2. EDITION

EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION

1. POWER PERFORMANCE TESTING

2. EDITION 1990

Submitted to the Executive Committee of the International Energy Agency Programme for Research and Development on Wind Energy Conversion Systems

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING

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Edited by

Steen Frandsen
Risø National Laboratory
DK 4000 Roskilde, Denmark

and

B. Maribo Pedersen
Technical University of Denmark
Lundtoftevej 100, Building 404
DK 2800 Lyngby, Denmark

Foreword

The evaluation of Wind Turbines (WT) must encompass all aspects of a Wind Energy Conversion System (WECS) ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of internationally agreed evaluation procedures for each of these areas is needed to aid the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the proposed recommendations for wind turbine testing to address the development of internationally agreed test procedures which deal with each of the above noted aspects for characterizing Wind Turbines. The IEA expert committees will pursue this by periodically holding meetings of experts, to define and refine consensus evaluation procedures in each of the following areas:

1. Power Performance
2. Cost of Energy from WECS
3. Fatigue Loads
4. Acoustics
5. Electromagnetic Interference
6. Structural Safety
7. Quality of Power
8. Glossary of Terms

This paper addresses the first of these efforts, and is an update of the first edition, published in 1982.

The expert committee will seek to gain approval of the procedures in each member country through the IEA agreements. The recommendations shall be regularly reviewed and areas in need of further investigation shall be identified.

Contents

Introduction

Since the production in 1982 of the first edition of the IEA Recommendation for Power Performance Testing, the need for accurate power curve determination has increased considerably due to the tremendous development within the wind power industry which has taken place since then.

This has called for a thorough review of the recommendations, and the present edition is the result of discussions with a great many people involved in power curve determination.

In particular there has been close contact with the groups of people who have been engaged in the development of national and international standards of which draft or approved versions already have appeared [1], [2].

A Major difference between the first and this second edition is a decrease in the total number of data points required for completion of a test. But more important is the underlining of the fact, that an accurate determination of wind speed is crucial for an accurate determination of the power curve and the prediction of the annual energy output. This reflects the more stringent demands on anemometer accuracy, and that test sites must be carefully investigated for homogeneity.

An extensive appendix on uncertainty analysis has also been added to the text in the hope of attracting the attention of the test engineers to the fact, that the reporting of test results is not complete without a statement of the accuracy of the results.

Scope and Field of Application

This document describes the recommended practices for testing and reporting power performance characteristics of a single Wind Turbine (WT). It provides a standard methodology, exclusively for comparing the energy production characteristics of WTs available in the market. The following is noted:

1. The methods presented herein are not limited to WTs that produce electricity. However for systems exhibiting large hysteresis effects at cut-in, particularly Wind Turbine Pumps (WTPs),due consideration should be taken to this fact, particularly when evaluating the uncertainty of the derived results. See ref. [4].
2. These procedures and practices are generally applicable to WTs of all sizes and classifications.
3. Specific procedures are recommended. Alternate procedures may be used if documentation demonstrating their equivalence to the Recommended Practice is provided.
4. This method does not address issues of reliability and durability.
5. The test results are valid only for the specimen tested. When applied to machines of the same model without tests, the uncertainty on the results may be somewhat increased.

RECOMMENDED PRACTICES FOR WIND TURBINE POWER PERFORMANCE TESTING

1. DEFINITIONS AND UNITS

Net Power (P) - The power available from a WT less any power needed for control, monitoring, display, or maintaining operation; i.e. power available to the user. P will be 10 minute average values unless otherwise specified.

Mean Power (MP) - The calculated average power of a WT, assuming a Rayleigh distribution of wind speed probability density based upon the annual average wind speed and 100 per cent availability - see section 6.1.

Maximum Power - The maximum net power of a WT, in normal operation.

Rated Power - Net power output which the WT is designed to achieve under normal operating conditions.

Power Curve - A graph which depicts the net power of a WT as a function of wind speed (see Figure 4).

Power coefficient, c_p - Net Power divided by the wind power of the undisturbed flow through the rotor swept area.

Annual Energy Output (AEO) - The calculated total net energy that would be produced by a WECS during a one-year period, assuming a Rayleigh distribution of wind speed probability density based upon the annual average wind speed and 100 per cent availability.

Annual Energy Output, Real Availability (AEOA) - The total net energy delivered under real load conditions when the wind conditions are good enough for operation, but subject to periods of inoperation. Breaks caused by technical faults, maintenance or other reasons therefore have to be taken into account.

Wind Speed (V) - The 10-minute average wind speed, unless otherwise specified.

Annual average wind speed ($\overline{V}$) - Wind speed averaged long enough to eliminate annual variations (i.e. many years).

Cut-in Wind Speed - The minimum wind speed at which the WT begins to produce energy that is deliverable to a load (see Figure 4).

Cut-out Wind Speed - The maximum wind speed at which the WT produces energy.

Maximum Design (Survival) Wind Speed - The maximum wind speed a WT in automatic, unattended operation, but not necessarily generating, has been designed to sustain without damage to structural components or loss of ability to function normally.

Anemometer Distance Constant - Quantity related to the response time of an anemometer.

Rotor Speeds - The rotational speed, or range of speeds, of the rotor of a WT operating between its cut-in wind speed and the wind speed corresponding to maximum power.

Bin Width - The size of the wind speed interval used in the Method of Bins data reduction procedure (i.e. a wind speed bin having a span of 5-6 m/s has a width of 1 m/s).

Hub Height - Height of the centre of the rotor above the terrain surface for horizontal axis wind turbines (HAWTs), or the mid rotor height for vertical axis wind turbines (VAWTs).

Units - Numerical values reported are to be given in metric Systeme Internationale (SI) units. If desired they may be followed, in parentheses, by the local units.

In this text the Wind Energy Conversion System will be called Wind Turbine (WT), Wind Turbine Generator (WTG), Wind Turbine Pump (WTP) or Machine under Test.

2. THE MACHINE UNDER TEST

The WT tested shall be thoroughly described and pertinent engineering and geometric data supplied. Photographs of the machine under test are desirable.

The installation procedure shall be thoroughly described. In the case of a standard production model WT, instructions of the manufacturer shall be followed.

In the case of testing of a standard production model WT, the manufacturer should provide a clear description of the model, serial number and year of manufacture of the machine tested.

Listed below is a sample of typical data, to which it is advised to pay special attention.

- Geometrical data: rotor size and type, number of blades, blade airfoil section data, pitch angle for fixed pitch machines, hub height of rotor and tower type. For propeller type windturbines it shall be stated if the rotor is positioned upwind or downwind of the tower.
- Transmission: description of gear box arrangement if any.
- Output energy carrier: electricity, heat or mechanical energy. If possible the characteristics of the energy converter (in this context electric generator, resistors, waterpumps etc.) shall be given.

- Control systems: description of cut-in and cut-out control, blade pitch angle control, regulation of rotor rotational speed etc.

Other information essential for the understanding of the operation of the WT shall be included.

A description of the integrated test installation shall be provided.

The installation under test (Wind Energy Conversion System) shall be considered to be the WT, the control systems, applied loads, and measuring instrumentation.

3. THE TEST SITE

A description and a map of the test site shall be provided. Selection of the site should minimize the possibility of local topographical features affecting the test results. In situations where obstacles, like nearby buildings, other wind turbines, trees, etc. may affect test results for certain wind directions, it is recommended that these test results be deleted or reported separately with adequate explanation. Preferably, the description of the test site should include a series of photographs, taken from the place of the WT, in all directions, and also include an annual wind direction distribution characteristic (wind rose). It is emphasized, that neglect of careful evaluation of test site imperfections can have serious implications for the accuracy of the power curve determination. For further detailed reading see Ref [3].

4. FIELD TESTING METHODOLOGY

4.1. General

The basic power performance characteristics of the WT shall be defined by the power curve, see Figure 4. The power curve shall consist of data collected from field tests conducted under "natural" atmospheric conditions (that is, the wind turbine tower is stationary and exposed to the natural wind). Data obtained from analytical WT model calculations, bench tests, "constant velocity" tests (towing tests) or wind tunnel tests shall not be employed to generate the WT power curve.

The atmospheric conditions shall be described primarily be the meteorological parameters, wind speed, air temperature, air pressure and wind direction, while the key parameter of the WT is the net power. Sections 4.2 and 4.3. state the specifications and locations of the test monitoring instruments.

4.2. Measurement of Atmospheric Conditions
- Specification and Location of Monitoring Instruments

4.2.1. Wind Speed

The anemometer employed to measure the wind speed should have a distance constant of 5 m or less. It should have an accuracy of ± 0.1 m/s or better over the speed range from 4 m/s to 25 m/s.

Calibration of the anemometer shall be conducted in such a way that it can be verified that the accuracy has been maintained during the test period for the machine under test. The calibration test procedure and test results, including the date of calibration, should be provided in an appendix to the machine test report (see section 7). Calibration by an independent laboratory using traceable standards is recommended.

Use of a secondary calibration source (anemometer manufacturer, etc.) is acceptable as long as traceability is maintained.

The guiding principle of anemometer placement shall be to minimize interference effects from the WT, the meteorological tower and the local topography.

The test anemometer shall be located at a height above the terrain surface, equal to the hub height. However, variations may be considered provided they adhere to the following guidelines:

a) for WT having hub heights greater than 10 m, the anemometer elevation shall be at hub height ± 10% of the hub height.

b) for WT having hub heights less than 10 m, the anemometer elevation shall be at hub height ± 1 m.

The test anemometer shall be placed between 2 and 6 rotor diameters from WT, see Figure 1. The tower centre line shall be the reference for the placement requirement on the anemometer.

For vertical-axis WT, the reference diameter to be used to define the distance between the anemometer and the WT is the maximum rotor diameter.

NOTE: Recent experimental evidence indicate, that more attention should be paid to proper placement of the anemometer on the meteorological tower.

A placement at the top of the tower will normally cause no problems and is recommended, whereas boom mounting may cause an appreciable error in measured wind speed if not carried out properly.

At the time of writing, no specific recommendations can be given, except that the distance of the anemometer from the mast, which is normally used, seems to be adequate, whereas the distance between the boom and the anemometer should be increased considerably over what is most often seen in practice.

4.2.2. Wind Direction

The wind direction shall be monitored in order to eliminate atmospheric data influenced by the WT or the meteorological tower as described in Section 4.2.1. and Section 4.5.3.

The wind direction measurement shall be accurate within ± 3 degrees. The transducer shall be located on the meteorological tower at the same height as the anemometer.

Care should be taken to avoid mutual interference between the anemometer and the wind direction sensor (wind vane).

4.2.3. Air Temperature and Pressure

The temperature and pressure measurements shall be made in accordance with common meteorological practice.

Air temperature and pressure shall be measured at the site so that net power can be corrected to the reference air density as described in section 5.2. The accuracy in the determination of the air density shall be better than ± 1%, and the accuracies of the temperature and pressure transducers shall be good enough to meet this demand.

4.2.4. Other Environmental Parameters

Snow or rain may considerably affect both anemometer readings and power output, and data obtained during such conditions should be handled with care.

To quantify the effects of such conditions, separate tests may be carried out, following the recommendations in all other respects.

4.3. Measurement of Parameters of the Machine under Test - Specification and Location

4.3.1. Rotor Speed

The Rotor speed should be measured with an accuracy within ± 1% of rotor speed at rated power.

This measurement may be omitted in the case of a nominally fixed speed wind turbine.

4.3.2. Net Power

The power monitoring instrumentation used for the test shall have a cumulative accuracy within ± 0.5% of the WT Rated Power. When testing a Wind Turbine Generator, the electric power is to be measured applying a three-phase watt-meter with a response time less than 1 second, and which measures the true r.m.s. value of the power. When testing small battery charging wind turbines, the accuracy range may be exceeded.

Calibration of the instrumentation shall be conducted in such a way that it can be verified that the accuracy has been maintained during the test period. The calibration shall be traceable to International Standards.

The measurement of power shall be performed in a manner that ensures that only the rate of energy delivered to a load is measured.

For measurements of quantities describing the quality of power reference is made to the separate part of these Recommendations on Quality of Power.

4.3.3. Applied Load

The applied test load shall be representative of the likely consumer load situation. Its key physical parameters shall be measured and documented consistent with the guidelines of this document and good engineering practice.

The applied load shall be placed in the WT power circuit, or its equivalent, in a manner which ensures that all of the net energy output of the Machine under Test is delivered to the load. Care shall be exercised to measure only the energy output delivered by the Machine under Test.

4.4. Data Acquisition System

Automatic digital data acquisition systems are recommended. Careful attention shall be given to the accuracy and resolution of any analog-to-digital (A/D) converters used in the data acquisition system, since they can potentially affect the outcome of an analysis procedure.

The data acquisition system shall be linear over the entire frequency/amplitude range of the test parameters.

Care shall be exercised to avoid sampling rates which are integer multiples of the fundamental frequency of net power.

The minimum sampling rate shall be 0.5 Hz.

4.5. The Test Procedure

4.5.1. Overview Comments

All aspects of the Test Procedure shall be clearly and definitively documented so that every physical test condition could be duplicated at any later point in time. A detailed Test Plan shall be written which addresses each applicable item in Section 4 of this document as well as the additional activities necessary for the proper conduct of the test and the maintenance of the Machine under Test.

All data shall be reviewed for accuracy and consistency on a periodic basis during the test to ensure maximum reliability of the data. Appropriate test logs shall be maintained to document all events during the test.

4.5.2. Collection of data

During the test period, readings shall be taken continually with a minimum sampling rate of 0.5 Hz, of wind speed, wind direction, net power and, if necessary (see Section 4.3.1.), of rotor speed.

Measurements of air temperature, air pressure and other environmental parameters need only to be taken once for each test period of max. 1 hour duration. For test periods lasting more than 1 hour, these parameters shall be recorded once per hour.

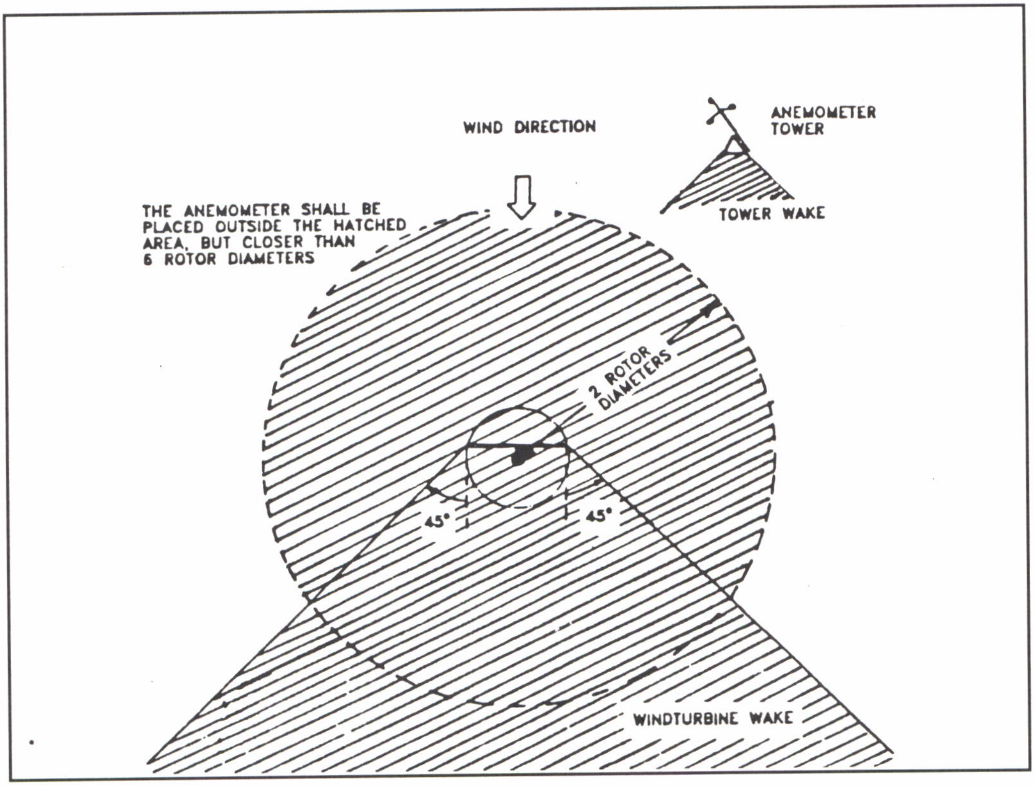

Figure 1. Sketch, showing area around the wind turbine where wind speed measurements cannot be made.

4.5.3. Elimination of Erroneous Data

If - for any reason - the measurement of any one of the sampled quantities is erroneous, the data sample shall be discarded.

If, during the course of the test, the test anemometer is in the wake of the WT rotor or structure, the measured wind speed will deviate from the free stream wind speed. To make sure that the wind speed measurement is not disturbed by the WT, data where the anemometer is within a sector downstream of the WT as defined in Figure 1 shall be discarded.

Data, where the anemometer might be in the wake of the tower, on which the instrument is mounted shall be discarded.

Data where the anemometer (and/or the WT) might be affected by nearby obstacles, like buildings, trees or other wind turbines shall be discarded (see Section 3).

The wind direction to be used in this procedure shall be the 10 min average wind direction.

Data obtained when blades are noticeably contaminated by the attachment of ice, dirt, salt or insects shall be discarded.

4.5.4. Limitation on Modifications and Adjustments to the machine under Test

Any adjustment or modification made to the machine during the test period shall be reported. Also, an engineering assessment of the impact of these changes on the WT performance shall be provided. Adjustments to either the load or generator field or their equivalents shall not be made in any sort of synchronization with the taking of data.

Any maintenance or repair of the machine under test required during the test period shall be reported.

In the case of a standard production model WT, the maintenance instructions of the manufacturer shall be followed.

Cleaning of contaminated blades (insects, salt) may be done if it is a part of the regular servicing of the machine, and mentioned in the machine manual.

4.5.5. Data Base Requirements

The total data base is formed of one or more continuous test periods, each of limited duration, Data records of less than 15 min. duration shall not be included in the data base.

To the extent it is possible the recording periods shall be chosen "randomly" in such a way

1. that no particular characteristics of the machine are favoured or depressed,

2. that no special climatological situation (except for rain and snow) is chosen or avoided for arecording period so as to enhance or degrade the performance.

The data shall be carefully examined for gross errors (see Appendix 1) both related to instruments and data acquisition system, and the specific test conditions (Sections 4.5.3 and 4.2.4.). Data recognized or suspected of being defective shall be discarded.

Prior to further data analysis, the data shall be reduced by means of pre-averaging of the recorded raw data. Within certain limits it can be shown, that the information contained in the data - with respect to power production - is only marginally affected by pre-averaging, i.e. the accuracy of the final power curve does not depend on how the data are averaged, as long as the pre-averaging time is longer than 1 minute.

However, for convenience, and to match the climatological standard on which the derivation of wind speed frequency distributions are based, 10 min. preaveraging of the data should be used

NOTE: A shorter pre-averaging time does not reduce the total required testing time, as the number of data sets per bin multiplied by the pre-averaging time shall be constant

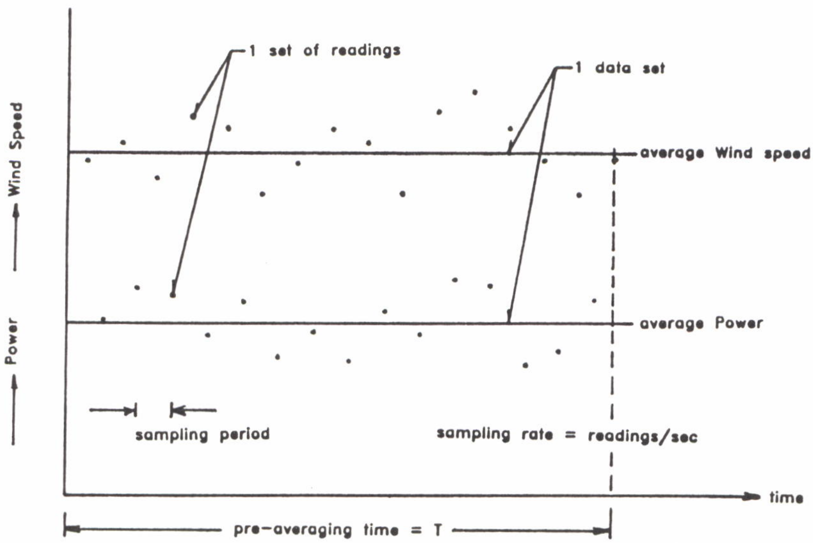

Figure 2. Sketch, illustrating the pre-averaging process.

Given a sampling frequency n and a pre-averaging time T sec, each set of averaged data shall be formed from (T•n) consecutive sets of readings, see Figure 2. No set of original readings must be included in the formation of more than one averaged data set.

The test shall not be considered complete until the following conditions for the reduced (averaged) data have been met:

* Maximum power (in averaged data) shall be experienced.
* Zero or negative power (in averaged data) shall be experienced in atleast 2 concutive bins below nominal cut-in wind speed, (see Section 5.3.).
* Each bin shall as a minimum contain data corresponding to 30 min. of recording, i.e. at least three 10 min. average values. Appendix 1 may be used as a guideline..

5. ANALYSIS OF FIELD TEST RESULTS

5.1. Wind Shear Correction

When Section 4.2.1. is adhered to, no corrections need to be applied to the wind speed reading for anemometer height different from hub height.

5.2. Correction of Power for Air Density Variations

Before data analysis according to section 5.3. is carried out, corrections to the data sets for air density variations must be applied.

The aim of the corrections is to bring the power curve and the calculated mean power as close as possible to the values which would be obtained if the measurements were all carried out at a standard air density at sea level of 1.225 kg/m^3 (1013.3 mbar, dry air, 15 degrees celcius or 288.15 degrees Kelvin).

For a stall controlled wind turbine each 10 minute average net power value shall be corrected by applying the following formula:

$$P_S = P_T\left[\frac{1.225}{\rho_T}\right]$$

where P_S = Power corrected to standard conditions

P_T = Uncorrected average power

ρ_T = Test air density

ρ_T is calculated from

$$\rho_T = 1.225\left[\frac{228.15}{T}\right]\left[\frac{B}{1013.3}\right]$$

where B = Barometric pressure, mbar

T = Air temperature, degrees Kelvin

T = t + 273.15

t = air temperature in degrees Celcius

For a pitch regulated WTG the correction is the same as for a stall controlled WTG as long as the measured power levels are below 70% of rated power.

For measured power levels above 70% of rated power, the correction applies instead to wind speed (and not to power) according to the following expression

$$V_S = V_T\left[\frac{\rho_T}{1.225}\right]^{1/3}$$

where V_T is the measured, uncorrected wind speed, m/s

V_S is the wind speed corrected to standard conditions

Care should be taken not to apply air density corrections to fractions of the power which are not dependent on air density, such as gearbox and generator losses.

If for instance the relation between net power P and rotor power P_R is of the form

$$P = \alpha P_R - \beta$$

With α and β constant, then the correction of power for air density variations should be

$$P_S = \frac{1.225}{\rho_T}(\alpha P_R) - \beta$$

This will be the case for grid-connected, constant speed WTG, where the electric losses normally will be proportional to the power produced, while the mechanical losses in the drive train will be rotor speed dependant and hence constant for a constant speed WTG.

5.3. Determination of Power Curve from Data

After the data reduction and the correction of data, data analysis is to be performed using the Method of Bins. In this procedure, the wind speed range of operation of the WT is divided into a series of intervals (bins). The speed range of operation is defined as wind speeds from 1 m/s below WT cut-in wind speed to cut out wind speed. The wind speed bin widths between 1 m/s below cut-in wind speed and the lowest wind speed with maximum power shall be 0.5 m/s. The wind speed bin widths between the lowest wind speed with maximum power and cut-out wind speed (or 20 m/s whichever is less) may be increased to 2 m/s. A data set - as described in section 4.5.5. - consists of the 10 minute average of both the wind speed and the net power. Data sets shall be accumulated in the bins, the wind speed determining the specific bin, see Figure 3.

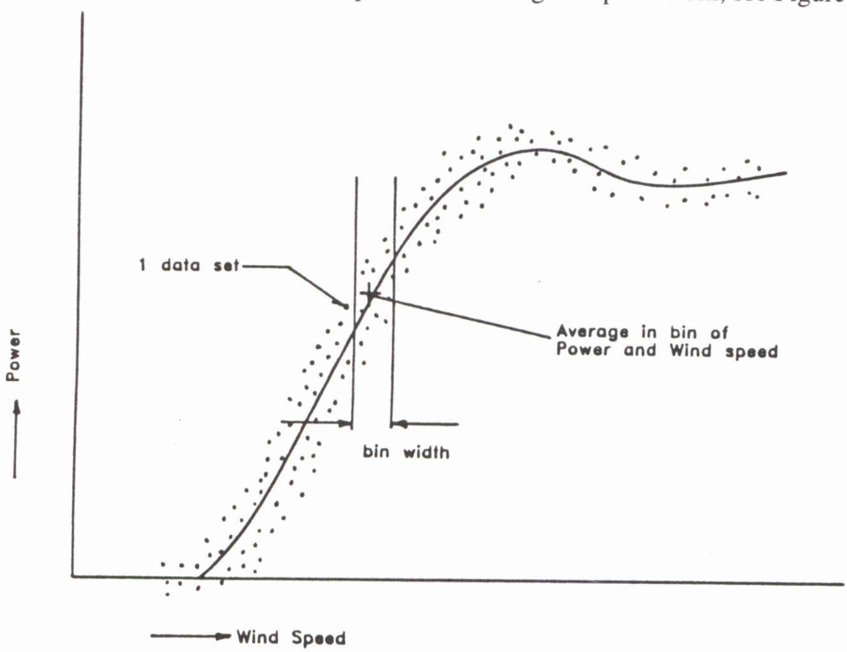

Figure 3. Bin-averaging of data sets.

Then the ensemble average of the data sets in each bin shall be determined by dividing the summed value of the wind speed data sets by the number of data sets, and by dividing the summed value of the net power by the number of data sets, i.e.:

$$V_i = \frac{1}{n_i} \sum_{j=1}^{n_i} V_{ij}$$

$$P_i = \frac{1}{n_i} \sum_{j=1}^{n_i} P_{ij}$$

Where V_{ij} = j - t h 10 minute average of wind speed in the i - th bin

P_{ij} = j - th 10 minute average of net power in the i th i - th bin

n_i = number of data sets in the i - th bin.

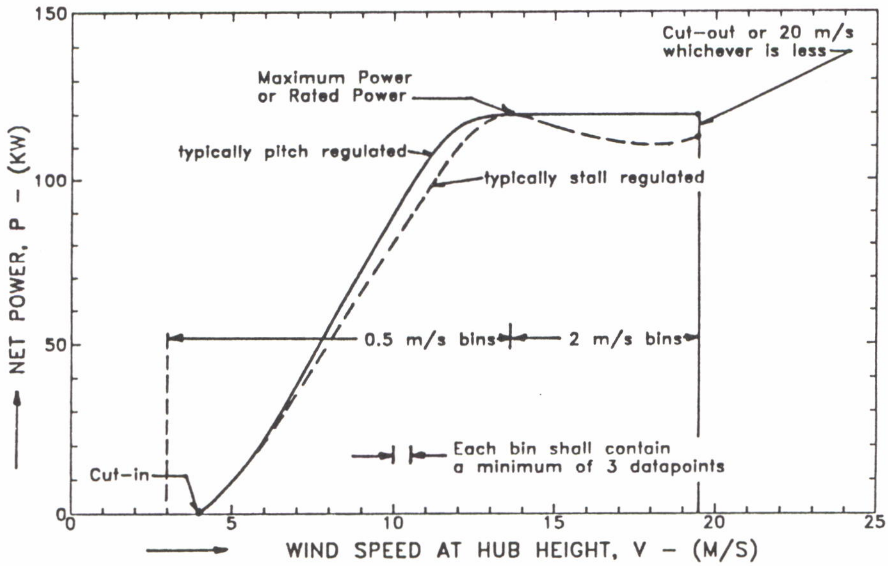

Figure 4. Examples of typical power curves.

The ensemble averages (V_i, P_i) are then plotted and a curve fitted through the plotted points. This curve is the WT Power Curve.

The minimum conditions of section 4.5.5. must be met before the curve is established.

The Power Curve is a linearly scaled Cartesian coordinate system graph of WT net power, corrected for air density variations, (ordinate) versus wind speed, (abscissa). See figure 4 as a detailed example.

Both scales start at zero. The ordinate scale should extend to at least 110% of the WT Maximum Power. The abscissa should extend to a wind speed of at least 20 metres/second.

The Power Curve is to be displayed graphically as indicated in Figure 4, and in form of a table as shown in Figure 5.

bin no. i	bin interval m/s	number of data sets n_i	bin averages		
			wind speed V_i - m/s	net power P_i - kW	rotor speed rpm
1	3.0 - 3.5	12	3.27	-6.22	42.5
2	3.5 - 4.0	18	3.73	-2.34	
3	4.0 - 4.5	26	4.28	2.36	
4	4.5 - 5.0	19	4.76	5.88	
5	5.0 - 5.5	33	5.24	11.81	nominally fixed speed
.	.	.	.	.	
.	.	.	.	.	
.	.	.	.	.	
21	13.0 - 13.5	14	13.22	119.7	
22	13.5 - 14.0	22	13.76	120.4	
23	14.0 - 16.0	11	15.07	116.5	
24	16.0 - 18.0	5	16.93	111.8	
25	18.0 - 20.0	4	18.87	113.1	

Figure 5. Example of table containing the results of the method of bins analysis.

6. DERIVED RESULTS

6.1. Power Coefficient (C_P)

The Power Coefficient is determined as

$$C_P = \frac{P}{1/2\,\rho\,AV^3}$$

Where P is net Power, watts

ρ is air density (1.225 kg/m^3)

A is rotor swept area, m^2

V is wind speed at hub height, m/s

6.2. Mean Power (MP)

The Mean Power is determined as

$$MP = \int_0^\infty f(V)\bullet P(V)\bullet dV$$

where f(V) = probability density function of wind speed,

and P(V) = experimental power curve.

Care should be taken in the numerical integration for the determination of MP in order not to introduce too large errors. MP shall be presented as a function of the annual average wind speed $\overline{V}$, Figure 6, assuming that the probability density function of wind speed is a Rayleigh distribution:

$$f(V) = \left(\frac{\pi}{2}\right)\left(\frac{V}{\overline{V}^2}\right)\exp\left[-\left(\frac{\pi}{4}\right)\left(\frac{V}{\overline{V}}\right)^2\right]$$

where $\overline{V}$ = Annual average wind speed at hub height. The uncertainty of MP shall be calculated and presented as a function of $\overline{V}$. The method of Appendix 1 may be used.

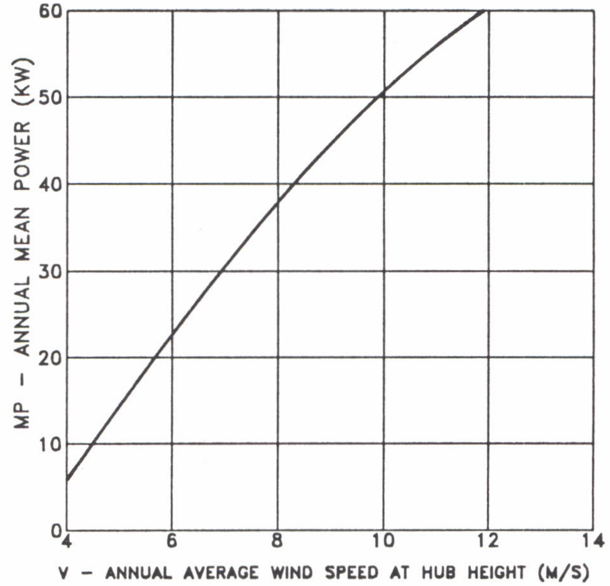

Figure 6. Example of a plot of Mean Power as a function of annual average wind speed, assuming that the probability density function of the wind speed is a Rayleigh distribution.

6.3. Annual Energy Output, 100% Availability (AEO)

The Annual Energy Output (AEO) in kWh is then given by

AEO = (8760 hrs)•(MP).

6.4. Annual Energy Output, Real Availability (AEOA)

The Real Annual Energy Output (AERO) is given by

AEOA = AEO•TA

where TA (Technical Annual Availability) is the time fraction of the year the wind turbine is technically ready for operation, whether the wind conditions are suitable or not. Unless determined through a long period of monitoring (more than a year) the TA will be an estimate, based on experience with wind turbines similar to the machine under test.

6.5. Influence of Environmental Parameters on AEO and AEOA

In stating AEO and AEOA for a particular site, the influence on AEO and AEOA of snow, rain and insect contamination of blades must be considered (see Section 4.2.4. and Section 4.5.3.).

7. INFORMATION TO BE REPORTED

The Report shall include, but not be limited to, the items listed below.

1. Machine under Test, including model and serial number of main components (if a production machine), and year of manufacture, see Section 2.
2. Instrumentation, including type and location, see Section 2. If calibration is applicable, the method of calibration used, the calibration time interval used, and the traceability of the calibration references to National Standards shall be documented.
3. Site layout (including sketch and photographs). See Section 3.
4. Installation, see Section 2.
5. Data acquisition system, see Section 4.4.
6. Load, including type, size and method of control. See Section 4.3.3.
7. Weather, see Section 4.2.4.
8. Test procedure, see Section 4.5.1.
9. Data corrections used, see Section 5.1. and Section 5.2.
10. Deviations from recommended practice.

Plots of the following shall be presented:

11. Net power versus, Wind Speed, see Section 5.3.
12. MP versus Annual Average Wind Speed, see Section 6.2.
13. The uncertainty of MP versus Annual Average Wind Speed.
14. Power Coefficient versus Wind Speed, see Section 6.1.
15. Rotational Speed versus Net Power Output (if applicable).

Raw data summaries shall be included as an appendix to the report.

8. ACKNOWLEDGEMENTS

The present edition of this document has been developed through a series of meetings with participants from different countries participating in the IEA R&D - agreement.

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A. Curvers, The Netherlands

T.F. Pedersen, Denmark

O. Fabian, Denmark

Steen Frandsen, Denmark, has written appendix 1.

9. REFERENCES

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[2] AWEA, Standard Performance Testing of Wind Energy Conversion Systems, AWEA 1.1 - 1988.

[3] Christensen, C.J. and Dragt, J.B. ed.: "Accuracy of Power Curve Measurements", RISØ - M - 2632, November 1986.

[4] Oostendorp, P. and Veldkamp, D.: "Testing Wind Pumps", CWD, T.U. Eindhoven, January 1988.

Appendix I prepared by Sten Frandsen

From practical experience, it is clear that significant uncertainties may be attached to a power curve measurement. It has been shown, ref. [1], that even at well conducted experiments with an extensive amount af data available, the final error on the estimated annual energy output from the machine may easily exceed 10 per cent. Bearing in mind that such error is reflected directly in the economic feasibility of wind power plants, the importance of the quality of the experimentally determined power curve becomes obvious.

Thus, to facilitate the use of the experimental power curve for commercial purposes, it is strongly recommended that the measured power curve is accompanied by a rigorous evaluation of uncertainties. The uncertainty analysis should as a minimum adhere to the procedure described in this appendix, although a more rigorous analysis of course is advisable. More general presentations of measurement uncertainty are found in textbooks and specialized journals, for instance ref. [2] and [3].

An analysis of the uncertainty of the annual energy output for a specific *type* of wind turbine exposed to a specific wind climate will include 1) uncertainty of estimation of the wind resources (wind speed distribution), 2) uncertainty of determination of the power curve of the individual specimen of the type, 3) uncertainty related to the variability of output of different specimens of the same type of wind turbine, and 4) uncertainty related to the availability of the machine. Included in the third category is also the effect of snow, insects etc. The target of the analysis presented here is solely to pinpoint uncertainties in the power curve measurement.

General on Error Analysis.

Error analysis theory defines three types of errors, namely

Bias Errors, which are systematic errors that are assumed to remain constant during the test. A typical bias error is an error in an instrument's calibration constant, offset or scaling parameter. Herein, the bias errors are given as bias limits: the error will with a probability of 1 be within the interval specified. Furthermore, it is assumed that bias errors are rectangular distributions.

Random Errors, errors related to the general "scatter" of the measured data points. Random errors are typically assumed Normal distributed and the error size is specified by means of the the process' standard deviation. Given enough data, such types of errors can in principle be reduced to any small value as described in this appendix, and

Gross Errors, which relate to incorrect use of data aquisition system, major instrument errors etc.

Given careful planning and execution of the test, errors of the last category, gross errors, are assumed eliminated. The documentation for this should be delivered as part of the test report.

This leaves bias and random errors, which must be determined/estimated one by one. Having determined the error components they are combined to form the final estimate of the measurement uncertainty.

To simplify the error analysis, one assumes that the final quantity of an experiment, $R = R(x_1, x_2, x_3, \cdots, x_N)$, being a function of N measured parameters, can be linearized:

$$R = \bar{R} + \alpha_1 \Delta x_1 + \alpha_2 \Delta x_2 + \cdots\cdots + \alpha_N \Delta x_N = \bar{R} + \sum_{i=1}^{N} \alpha_i \Delta x_i \tag{1}$$

where $\bar{R}$ is the mean value, Δx_i are pertubations around the mean value and α_i are constants denominated ***sensitivity factors.*** These are given as

$$\alpha_i = \frac{\partial R}{\partial x_i} \tag{2}$$

Assuming that the error sources are independent, the ***resulting bias error***, B_r, and the indicator of random errors, the ***resulting precision index***, S_r, are obtained as the root-sum-squares of the individual bias errors and precision indices, respectively, of the N sets of measured parameters:

$$B_r = \left\{ \sum_{i=1}^{N} (\alpha_i B_i)^2 \right\}^{\frac{1}{2}} \text{ and } S_r = \left\{ \sum_{i=1}^{N} (\alpha_i S_i)^2 \right\}^{\frac{1}{2}} \tag{3}$$

B_i are to be interpretated directly as the ***bias error limits*** on parameter x_i, i.e. the deviation of the true values from the measured value will not exceed B_i.

The ***precision indices***, S_i, may be calculated from characteristics of the recorded data. The so-called *Central Limit Theorem* will under certain assumptions predict that the process of mean values ($\bar{x}_i$), each formed of M independant estimates, will have a Normal distribution with a standard deviation given by

$$S_i = \sigma_i / \sqrt{M} \tag{4}$$

where M is the number of measurements and σ_i is the root-mean-square of x_i. In other words, the accuracy of the mean value may be calculated on the basis of the process of which we formed the mean value.

The ***resulting, total error*** is then calculated by root-sum-squaring [1] of the two error types, bias and random errors:

$$U_r = \left\{ B_r^2 + (tS_r)^2 \right\}^{\frac{1}{2}} \tag{5}$$

where the constant t is the Student's "t" value. The Student's t-distribution approximates for a larger number of data (degrees of freedom) the normal distribution [2]. The value of

[1] It should be noted that there is no general agreement on how to add bias and random errors. Also simple summation may be applied: doing so will influence the confidence limits, i.e. the probability of the true value being in the given interval.

[2] In principle, $t = 2$ corresponds to the 95% per centile only when large numbers of averaged values are considered, typically specified as more that 30 values. However, the author finds that the large uncertainty on the error analysis itself justifies using $t = 2$ for all bins no matter the number of data points.

t is related to the probability that the true value of the quantity sought in the test is to be found in the interval

$$[\bar{R} - U_r ; \bar{R} + U_r] \tag{6}$$

where $\bar{R}$ is the mean value of the measured data. Choosing $t = 2$ implies that for a relatively large number of data - if the total bias and the total random error are approximately of the same size - the probability of the true value being in the interval, Expression (6), is approx. 95%.

The expressions, Eqs. (3), can be normalized:

$$b_r = \left\{ \sum_{i=1}^{N} (\theta_i b_i)^2 \right\}^{\frac{1}{2}} \text{ and } s_r = \left\{ \sum_{i=1}^{N} (\theta_i s_i)^2 \right\}^{\frac{1}{2}} \tag{7}$$

where

$$b_i = \frac{B_i}{\bar{x}_i}, \quad s_i = \frac{S_i}{\bar{x}_i} \quad \text{and} \quad \theta_i = (\frac{\bar{x}_i}{\bar{R}}) \frac{\partial R}{\partial \bar{x}_i} = \frac{\bar{x}_i}{\bar{R}} \alpha_i, \tag{8}$$

b_i and s_i being the *relative* bias errors and precision indices, respectively, and θ is the normalized sensitivity factor. In this formulation, it is then seen that if a relative error of, say, 1 per cent in parameter x_i reflects in the result also with 1 per cent, then $\theta = 1$.

Error Analysis on Power Curve Measurements.

It is strongly recommended that the test engineer makes clear to himself the difference between bias and random errors. A random error is the inherent misrepresentation one gets when trying to descibe a large population by the characteristics of only a sample of that population, whereas a bias error is an error related to *systematic* misconception of the test instruments' calibration/reading or the test circumstances.

Once this difference is understood, it will be obvious that the major problem in any error analysis is to determine the size and character of the bias errors. Note, that a *recognized* bias error - for instance an offset on an instrument calibration for which correction in the calibration constants has been made - is evidently no longer a bias error. After such correction, some bias error will remain, and that remaining error is to be used in the calculations.

The machine under test is assumed not to have been changed or modified during the test, and that the effect of wear or damage during the test of any component of the machine are small enough to be disregarded. It is known that for example dirt and water on the blades may alter the performance significantly. If this or similar effects are assumed to be of importance, *separate* tests may be carried out to investigate such effects. The present error analysis refers to a machine of which no characteristics to the best of the test engineers knowledge changes during the test period.

For a power performance test carried out in accordance with these recommendations, the basic physical relationship sought is

$$P = P(v) \tag{9}$$

i.e. power output as a function of wind speed. *A priori*, the power output is also assumed to be a function of air density. Thus, the test basically includes three measured quantities, namely power, wind speed and air density, while wind direction is measured in order to avoid the gross error of the anemometer being in the wake of the machine or the meteorological tower itself.

The error analysis should be made both *bin-wise* and as a function of the *annual mean power output.* Simplifications - not to be discussed herein - as to the magnitudes of the dimensionless sensitivity factors illustrate the relative importance of the parameters: while the normalized sensitivities corresponding to the measured quantities *power* and *air density* may be approximated as $\theta_p \sim 1$ and $\theta_\rho \sim 1$, the power curve function's sensitivity to errors in measured wind speed is not obvious. However, it can be shown that *at the wind speed of maximum power coefficient* $\theta_v \sim 3$, i.e. a relative error in wind speed triples in the resulting power curve error. Most often, a low power curve error at wind speeds at and around the maximum power coefficient will be of major importance for the uncertainty on *annual mean power.* Instead of relying on such approximations,the dimensional sensitivity factors $\alpha_{i,v}$ can be read from the measured power curve [3].

The resulting expression [4] for the total error on power in power curve bin no. i can be written as

$$\begin{aligned} U_i &= \Big\{ [\alpha_{i,v}^2(B_{i,v1}^2 + B_{i,v2}^2) + \alpha_{i,p}^2 B_{i,p}^2 + \alpha_{i,\rho}^2 B_{i,\rho}^2] \\ &+ \frac{t^2}{n_i} [\alpha_{i,v}^2 \sigma_{i,v}^2 + \alpha_{i,p}^2 \sigma_{i,p}^2 + \alpha_{i,\rho}^2 \sigma_{i,\rho}^2] \Big\}^{\frac{1}{2}} \end{aligned} \tag{10}$$

where n_i is the number of (pre-averaged) data points in bin no. i, and $\sigma_{i,*}$ are the standard deviations of the measured quantities in bin no. i. All parameters in Eq.(10) refer to local (i.e binwise) values of the quantity. The sensitivity factors $\alpha_{i,*}$ effectively "translate" the uncertainty of each parameter into power.

Employing the Student's "t" value $t = 2$ corresponds to an error per centile of approx. 95% The remaining terms are described in Table A.

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[3] For practical purposes, the sensitivity factors $\alpha_{i,*}$ may be approximated as:

$$\alpha_{i,v} = \left.\frac{\partial P(v)}{\partial v}\right|_{v=v_i} \sim \frac{P_{i+1} - P_{i-1}}{v_{i+1} - v_{i-1}}, \quad \alpha_{i,p} = 1 \text{ and } \alpha_{i,\rho} \simeq \frac{P_i}{\rho_i} \sim \frac{P_i}{1.2}$$

v_i and P_i are bin averages of wind speed and power, respectively.

[4] The expression, Eq. (10), is valid if (a) the measured parameters are not timewise auto-correlated and (b) if each of the measured parameters can be considered mutually independent (if dependent, cross-terms would have to be included). With good approximation this will be the case when the pre-averaging time of data is larger than the time scale ("memory") of turbulence, typically 30-60 seconds. Using 10 minute averages as suggested in this document tends to cause a conservative estimate of the precision index. The importance of inter-correlation of the parameters has been studied thoroughly in ref. [4].

In general, the bias errors are difficult to quantify, typically being related to uncertainty of calibration of instruments. The calibration procedure will have a random component which should be insignificant for a carefully conducted calibration. The data sheets of the instruments may contain explicit information on uncertainty; however, it is strongly recommended to consult the manufacturer on how uncertainty estimates have been obtained.

Bias Error		Comments:
$B_{i,v1}$	Wind speed, instrument:	Systematic error (accuracy) on calibration and use of wind speed instrument.
$B_{i,v2}$	Wind speed, site:	Estimated error on the correlation function between wind speed measured at met tower site and wind speed at the machine site.
$B_{i,p}$	Power, instrument:	Accuracy of power sensor.
$B_{i,\rho}$	Air density, instrument:	Air density is determined indirectly by measurement of temperature and pressure. Here the combined error shall be inserted.
(Random) Precision index		Comments:
$S_{i,v}$	Wind speed:	Within each bin, the mean wind speed is calculated. The precision index can be calculated explicitly, Ref. (1), as $S_{i,v} = \Delta v_b/\sqrt{12 n_i}$ where Δv_b is the bin width and n_i the number of data values in the bin.
$S_{i,p}$	Power:	Within each bin, the mean power is calculated. The precision index is explicitly calculated by means of Eq. (4).
$S_{i,\rho}$	Air density:	May in general be neglected.

Table A. *Errors of major importance in power performance measurements. The precision index is computed by means of Eq.(4):* $S_{i,*} = \sigma_{i,*}/\sqrt{n_i}$.

Likewise, a bias error related to a non-perfect test site will be hard to quantify; but since this error, along with the anemometer calibration error, is crucial for the overall accuracy of the test it is vital to invest the necessary time to analyse the air flow at the test site.

Resently, investigations have shown that flow distortion around the boom on which the anemometer is mounted may lead to significant errors in the readings of the anemometer. This may serve as a typical example of the nature of bias errors. When identified such error is of cource corrected .

At first sight, the random errors (scatter on measured data points) may seem a large contribution to the integrated uncertainty than it actually does. As stated, the random error component is directly quantified by characteristics of the recorded data and furthermore: *the contribution to the total error from the random error component is reduced to any small number simply by sampling more data.*

Calculating the resulting error in each bin, the chosen binwidth directly influences the random error component: the smaller bins the larger random uncertainty. In comparing binwise uncertainties from two experiments, the binwidth must be the same.

Finally, it is worth noting that while the pre-averaging time may effect the calculated precision index, it has little or no influence on the true random error.

Error on Annual Mean Power.

The bias error and precision index on power in bin no. i are obtained from Eqs. (3):

$$\boxed{\begin{aligned} B_i &= \left[\alpha_{i,v}^2 \left(B_{i,v1}^2 + B_{i,v2}^2\right) + \alpha_{i,p}^2 B_{i,p}^2 + \alpha_{i,\rho}^2 B_{i,\rho}^2\right]^{\frac{1}{2}} \\ S_i &= \left[\alpha_{i,v}^2 S_v^2 + \alpha_{i,p}^2 S_{i,p}^2 + \alpha_{i,\rho}^2 S_{i,\rho}^2\right]^{\frac{1}{2}} \end{aligned}} \tag{11}$$

where absolute measures of errors and error indicators are used. If the measured quantities (v, ρ and p) have two or more error sources attached to them, they shall be included in a way semilar to the two different wind speed error sources in Eq.(11).

Calculating the uncertainty on annual mean power, one must calculate bias and random errors *separately* and only combine them at the end of the calculations. While the bias errors within each bin, Eq.(11), were assumed independent and therefore root-sum-squared, the resulting binwise bias errors are expected to be fully correlated and to have the same sign. Therefore, the bias error on annual average power is formed by linear summation of the binwise errors:

$$B_r = \sum_{i=1}^{K} B_i(\Delta v_b f(v_i)). \tag{12}$$

where K is the number of bins included in the analysis, Δv_b is the binwidth and $f(v_i)$ is the value of the wind speed frequency distribution at v_i. Thus,

$$\boxed{\varepsilon_i = \Delta v_b f(v_i)} \tag{13}$$

is the fraction of time spent in bin no. i. Effectively, Eq.(12) is a weighting of the bin errors with the distribution of wind speed. Inserting Eqs.(11) and (13) in Eq.(12) yields

$$\boxed{B_r = \sum_{i=1}^{K} \varepsilon_i \left[\alpha_{i,v}^2 (B_{i,v1}^2 + B_{i,v2}^2) + \alpha_{i,p}^2 B_{i,p}^2 + \alpha_{i,\rho}^2 B_{i,\rho}^2\right]^{\frac{1}{2}}} \tag{14}$$

Binwise, the individual bias errors are combined by the "root-sum-square" method to form the total error assuming that they are independent.

The resulting precision index[5] on annual production is given as

[5] The somewhat complicated expression, Eq.(15), takes into account that the distribution of wind speed during the test is not identical to $f(v_i)$. Should this be the case, i.e. $\varepsilon_i = n_i/M$, then

$$S_r = \sqrt{\sum_{i=1}^{K} \varepsilon_i^2 S_i^2}.$$

$$\boxed{S_r = \frac{\sum_{i=1}^{K} \varepsilon_i (\frac{n_i}{M}) S_i^2}{\sqrt{\sum_{i=1}^{K} (\frac{n_i}{M})^2 S_i^2}},} \tag{15}$$

where S_i is given by Eq.(11) and ε_i by Eq.(13). $M = \sum_{i=1}^{K} n_i$ is the total number pre-averaged data set considered.

The total uncertainty on annual mean power output is a function of annual mean wind speed, $\bar{V}$:

$$\boxed{U_r(\bar{V}) = [B_r^2 + t^2 S_r^2]^{\frac{1}{2}}} \tag{16}$$

It shall be stressed once again that only uncertainty regarding the performance test has been dealt with, leaving the task of determining the uncertainty of power output from the machine ***type*** at a specific site: in this case also uncertainty on determination of the wind speed distribution parameters and the variability in performance of the specimens of the considered type of machine must be taken into account. Uncertainty of wind speed distribution is dealt with to some extent in ref. [5].

And finally, the per centile corresponding to the total error on annual production is stated as 95%. In reality the per centile depends strongly on the relative sizes of bias and random errors, but also the general complexity of the problem may introduce significant uncertainties into the analysis.

Example

Imagine that the test instruments exactly complies with the recommendations given in this document. The instruments have been calibrated thoroughly, leaving *estimated* bias errors as given in Table X1. The table also specifies a 2 % error related to the test site: if the test site is not homogeneous the wind speed characteristics may not be identical at the met tower position and at the position of the wind turbine, though often one may expect the two mean wind speeds to be proportional.

Instrument	**Parameter**	**Estimated bias error**
Anemometer	$B_{i,v1}$	0.1 m/s in range 4 to 25 m/s
Site effects	$B_{i,v2}$	2% of actual wind speed
Air density	$B_{i,\rho}$	1% $\sim 0.012 kg/(m^3)$
Power sensor	$B_{i,p}$	0.5% of rated power (6kW)

Table X1. *Bias errors of the power curve measurement, instruments and site effect. The test site is located in flat terrain with few or no obstacles and the bias error is therefore set as low as 2 %. The magnitudes of the errors correspond to the recommendation. In the specific experiment the magnitude of the bias errors must be individually evaluated.*

BIN No. i	No. of POINTS n_i	WIND SPEED INTERVAL (m/s)	WIND-SPEED v_i (m/s)	POWER P_i (kW)	$\sigma_{i,p}$ (kW)	Sensitivity Factors $\alpha_{i,v}$ (kW(m/s)	$\alpha_{i,\rho}$ kW(kg/m^3)
1	0	4.75 - 5.25	5.00	0	0	0	0
2	10	5.25 - 5.75	5.66	14.1	8.1	24	12
3	58	5.75 - 6.25	5.99	23.8	7.7	31	19
4	92	6.25 - 6.75	6.52	45.3	11.8	42	37
5	90	6.75 - 7.25	6.98	66.2	13.4	48	54
6	105	7.25 - 7.75	7.49	93.3	15.2	58	76
7	76	7.75 - 8.25	8.01	124.5	16.2	60	102
8	90	8.25 - 8.75	8.50	153.0	18.5	68	125
9	45	8.75 - 9.25	9.00	192.5	27.8	77	157
10	60	9.25 - 9.75	9.51	230.1	27.5	81	188
11	59	9.75 -10.25	9.98	273.6	29.5	91	223
12	48	10.25 -10.75	10.49	321.1	23.7	73	262
13	41	10.75 -11.25	10.96	346.3	33.4	68	283
14	25	11.25 -11.75	11.54	388.9	35.8	85	317
15	19	11.75 -12.25	11.94	430.8	27.0	98	352
16	14	12.25 -12.75	12.54	486.7	36.9	88	397
17	14	12.75 -13.25	13.02	519.1	37.3	66	424
18	13	13.25 -13.75	13.44	552.5	34.2	47	451
19	13	13.75 -14.25	13.94	566.4	22.8	31	462
20	10	14.25 -14.75	14.40	583.8	27.7	30	477
21	8	14.75 -15.25	15.02	596.1	18.3	26	487
22	5	15.25 -15.75	15.56	610.0	6.2	14	498
23	1	15.75 -16.25	15.94	610.0	6.2	0	498
24	0	16.25 -16.75	16.50	~610.0	6.2	0	498

Table X2. *Data from a power performance test including a total of 150 hours of recorded and valid data, forming 896 10 minute average values. The bin size has been chosen to 0.5 m/s. Also given are the sensitivity factors. The sensitivity factor on power is* $\alpha_{i,p} \equiv 1$.

The data recorded are presented in Table X2. Each data point is 10 minute averages. The total, integrated recording time is approx. 150 hours, forming 896 10 minute average values. In each 0.5 m/s-bin, averages of wind speed and electrical power, v_i and P_i, has been formed of the n_i average values in the bin. The standard deviation on power, $\sigma_{i,p}$, has been calculated from the data. To account for the slope of the (averaged) power curve within each bin, a correction[6] to $\sigma_{i,p}$ shall be applied:

$$\sigma_{i,p}^2 = \sigma_{i,p}^2 - (\alpha_{i,v}\frac{\Delta v_b}{\sqrt{12}})^2.$$

The sensitivity factors $\alpha_{i,*}$ are calculated in accordance with the formulas given as footnote in the text and shown in the last columns of Table X2.

[6]Note that the correction corresponds exactly to the binwise standard deviation on wind speed, $\sigma_{i,v}$. This is consistent with the fact that when $\Delta v_b \rightarrow 0$ then $\sigma_{i,v} \rightarrow 0$. Thus, another possibility would be to disregard the random error on wind speed and make no correction to the random error on power. The confusion is generated by using the simple bin method instead of some more accurate line regression.

Standard deviations on air density, $\sigma_{i,\rho}$, and wind speed, $\sigma_{i,v}$, has not been determined from the data. With good approximation, $\sigma_{i,v}$ is found (see Table A) to be

$$\sigma_{i,v} \sim \frac{\Delta v_b}{\sqrt{12}} \sim \frac{0.5}{\sqrt{12}} \sim 0.14\ m/s$$

Standard deviation on air density may be "guestimated" since it is of minor importance: $\sigma_{i,\rho} \sim 0.01\ kg/m^3$.

Table X3 shows the error components bin by bin. The binwise uncertainty is shown in the extreme right column, having a maximum of approx. 30 kW which in that bin corresponds to 6%. The power curve is plotted in Figure X1 together with the 95 % confidence interval. Note that the confidence interval is dependent of the binsize.

BIN		Bias Errors			Precision Indices			Bin-wise		
i	ε_i	$B_{i,v}\alpha_{i,v}$	$B_{i,\rho}\alpha_{i,\rho}$	$B_{i,p}\alpha_{i,p}$	$S_{i,v}\alpha_{i,v}$	$S_{i,\rho}\alpha_{i,\rho}$	$S_{i,p}\alpha_{i,p}$	B_i	S_i	Total error
1	0.053	0.0	0.0	6.0	0.0	0.0	0.0	6.0	0.0	6.0
2	0.054	3.6	0.1	6.0	1.1	0.0	2.3	7.0	2.6	8.7
3	0.053	5.7	0.2	6.0	0.7	0.0	0.8	8.3	1.0	8.5
4	0.052	7.0	0.4	6.0	0.6	0.0	1.1	9.3	1.2	9.6
5	0.051	8.5	0.6	6.0	0.7	0.1	1.2	10.4	1.4	10.8
6	0.049	10.2	0.9	6.0	0.8	0.1	1.3	11.9	1.5	12.2
7	0.046	11.2	1.2	6.0	0.9	0.1	1.6	12.7	1.9	13.3
8	0.043	13.5	1.5	6.0	1.0	0.1	1.7	14.9	2.0	15.4
9	0.040	15.7	1.9	6.0	1.6	0.2	3.8	16.9	4.2	18.9
10	0.036	17.8	2.3	6.0	1.5	0.2	3.2	18.9	3.6	20.2
11	0.033	20.7	2.7	6.0	1.7	0.3	3.4	21.7	3.9	23.1
12	0.029	17.2	3.1	6.0	1.5	0.4	3.1	18.5	3.4	19.8
13	0.026	15.6	3.4	6.0	1.4	0.4	5.0	17.0	5.2	20.0
14	0.023	21.7	3.8	6.0	2.4	0.6	6.7	22.8	7.2	27.0
15	0.020	25.3	4.2	6.0	3.1	0.8	5.3	26.4	6.2	29.2
16	0.017	22.1	4.8	6.0	3.1	1.1	9.4	23.4	9.9	30.7
17	0.014	20.4	5.1	6.0	2.7	1.1	9.6	21.9	10.0	29.7
18	0.013	14.7	5.4	6.0	2.0	1.3	9.3	16.8	9.6	25.5
19	0.011	9.7	5.5	6.0	1.3	1.3	6.2	12.7	6.5	18.1
20	0.009	8.4	5.7	6.0	1.2	1.5	8.7	11.8	8.9	21.3
21	0.007	7.2	5.8	6.0	1.1	1.7	6.4	11.0	6.7	17.3
22	0.006	4.9	6.0	6.0	0.9	2.2	2.6	9.8	3.6	12.1
23	0.005	0.0	6.0	6.0	0.0	5.0	6.2	8.5	8.0	18.0
24	0.004	0.0	6.0	6.0	0.0	5.0	6.2	8.5	8.0	18.0

Table X3. *Derived results of the error analysis including binwise uncertainty of the power curve and summation for determination of the impact of power curve uncertainty on uncertainty on annual mean power output. In the example, the mean wind speed is assumed to be $\bar{V}$ =7.1 m/s. The corresponding annual mean production is 132 kW.*

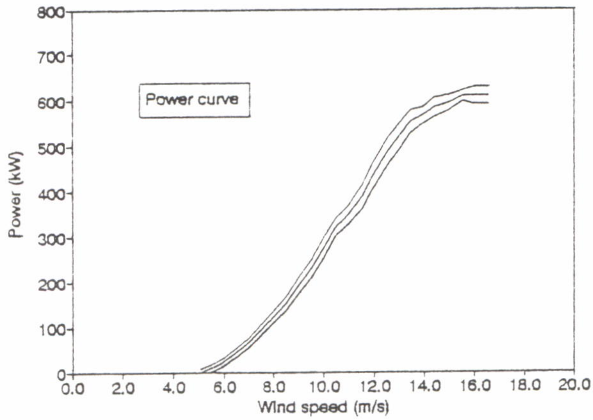

Fig. X1. *Measured power curve plotted with the 95% confidence interval.*

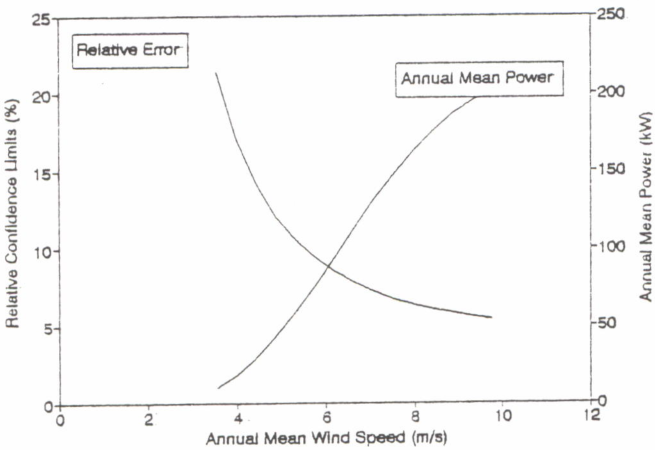

Fig. X2. *Relative importance of error on power curve on error on annual mean power output.*

The resulting bias error and precision index on annual power output is calculated for Rayleigh wind speed distribution with the annual mean wind speed being $\bar{V} = 7.1$ m/s:

$$B_r = \sum_{k=1}^{K} \varepsilon_k B_i \sim 9.4\ kW$$

$$S_r = \frac{\sum_{i=1}^{K} \varepsilon_i n_i S_i^2}{\sqrt{\sum_{i=1}^{K} n_i^2 S_i^2}} \sim 0.5\ kW,$$

The resulting uncertainty on annual mean power is then

$$U_r = \left[9.4^2 + 4 \cdot 0.5^2\right]^{\frac{1}{2}} \sim 9.5\ kW$$

which corresponds to 7.2 % of annual mean power. With the data available the random error appears to contribute insignificantly to the total error. Assuming the "site" bias error, $B_{i,v2}$, is 4 % of actual wind speed (instead of 2 %) leads to a resulting uncertainty of 11.7 % for the the same annual mean wind speed.

U_r is a function of annual mean wind speed and presenting the uncertainty analysis, calculation of U_r should be performed for different, relevant mean wind speeds, as shown in Figure X2. As seen the relative error increases strongly when annual mean wind speed decreases.

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Available on request from:

B. Maribo Pedersen
Dept. of Fluid Mechanics
Technical University of Denmark
Building 404
Lundtoftevej 100
DK-2800 Lyngby
Denmark

H.J.M. Beurskens
ECN
Westerduinweg 3
Postbus 1
NL-1755 ZG Petten
The Netherlands

G. Elliot
National Wind Turbine Centre
Dept. of Trade & Industry
National Engineering Laboratory
East Kilbride
Glasgow
G75 OQU
Scotland

D. Ancona
Wind Energy Division
Room 5F-081
Department of Energy
Forrestal Building
Washington D.C. 20585
USA

S.E. Thor
FFA
Box 11021
S161 11
Sweden