed measurement procedures by obtaining and maintaining EN 45001 accreditation. Measurements will not be done by MEASNET but by each participating institute. Customers therefore have the advantage to contract that MEASNET member for a measurement, which offers the best commercial conditions.

## 6.2 Internal Structure and Requirements of MEASNET

### 6.2.1 Structure of MEASNET

To ensure high quality measurements, uniform interpretation of standards and recommendations as well as interchangeability of results, the members established an organisational structure for MEASNET (Fig. 6.1). Within this structure mutual periodical quality procedures for measurements and evaluations will be performed. The highest tier is the Council of Members. An Executive Board, composed of three representatives from different member institutes executes the tasks delegated by the Council of Members. One or more Expert Groups, specialising in certain measurement tasks, advise and support the Executive Board and the Council of Members on the definition of the measurement procedures. Assessment Teams are established to perform assessments for the admission of new members and for quality confirmation of MEASNET members. MEASNET members must be accredited to EN 45001 for the MEASNET approved measurements.

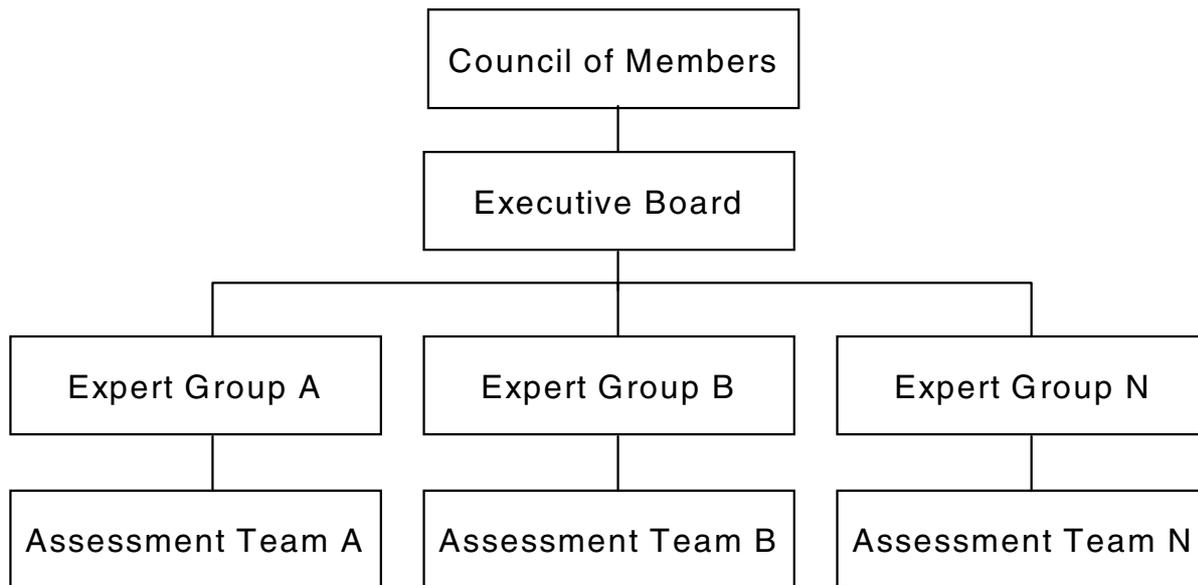


Figure 6.1 Organisational structure of MEASNET

### 6.2.2 Requirements of MEASNET

In order to ensure generally acceptable, high quality measurements the member institutes shall fulfil the following requirements:

- legally independent from industry.
- adequate experience in the field of wind energy and wind energy related measurements.
- qualified and experienced measurement staff.
- carry out measurements according to the MEASNET rules and procedures, at least power performance measurements.
- EN 45001 accreditation of the agreed measurement procedures. If the EN 45000 accreditation system is not implemented in the home country of the organisation, the agreed alternative acceptance requirements will be applied\*).
- presentation of measurement results according to the MEASNET format.
- accept the policy of co-operation and exchange of information on measurement and evaluation procedures and on problems arising in measurement campaigns.
- MEASNET members will accept each other results as far as they are carried out according to the MEASNET procedures.
- MEASNET members will subject themselves to an internal MEASNET quality evaluation programme.

\*) If the EN 45000 accreditation system is not implemented in a country, the MEASNET Council of Members will decide on alternative acceptance procedures for the candidate organisation.

MEASNET membership is not restricted to the member institutes but is open for other organisations as long as they are independent of industry and fulfil the membership requirements set up by MEASNET. The seat of MEASNET is the address of the institute of the current Executive-Chairman of MEASNET. Actual address for 1997 and 1998 is DEWI in Germany. As this seat will change with the Executive-Chairman the formal contact address of MEASNET for initial contacts is the seat of the EUREC-Agency in Leuven.

MEASNET c/o EUREC-Agency  
Kapeldreef 75  
3001 Leuven - Heverlee, Belgium  
Tel.: ++32-16-281-522  
Fax.: ++32-16-281-510

All commercial contacts can be made of course directly with the desired member institutes.

### 6.3 MEASNET Recognised Measurements

During the course of the two projects, the members of MEASNET agreed on the following measurement and quality evaluation procedures to be performed under the MEASNET quality criteria:

- anemometer calibration
- power performance
- noise
- power quality.

Special attention was given to the calibration of anemometers as the most crucial part of a power curve measurement. As an intermediate result of the round robin tests was agreed that not all MEASNET members are approved for absolute anemometer calibrations. Absolute anemometer calibration is considered to be a general commercial service offered to customers. The not approved institutes may perform relative calibrations which allow for own power curve measurements only. In the beginning of the project it was not foreseen to distinguish between the two calibration methods, but it turned out to be necessary. Until the end of the project the participants did not obtain an agreement about relative calibration method due to missing experience.

All agreed measurement procedures except power quality, take into account the final and draft documents of international organisations, e.g. IEC, IEA and in addition requirements derived from results of related projects and measurement experiences. The agreed noise measurement procedure is an example for the necessity of additional MEASNET measurement requirements. The performed round robin evaluation of a measured data set led, after some necessary correction measures of the different institutes, to comparable results because the IEC recommendation concerning the evaluation of tonality was improved.

For the power quality measurement procedure a IEC standard is not yet existing. Therefore the members of MEASNET decided to use the respective German guidelines until IEC recommendations will be worked out. At the moment Germany is the only country, where such measurements are required by the utilities. In Germany this guidelines for power quality measurements had been worked out during the last two years by a group of experts coming from the involved measurement institutes, industry, utilities and state governments. They include two years of experience gained by the three German measurement institutes and therefore are already a good starting point for a future international harmonisation within MEASNET.

A MEASNET member must at least be approved for power performance measurements. This requirement was established to guarantee that MEASNET members have enough experience and understanding in wind energy related questions. In the actual status of the project not all founding members have finished yet the quality evaluation procedure for the different agreed measurements. A member must not be approved for all measurement types and can be approved for additional measurements at any time he performed successfully the quality evaluation procedure. The MEASNET measurement approval is valid for five years as far as the institute passes successfully all internal quality evaluation programmes during this time and maintains the accreditation to EN 45001. An official MEASNET acceptance document indicates the measurement types for which the MEASNET member is approved for. Customers should ask the institute of their choice to present this document.

Measurement reports performed under the quality criteria of MEASNET will be stamped by the measuring institute with a stamp which consists of the MEASNET logo and, written around the logo, the name of the institute. As an example the general logo of MEASNET is shown in Fig. 6.2.

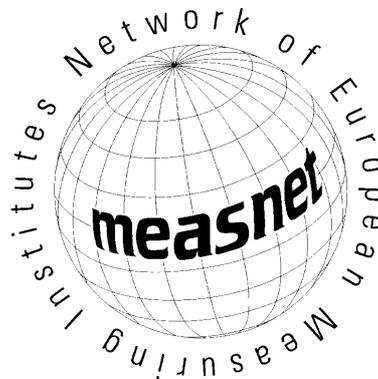


Figure 6.2 Logo of MEASNET

MEASNET is now operative and the institutes are allowed to offer their MEASNET approved, high quality measurements from October 1997 on.

## 6.4 Performed Quality Evaluations

Several quality evaluations have been made during the two projects. The most intensive one was for anemometer calibration, because a procedure had to be found, how to judge the quality of the wind tunnel which should be used for the anemometer calibration. The standard anemometers in use by each institute were sent around for calibration to each of the MEASNET founding members. One of the evaluation difficulties was how to define the correct wind speed reference to which the calibration results of each institute had to be compared. After an additional evaluation of the influence of anemometers under skew wind flow conditions and after several correction measures a mutually agreed comparison base was found. As a result of this round robin the institutes decided to have the above mentioned two types of approved anemometer calibrations, the absolute and the relative anemometer calibration.

Other round robin evaluations were performed for power performance and noise measurements. In both cases a set of measured data were sent around for evaluation by the individual institutes. Differences in the evaluation results were discussed and led to correction measures concerning the established measurement and quality evaluation procedures. All round robin tests showed, that the idea of MEASNET to harmonise the interpretation of standards and the applied measurement methods is of very high importance. Guidelines for evaluation, for example stated in the existing IEC standards, even when correctly applied led to different interpretations of requirements and consequently to differences in the results.

## 6.5 Conclusion

MEASNET members are interested commercially in performing measurements in the field of wind energy. In spite of all difficulties encountered during the project the institutes always found a solution which could be accepted finally by all members. It was of great advantage for the progress of the work that the experts of the founding members are used to work together in many other joint European research projects since more than a decade. As a result of their intensive and detailed work, MEASNET members now mutually accept their measurement results and guarantee high quality by regularly performed quality evaluation programmes.

The advantages for the industry to contract a MEASNET institute are:

- the measurements are accepted in other countries,
- are of high and comparable quality,
- and can be ordered on the basis of competitive offers from the member institutes.

For the first time measurement institutes work together and were able to find agreed procedures with the goal to harmonise the interpretation of measurement procedures established in international standards and recommendations. The different performed quality evaluation tests during the course of the two projects showed the necessity of such a grouping, if measurements performed by different institutes shall be comparable to each other. The fact that all MEASNET members are also engaged in the different existing IEC, IEA and CENELEC working groups will help to integrate the gained MEASNET experience in the respective international measurement standards and recommendations.

At the moment MEASNET is only a wind energy activity. But the participants are convinced that measuring institutes engaged in other renewable energies will encounter the same harmonisation problems when they have to enter a real commercial market situation. Perhaps MEASNET serves as an example for them of how to work together and solve the harmonisation and quality evaluation problems.

EUROPEAN WIND TURBINE STANDARDS II  
PART 1  
LOAD SPECTRA AND EXTREME WIND CONDITIONS  
SUB A  
WIND FARMS – WIND FIELD AND TURBINE LOADING

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## **Abstract**

When operating under wake conditions, an increase in fatigue life consumption on wind turbines has been observed. The changes in the load patterns originate both from modifications in the mean wind field, and from modifications in the turbulence field. By performing a parameter study, the significant wind field parameters, in relation to the increased wind turbine fatigue consumption in wakes, are identified. The analysis is based on a large number of aeroelastic simulations and it has been performed for five significantly different wind turbine concepts. For each of these the effect on selected equivalent loads, originating from realistic perturbations in the selected parameters, is determined by means of a two level factorial method.

It has been demonstrated that the deterministic wake deficit as well as the modified turbulence characteristics – turbulence length scale, turbulence intensity, and coherence decay – all are of primary importance in relation to fatigue loading under wake conditions. The effects of each of the above parameters was furthermore shown to be approximately additive in a fatigue life consumption sense.

Finally a set of simple models has been investigated which subsequently resulted in a recommendation for the quantification of the identified key parameters. The recommendation can serve as a resource for certifying bodies and is further, if it is found appropriate, easily included in the IEC-code framework. The wake load cases is thus simply defined by suitable modifications in the parameters presently used in definition of the conventional load cases.

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EUROPEAN WIND TURBINE STANDARDS II  
PART 1  
LOAD SPECTRA AND EXTREME WIND CONDITIONS  
SUB B  
COMPLEX TERRAIN AND FATIGUE LOADING

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EUROPEAN WIND TURBINE STANDARDS II  
PART 1  
LOAD SPECTRA AND EXTREME WIND CONDITIONS  
SUB C  
EXTREME WIND CLIMATE EVENTS

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EUROPEAN WIND TURBINE STANDARDS II  
PART 2  
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EUROPEAN WIND TURBINE STANDARDS II  
PART 3  
INTEGRATION OF BLADE TEST IN DESIGN

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EUROPEAN WIND TURBINE STANDARDS II  
PART 4  
POWER PERFORMANCE IN COMPLEX TERRAIN

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EUROPEAN WIND TURBINE STANDARDS II  
PART 5  
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