INTERNATIONAL ENERGY AGENCY

Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems
ANNEX XI

30th Meeting of Experts

State of the Art on Power Performance Assesments for Wind Energy Conversion Systems

Athens, December 8.-9., 1997

Organized by : C.R.E.S.

Scientific Coordination :

B. Maribo Pedersen
Dept. of Fluid Mechanics
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CONTENTS

page

A. FRAGOULIS
Introductory note 1

H. KLUG et al.
How Complex can a Wind Speed Measurement be ? 3

U. FOLLRICHS, S.GLOCKER
Tilt Angle Sensitivity of Different Reference Anemometers 21

G. RONSTEN
Influence of Various Meteorological Conditions on the Annual Energy Production of Näsudden II (Ø=80m) 25

G. RONSTEN
How Relevant, Referring to Power Performance for Large Wind Turbines, is the Hub Height Wind Speed? 29

TROELS FRIIS PEDERSEN
Some Aspects of Power Curve Measurements in Complex Terrain 35

F.MOUZAKIS, E. MORFIADAKIS, A.FRAGOULIS
Power Performance Measurements in Complex Terrain 43

KAREN CONOVER
Experience with Power Performance Measurements in the US Wind Turbine Verification Program 57

HAL LINK
Investigation into the Suffiency of Data in Wind Power Performance Testing 61

U. FOLLRICHS
Measurements on Large Wind Turbines 67

A. CURVERS
Activities at ECN with Respect to Site Calibration 71

STEN FRANDSEN
Power Performance Assessment 73

STEN FRANDSEN
Notes from Discussion 99

B.MARIBO PEDERSEN
Summary 101

LIST OF PARTICIPANTS 103

IEA R&D WIND - ANNEX XI
List of previous Meetings of Experts 105

30th IEA Experts Meeting

STATE OF THE ART ON POWER PERFORMANCE ASSESSMENT FOR WIND ENERGY CONVERSION SYSTEMS

December 8.- 9. 1997, C.R.E.S., Greece

INTRODUCTORY NOTE

prepared by
Dr. A. Fragoulis

It is widely accepted that in spite of the fact that during the last years wind energy technology and the wind energy 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 to standardization and certification. All these issues are strongly dependent on power performance verification and assessment practices. Currently, several EU funded research projects as well as standardization bodies are working on different aspects of the issue.

It is the intention of this meeting to clarify the status of power performance verification and assessment and identify the future needs in terms of applications, research fields and standardization actions, putting emphasis on the following items:

- Power performance verification for wind farms

The market is clearly in favour of implementing wind farms. On the other hand, the non-existence of reliable procedures for power performance assessment of wind farms leads to adoption of practices that ignore the complicated aspects of the issue.

- Power performance verification for large wind turbines

After a long period of prototype design, manufacturing and testing, large wind turbines are commercially available and consequently the need for feasible power performance assessment procedures for those machines is present and will dramatically increase. Nevertheless, the practices and instrumentation developed and used for systems of lower capacity may not be adequate for the case.

- Power performance verification for wind turbines operating in complex terrain

A significantly large amount of the most promising areas for wind energy exploitation are located in complex terrain. The topography characteristics along with the wind structure in those areas impose significant uncertainties in power performance verification. New procedures have been applied and verified, and by the aid of the future international or national standards the large scale integration into these areas will be strongly supported.

- Assessment of the available international and national standards

The urgency for the international standardization bodies to encounter the issue is strong as the market needs are increasing.

- Assessment of developed, applied and verified tools for WECS power performance

Significant amount of experimental work has been done on the fields of power performance assessment, site calibration and site assessment. Procedures have been developed and tested whereas the needs for the use of sophisticated machinery is justified. Recent improvements in the field of simulation work reveal the potential of using analytic tools in assessment procedures.

HOW COMPLEX CAN A WIND SPEED MEASUREMENT BE?

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ABSTRACT

Within the tremendous development of wind energy over the last years the towers of wind turbines have reached giddy heights up to 100 m for 1.5 MW turbines. Measuring a power curve on such a turbine is very expensive due to the increasing costs for large meteorological masts. Extrapolating the wind speed measured at slightly lower heights to hub height wind speed (e.g. from 50 m to 60 m) can be a cost effective alternative for power curve measurements.

Another complex task is the power performance measurement in complex terrain. According to the IEC standard a site calibration (two meteorological masts, the second mast is replaced by the wind turbine) is necessary. For cases where this is not possible because the turbine is already in operation an alternative method was tested. The flow field around the parked turbine was determined by an LDA measurement on a model of the turbine in a wind tunnel . Then the calibrated nacelle anemometer wind speed on the parked wind turbine corrected for the flow disturbance determined in the wind tunnel can be used for site calibrations. For power curve verification (comparison to a power curve of that type measured in flat terrain) an alternative method based on nacelle wind speed measurements (now for an operating wind turbine) has been tested in flat and in complex terrain.

A site calibration with two met masts was performed and the influence of measurement period, width of the wind direction sectors and wind speed range was investigated.

For two different anemometers the influence of flow inclination on the wind speed measurements was determined for different wind speeds in the wind tunnel and in the open.

The influence of different meteorological conditions on the power curve of a large WTGS was investigated. The dependance of the calculated AEO (Annual Energy Output) on turbulence intensity, wind shears and temperature gradient was investigated.

1 EXTRAPOLATION

DEWI has performed temperature and wind speed measurements on two large meteorological masts (70m and 130 m) used for power performance measurements and determined the uncertainty of extrapolating the wind speed measured at lower heights to hub height wind speed. If the measured temperature profile is taken into account for the extrapolation algorithm (Monin-Obukhov similarity theory) the hub height wind speed can be predicted with an uncertainty of less than 1.5% and the vertical wind shear can be deduced as well.

1.1 Met Mast Costs

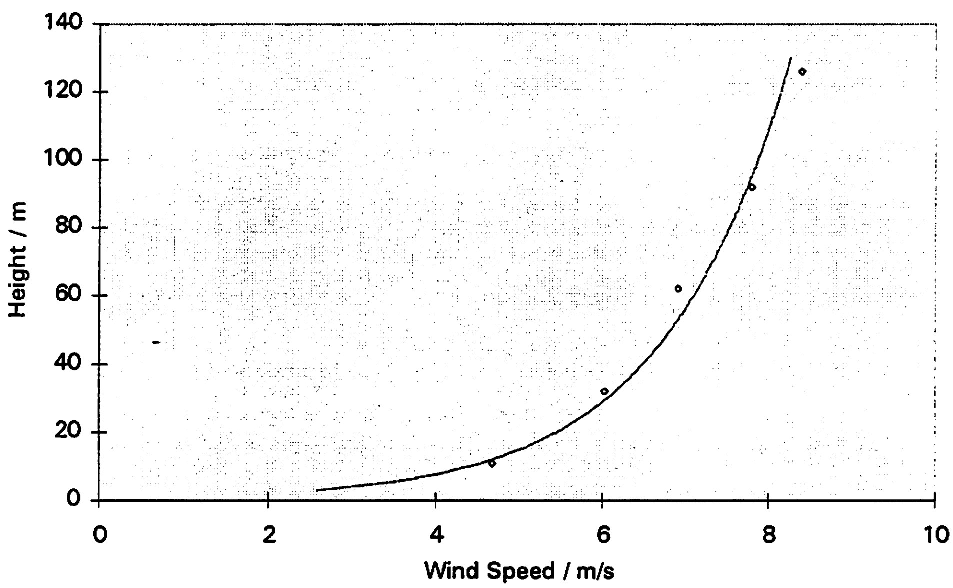


Fig. 1: Measured wind speed profile

Fig. 1 shows the wind speed profile from measured average wind speeds over the years 1993-1996 at the DEWI Test Site. Fig. 2 looks quite similar but here the x -axis is the wind speed while the y-axis shows the cost of met masts for mobile measurement systems.

1.2. Extrapolation Methods

A simple assumption for the distribution of wind speed over the height is the logarithmic profile:

$$v = \frac{v^*}{\kappa} \ln\left(\frac{h}{z_0}\right).$$

with:	v:	wind speed at height h
	v^*:	friction velocity
	κ :	von Karman constant
	z_0:	roughness length

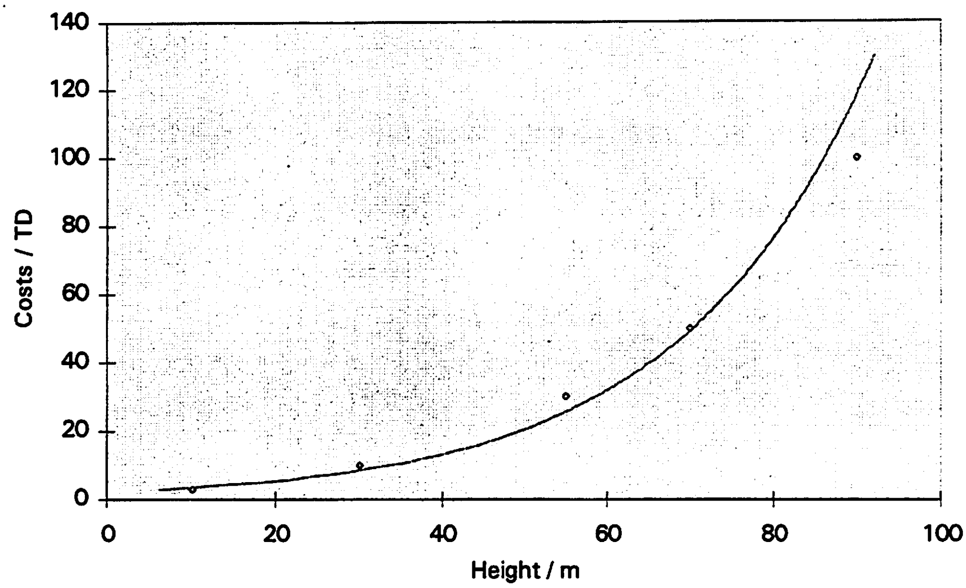


Fig. 2: Met mast costs

According to the Monin-Obukhov similarity theory[2] the wind speed profile can be described as:

$$v = \frac{v^*}{\kappa}\left(\ln\left(\frac{h}{z_0}\right) - F\left(\frac{h}{L}\right)\right).$$

with:

L: Monin-Obukhov length

The Monin-Obukhov length L is a parameter for the atmospheric stability and links the wind speed profile to the vertical temperature distribution, which is of similar form than the wind speed profile. Businger [1] and Dyer [2] derived expressions for the function F, which are strongly dependent on the atmospheric stratification. During unstable conditions, typically at day time, the temperature profile -temperature at ground higher than at upper height levels- leads to an enhanced momentum transfer in the atmospheric boundary layer and thus to small vertical wind shears and higher turbulence level. On the other hand during stable conditions, e. g. cold ground at night, the turbulence is relative low and large vertical wind shears occur.

1.3 Results

The above equation was fitted to the wind speed and temperature measurements by the least square method, using an iteration procedure. With these profiles the wind speed at 92 m was estimated from the measured wind speed at 11m, 32m and 62 m and the temperature at 2.5 m and 90 m.

Details about the extrapolation method and the results are reported in [3], [4]. For the extrapolation in the range of 30 m (62 m to 92 m) the Monin-Obukhov extrapolation results in a very good agreement between the extrapolated and measured wind speed at 92 m Height while the results of the simple logarithmic extrapolation (temperature profile not taken into account) are poor (see table below). The power curve of the AEOLUS II wind turbine measured with hub height wind speed was then compared to power curves determined with extrapolated wind speeds. The uncertainty in the annual energy production calculated with the help of the extrapolated power curve was less than 1%.

In another case where the wind speed was extrapolated from 57 m to 68 m the deviation between extrapolated and measured wind speed was higher but still below 2%. This might be due to the fact that this turbine is operating close to the coastline and the wind sector used was wind coming from the sea [5]. In the land sea transition wind profiles can differ significantly from the wind profiles in flat terrain more inland.

It can be concluded that in flat terrain and for large wind turbines (hub heights above 60 m) the extrapolation method is a cost effective alternative for power curve measurements. The wind profile should be measured at least up to 75 % of the hub height.

AEOLUS II (92 m)	Mean Deviation [m/s]	Power Curve AEP [%]
Log	-0.33	+10.2
Obu	-0.01	+ 1.1

TACKE TW 1.5 (68m)	Mean Deviation [m/s]	Power Curve AEP [%]
Log	-0.15	+5.1
Obu	-0.11	+3.6

Table 1: The mean deviation between all the measured and extrapolated wind speed data and the difference in the annual energy production (AEP).

There can be a significant influence of vertical wind shears on the power performance [6] so that information about the wind speed over the entire rotor area is of great interest. The Monin-Obukhov similarity theory taking the measured temperature profile into account gives also information about the vertical wind shear above the measurement height.

2 SITE CALIBRATION (Nacelle Anemometers)

Another complex task is the power performance measurement in complex terrain. According to the IEC standard [7] a (validated) flow model (not known to the authors) or a site calibration (two meteorological masts, the second mast is replaced by the wind turbine) is necessary, see chapter 4)

For cases where a power curve measured in flat terrain does not exist and a site calibration is not possible because the turbine has already been erected another alternative has been tested:

The flow field around the nacelle (scaled model) was measured in the wind tunnel (wind turbine parked) with an LDA (Laser Doppler Anemometer) and the correction factor between the free wind speed and the wind speed at the nacelle anemometer position was determined. Then a site calibration can be performed with one meteorological mast and the parked wind turbine instead of two meteorological masts. This work was done within an EU project SMT4-CT96-2116 (European Wind Turbine Testing Procedure Developments).

Figure 3 and 4 show the flow field around two different nacelles. The rotor is on the right side. For the turbine in Fig. 3 the undisturbed wind speed was 9.5 m/s the wind speed at the nacelle anemometer position was 8.3 m/s. So the correction factor when using the wind turbine (calibrated nacelle anemometers) as a wind speed mast would be about 15 %. As the wind speed gradient at this position is still large this would result in a large uncertainty for the site calibration measurement. Further measurements will be done looking for a higher nacelle anemometer position where the flow disturbance of the nacelle is smaller.

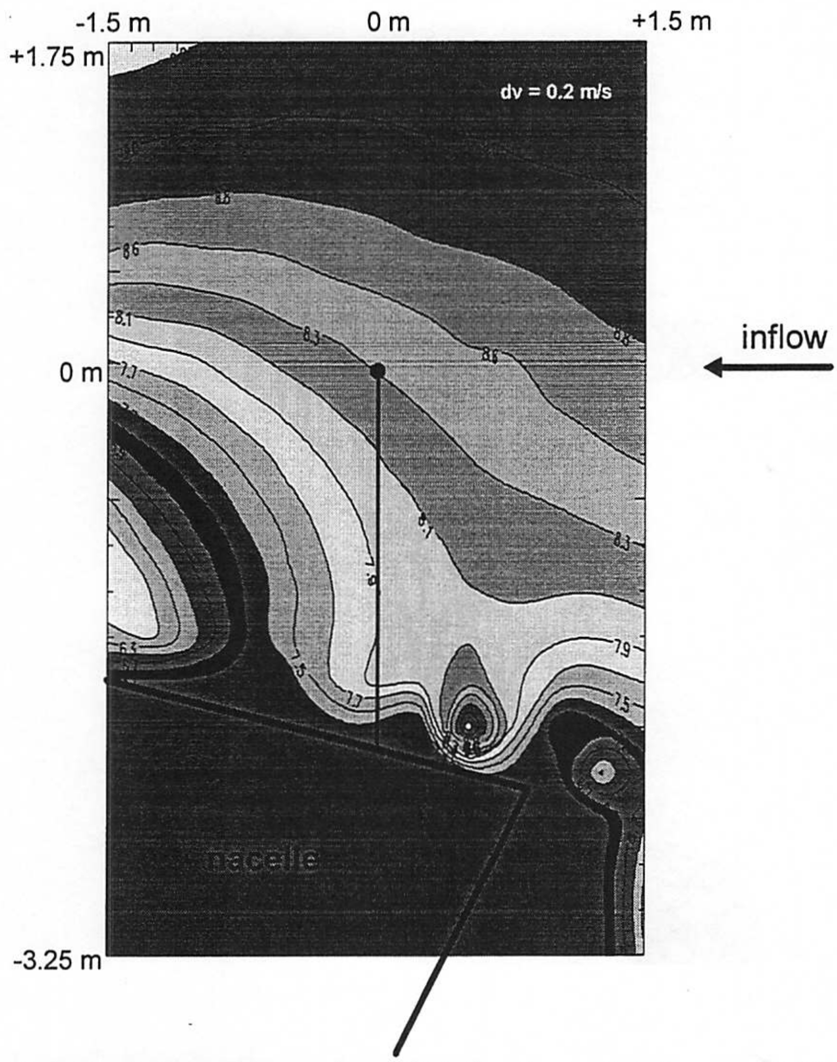


*Fig.3: Flow field around a nacelle model (1:25) in the wind tunnel measured with an LASER Doppler system. Shown are isovents (Δv:0.2 m/s) calculated from 240 measurement points (20*12).The nacelle anemometer position is indicated.*

In Fig. 4 the flow disturbance at the nacelle anemometer position is about 2.5 % but this position should be very sensitive to yaw changes and inclined flows (vertical wind component). This will be investigated in further LDA measurements in the wind tunnel. But it can already been concluded that an anemometer position more than 2 m above the centre of the nacelle is a position where the flow field is disturbed less than 0.5 %. For this kind of nacelle a calibrated nacelle anemometer above the nacelle can be used for a site calibration. This will be verified by measurements on a real turbine of this type.

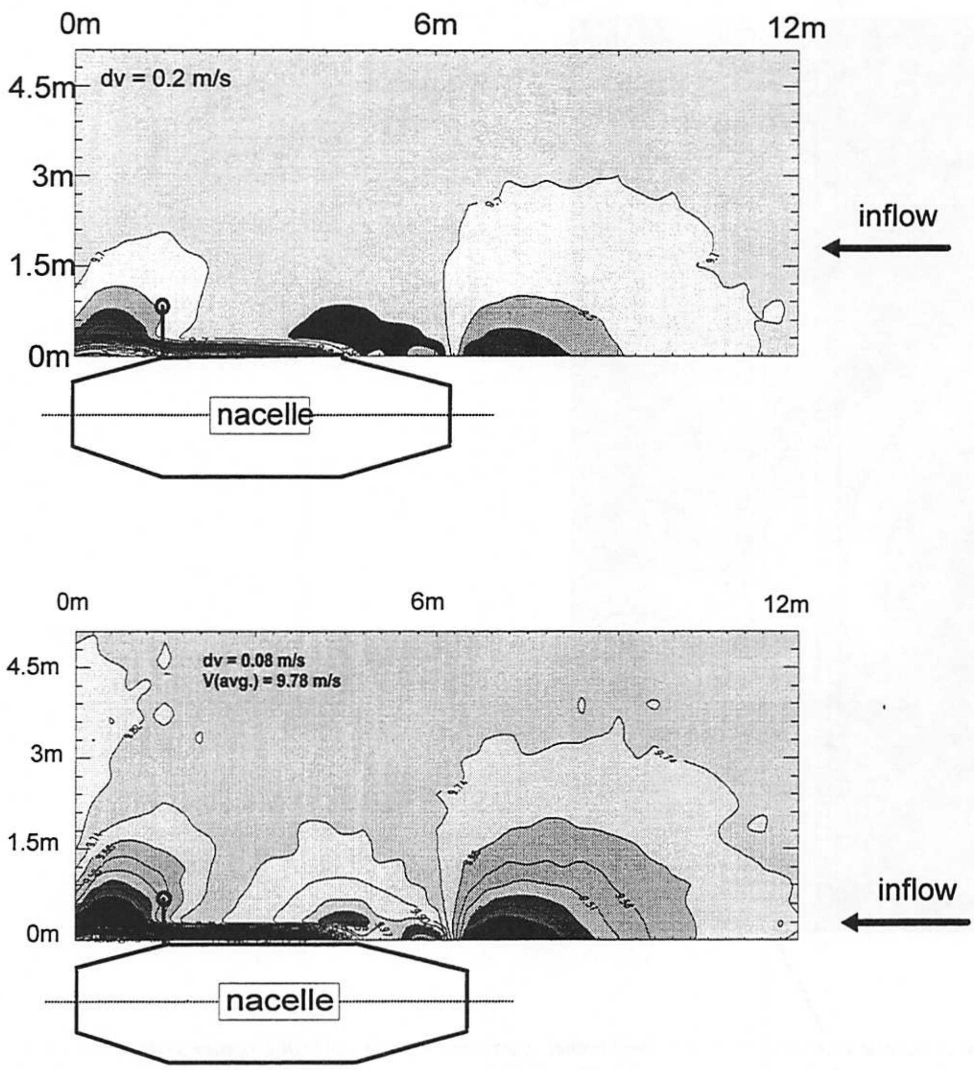


*Fig.4: Flow field around a nacelle model (1:15) in the wind tunnel measured with an LASER Doppler system. Shown are isovents (Δv:0.2 m/s above and Δv:0.08 m/s below ≡1% difference in flow speed) calculated from 600 measurement points (15*40). The nacelle anemometer position is indicated.*

2.1 Influence of Non-Regular Inflow

The nacelle model of the Nordtank NTK 500/37 (scale 1:15) was used to investigate the influence of non-regular inflow. Vertical inclination as well as lateral inclination of the inflow were considered to find out the allowable range of inflow deviation at 4 different anemometer positions.

Figure 5 shows the position of the 4 investigated points together with the reference point for determination of the „undisturbed“ wind speed. By relating the wind speed to the reference point wind speed V_{ref} influences caused by the model on the flow field in the wind tunnel can be taken into account.

Point 1 is identical to the former anemometer position of the WTGS as used at RISØ's test site, point 2 is the anemometer position of the series-produced WTGS. It has to be mentioned that on the real turbine the anemometer is not exactly on the center line from rotor to backside, because also the wind direction is measured on the nacelle at the same height by means of a wind vane.

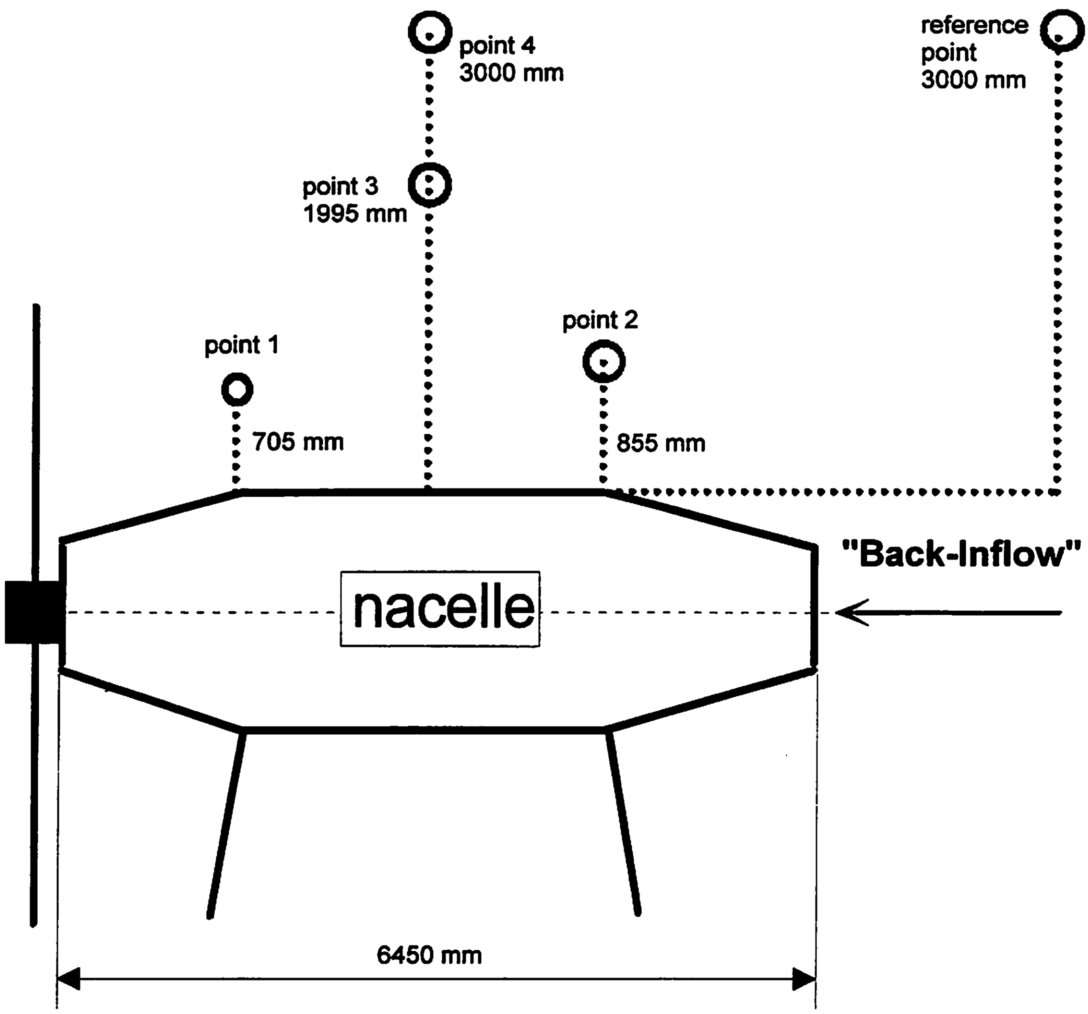


Figure 5 Nacelle model (1:15) and anemometer positions (all on the center line from rotor to backside). All values refer to the „real" distances at the turbine.

From the first measurements (Figure 4) the following deviations in wind speed between „free" inflow (at the reference point) and the 4 anemometer positions can be determined:

measurement point	1	2	3	4
deviation [%]	- 1.14	+ 2.18	+ 0.64	+ 0.70
reference wind speed: 9.73 m/s				

Table 1: Deviations at the 4 anemometer positions.

2.2 Vertical Inclination of Inflow

Especially in complex terrain a vertical inclination of the inflow wind speed vector can occur, leading to a perturbation of the wind speed measured at the nacelle anemometer. In the wind tunnel experiment 4 inflow inclinations (-10°, -5°, +5°, +10°) were investigated for the 4 different anemometer positions. The deviations are related to the measured wind speed at 0°-inclination at the same point.

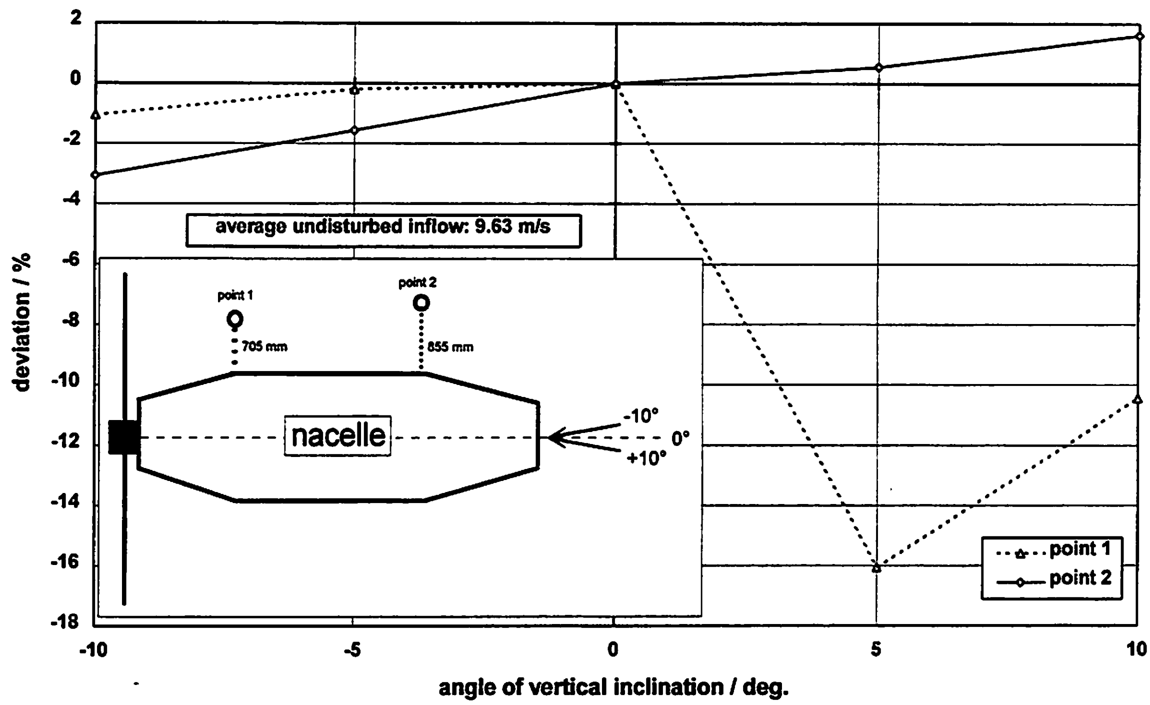


Figure 6a: Deviation in wind speed at vertical inclination (point 1 & 2).

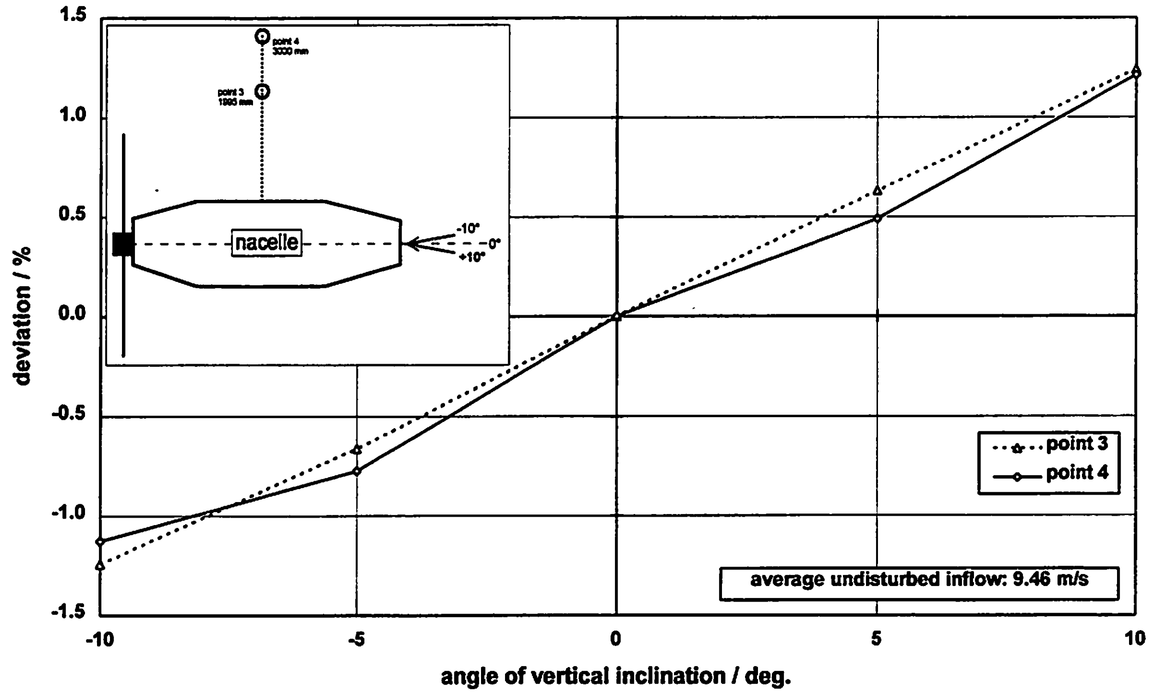


Figure 6b: Deviation in wind speed at vertical inclination (point 3 & 4).

Especially anemometer position 1 is very sensitive to positive vertical inclination angles, whereas point 2 shows higher deviations only at negative inclination angles. The positions 3 and 4 are not very sensitive to this vertical inclination angles (≤ 10°); their deviations are within ± 1.25 %.

2.3 Lateral Inclination of Inflow

As a typical meteorological phenomena, the wind direction is not stable over longer time periods. Therefore, the question of yaw misalignment and its influence on the flow field around the nacelle needs to be answered. For 7 different lateral inclinations (0°, 10°, 20°, 30°, 45°, 60°, 90°) the wind speed at the 4 anemometer positions is determined and related to the wind speed measured at the reference point.

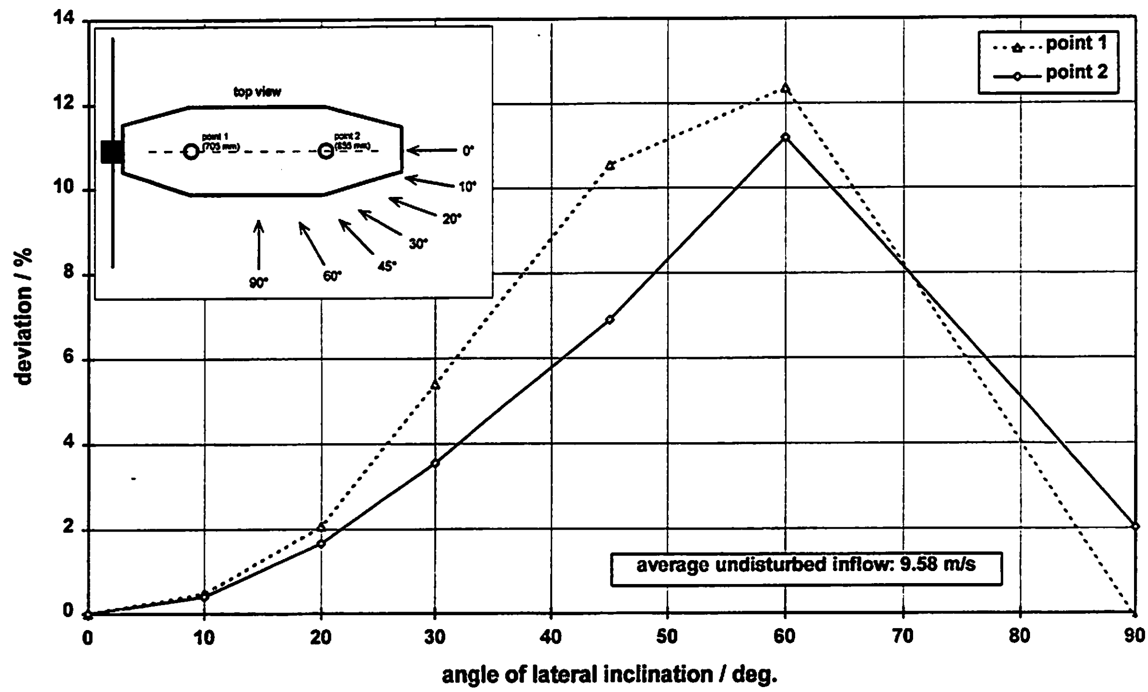


Figure 7a: Deviation in wind speed at lateral inclination (point 1 & 2).

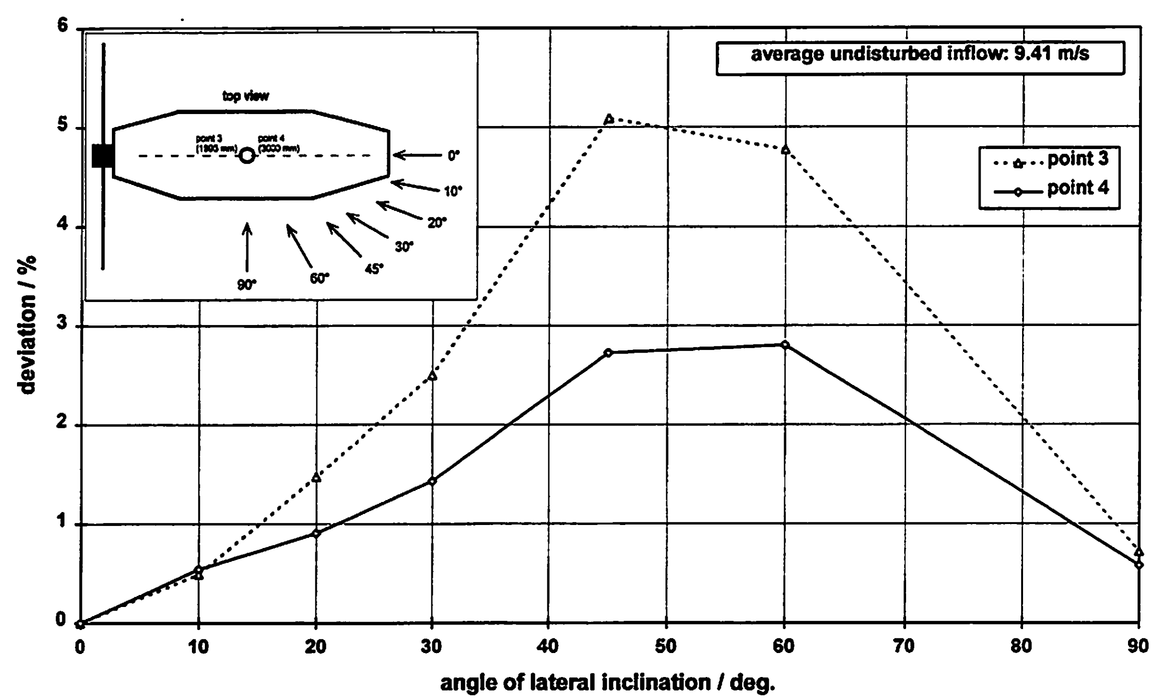


Figure 7b: Deviation in wind speed at lateral inclination (point 3 & 4).

inflow (90°) the measurement was influenced by the blockage effect of the nacelle model on the wind tunnel, so the shown values at 90° have only limited significance.

3 POWER CURVE VERIFICATION

For power curve verification (comparison to a power curve of that type measured in flat terrain) an alternative method has been tested.

The correction factor between the free wind speed and the wind speed measured at the nacelle (wind turbine operating) was determined in flat terrain. The power curve in complex terrain has been determined via the nacelle wind speed using this correction factor.

Fig. 8shows the differences between the power curve measured in flat and in complex terrain. This terrain was not very complex but some hills were around the test site so that the site was not fulfilling the IEC criteria for an ideal test site. In that cases a site calibration would be necessary. The results show that the power curves are very close. The slightly increased power curve in the higher wind speed range can be explained by the slightly higher rotational speed of the turbine in complex terrain. The difference in the calculated annual energy output is only 1.7%. It can be concluded that the nacelle wind speed measured power curve can be used for power curve verifications. Both nacelle anemometers (in flat and in complex terrain) must be individually calibrated and it has to be made sure that in both cases the anemometer position on the nacelle is exactly the same. The power curves measured vs. nacelle anemometer can be used e.g. for warranty applications or optimisations of the wind turbine at the specific site.

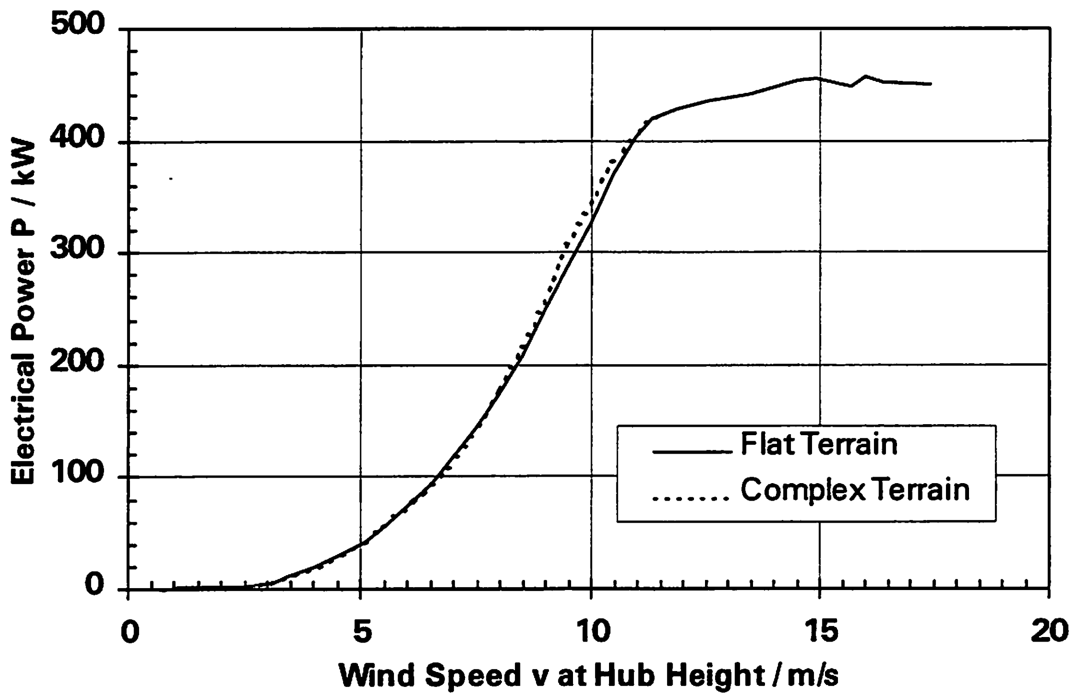


Fig.8: Power curves of the same turbine type in complex and flat terrain evaluated with calibrated nacelle anemometers

4 SITE CALIBRATION WITH TWO METMASTS

To get the relationship between the two sites a site calibration using two met masts was carried out over a period of three months. A site description is given in chapter 2.2 . The wind speed was measured with two identical masts at 50 m height and a distance of 200 meters.

Figure 9.1 shows the bin averaged ratio of the two wind speeds (sorting sector 10 deg, range 4-16 m/s and 5-10 m/s). Although the site dos not look very complex, a significant influence is recognisable at 190 degrees. This influence is presumably caused by a small hill south-westerly of the met mast.

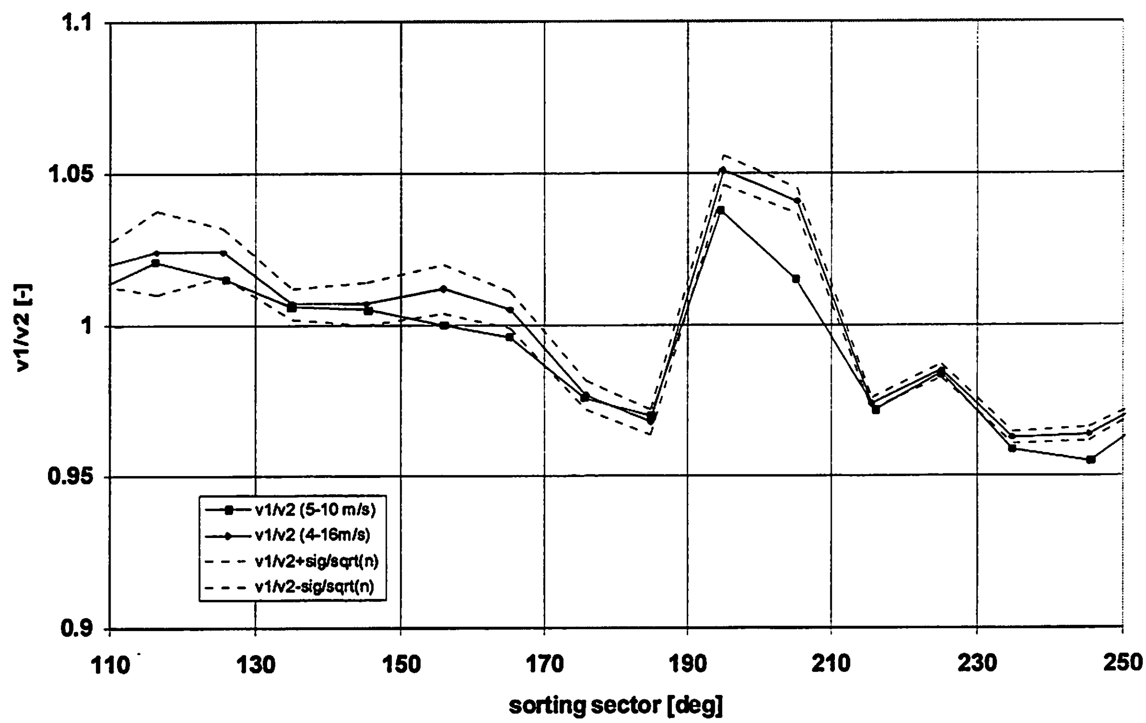


Fig. 9.1 Result of the site calibration using two met masts over a period of 3 months

A measuring period of three months for site calibration is usually too long. The IEC recommendation is 24 hours for each 30 degree sector. The question now is how long should be measured and how small should the sorting sector be for an agreement with the total measuring period (assuming a period of 3 months is sufficient to get the real site condition). For this case the site calibration was done for different sorting sectors from 5 to 30 degrees and different measuring periods from 4 to 36 hours (for each sector).
Figure 9.2 shows the result of the calculation for different sector sizes. Wind direction sectors of 10° seem to represent the conditions sufficiently.

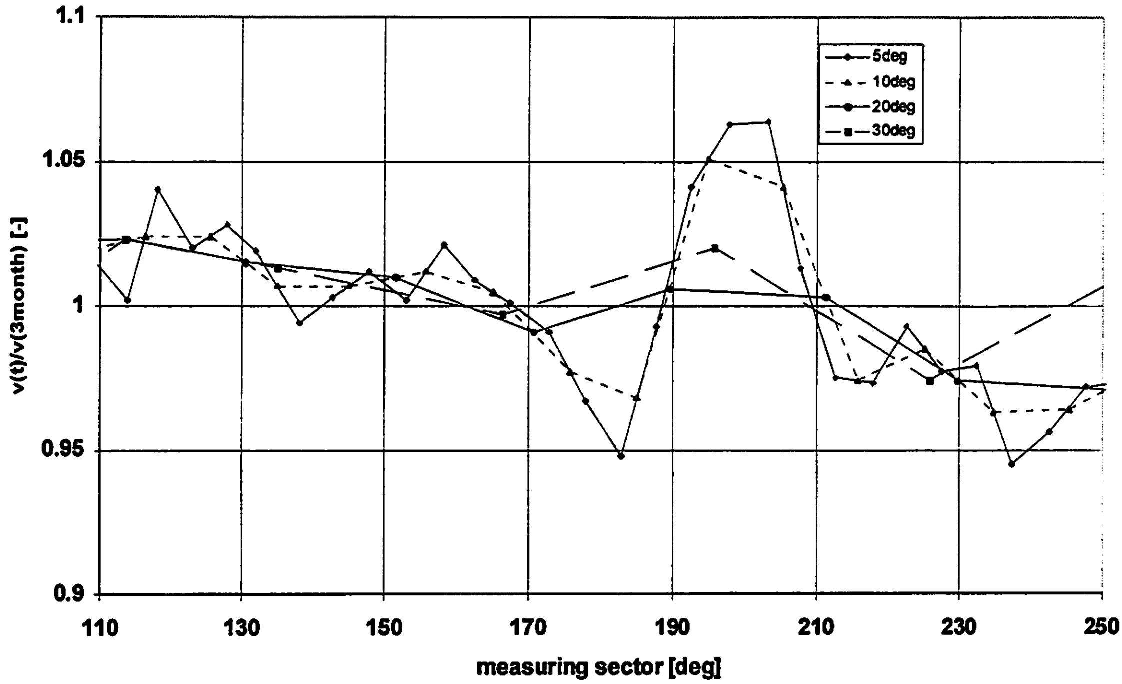


Fig. 9.2 Result of the site calibration using different wind direction sizes (4-16 m/s)

Figure 9.3 shows the results for different measuring periods. For most sectors the results of short time measuring fits the long time average already after eight hours (for each sector) with a deviation of approximately one percent.
Only for two sectors (185 ° and 195 °) the deviation is less than one percent after 24 hours. (per sector).

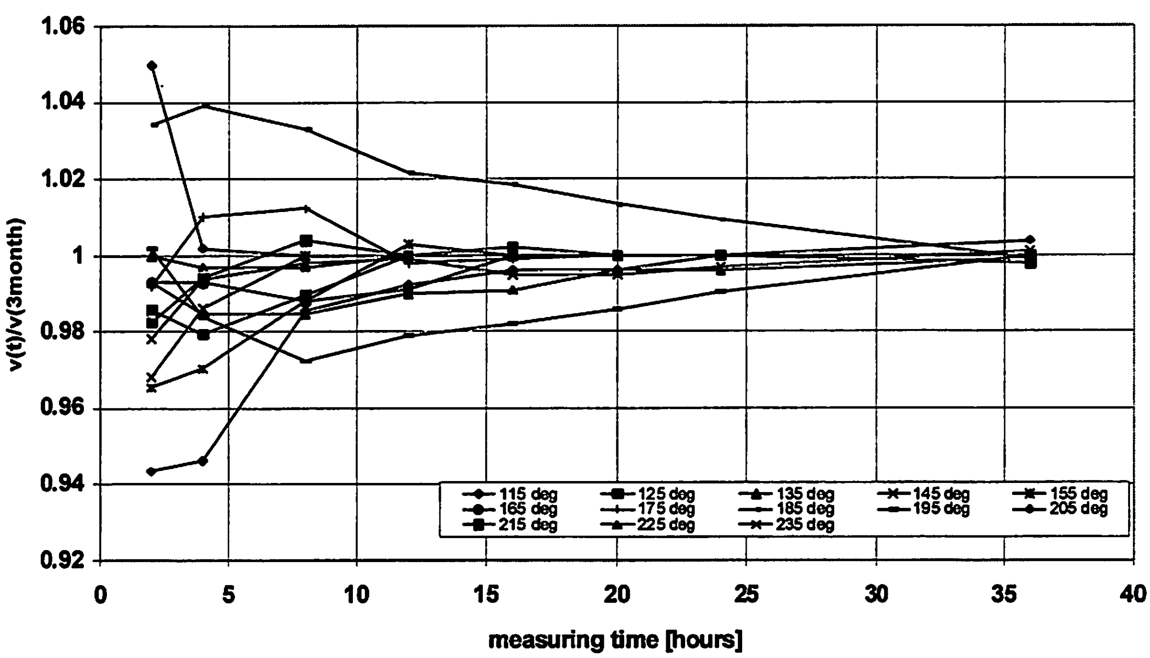


Fig. 9.3 Result of the site calibration using different measurement periods (for each sector)

From this measurement results could be concluded that 10°-sectors and a measurement period of 24 hours per sector (wind speed range 4-16 m/s) should be recommended for site calibrations.

5 INFLUENCE OF FLOW INCLINATION ON ANEMOMETER READINGS

For two different anemometers (Thies and RISØ) the influence of flow inclination on the wind speed measurements was determined for different wind speeds in the wind tunnel and in the open.

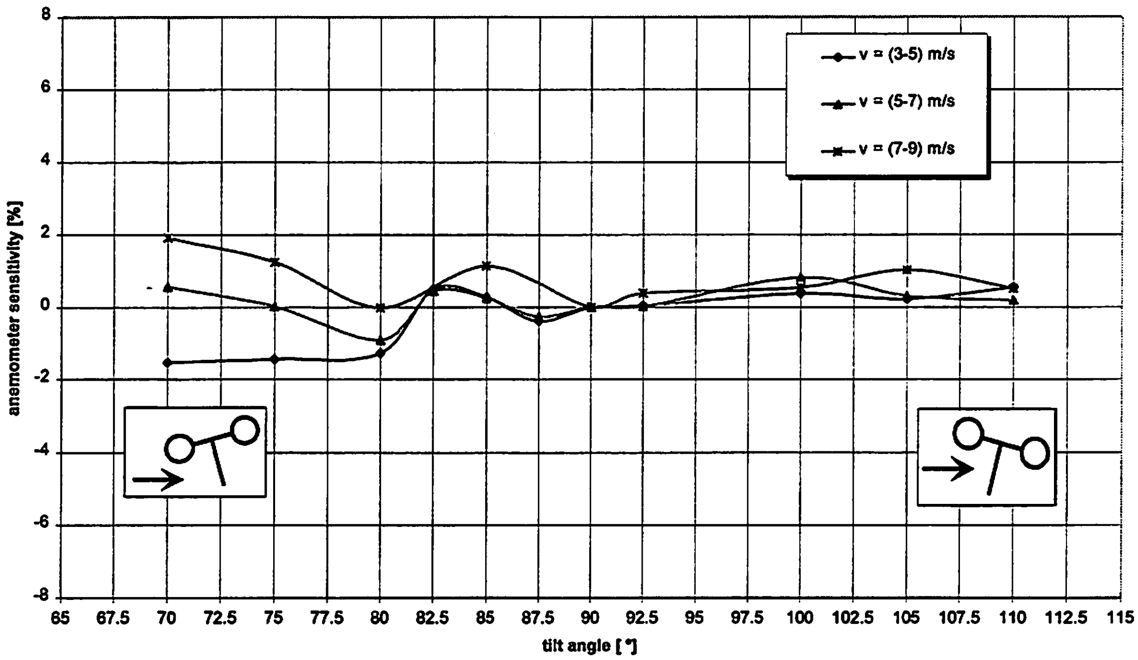


Fig. 10.1 Outdoor Measurement - Thies

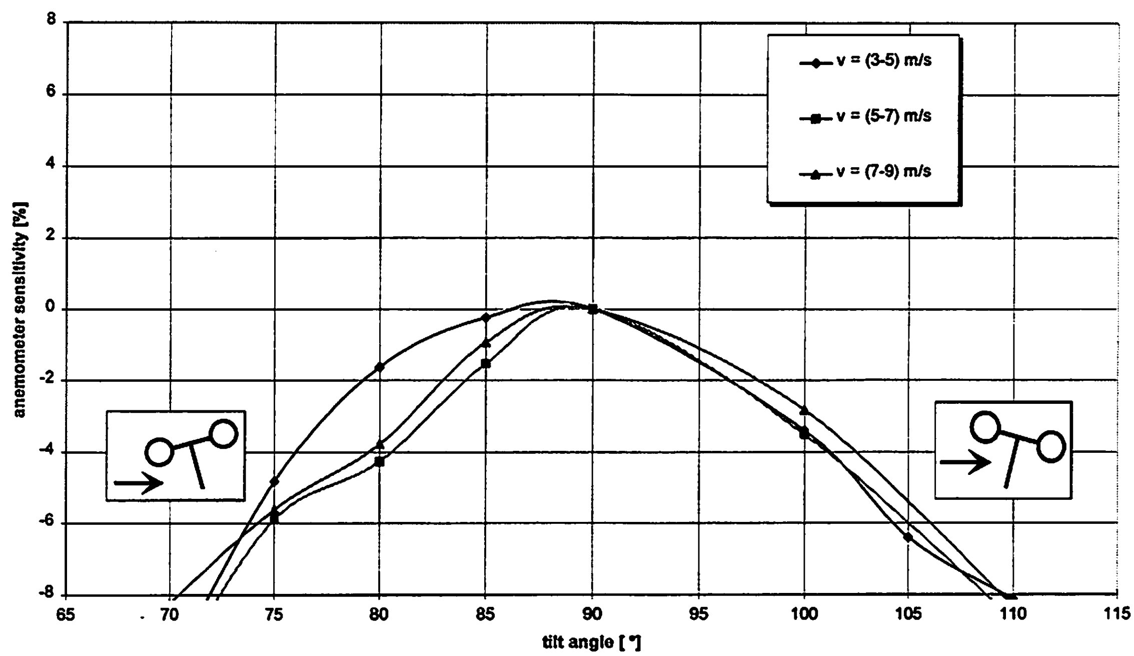
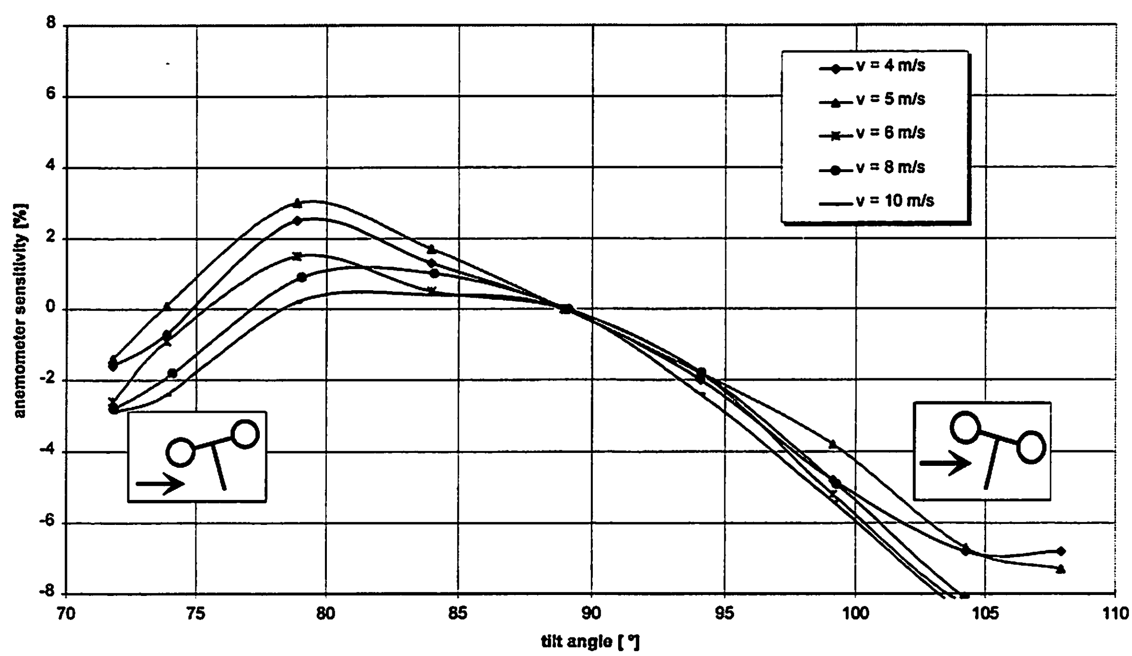


Fig. 10.2 Outdoor Measurement(RISØ-Anemometer)

Fig. 10.3 (below) Wind Tunnel Measurement (RISØ-Anemometer)



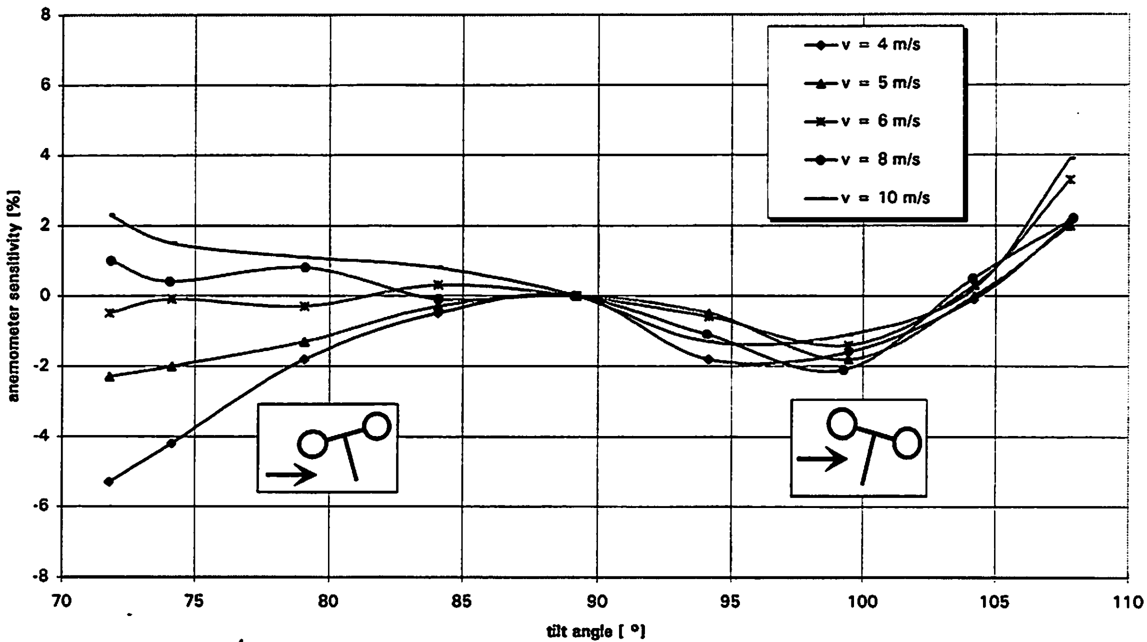


Fig. 10.4 ~~Outdoor~~ Wind Tunnel Measurement (~~RISØ~~ Thies-Anemometer)

It can be concluded that the inclined flow effects on anemometers are wind speed dependent. These effects are influenced by the shape of the cups and the body of the anemometer. There is a different behavior in the open than in the wind tunnel which can not be explained at the moment.

6 INFLUENCE OF METEOROLOGICAL CONDITIONS ON POWER PERFORMANCE

6.1. Influence of Turbulence Intensity

The turbulence intensity of the wind speed is calculated according to the following equation:

$$t_i = \frac{\sigma_v}{\bar{v}}$$

The average turbulence intensity at hub height (92m) of the AEOLUS II (3 MW) in the selected wind direction sector (225°-315°) during the measuring period (01.01.94-30.06.95) is 7.22 %.

The results are graphically shown in the following figure:

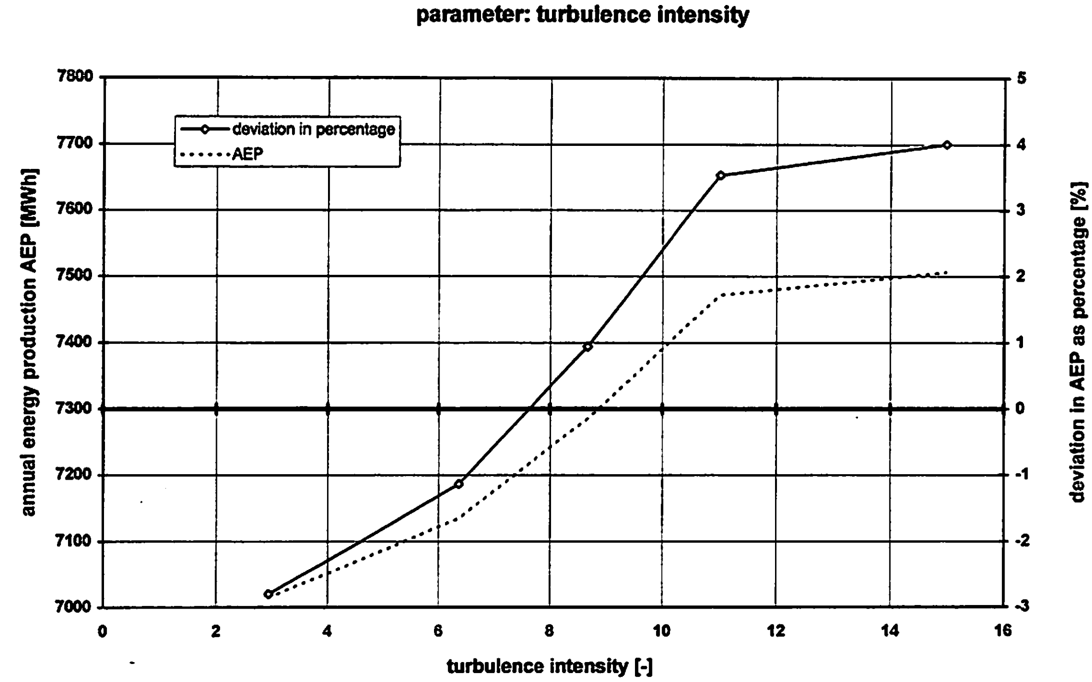


Fig. 11: Annual energy production at a site with the characteristics measured at "Jade Windpark", (Weibull parameters: A=8.9 , k=2.23)

Whether there is an increase or a decrease in power depends mainly on the kind of curve: in the part of the power curve where the graph is left-curved, the electrical power increases with higher turbulence intensity; in the part of the power curve where the graph is right-curved, the electrical power decreases with higher turbulence intensity.

6.2. Influence of Wind Gradient

The wind speed at the site "Jade-Windpark" is measured in five different heights: 11m, 32m, 62m, 92m and 126m . From this values an absolute wind gradient (weighted with its contribution to the rotor disk area) is calculated and divided into the following classes:

0 - 0.01 (m/s)/m,	0.01 - 0.02 (m/s)/m,	0.02 - 0.03 (m/s)/m,
0.03 - 0.04 (m/s)/m,	0.04 - 0.05 (m/s)/m,	> 0.05 (m/s)/m.

For each two classes the power curves are shown in the following figure:

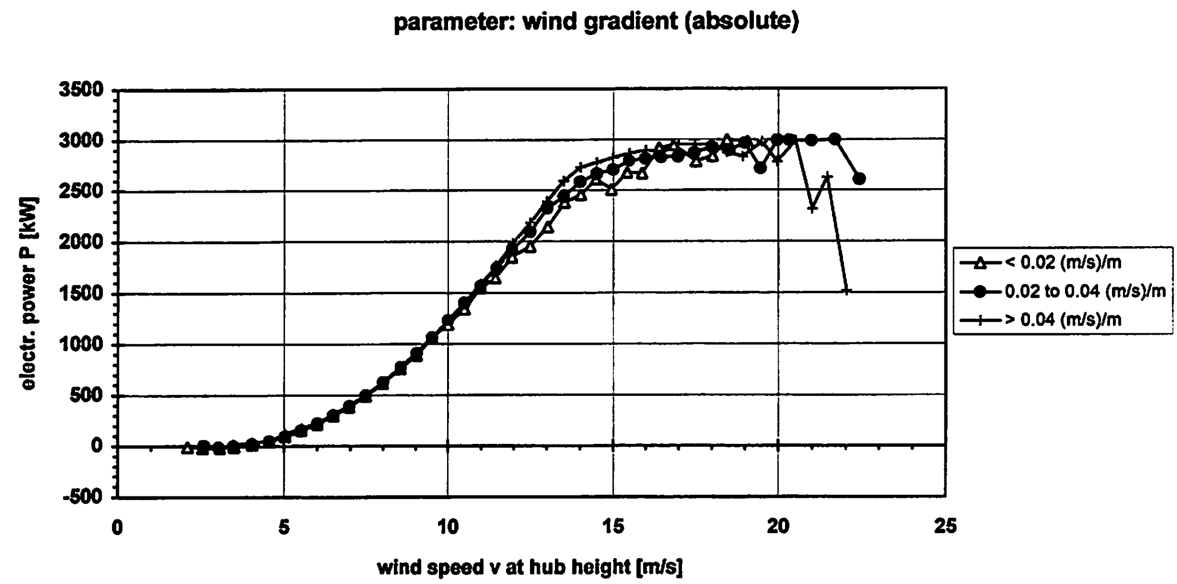


Fig. 12: Power Curves of the AEOLUS II as a function of wind gradient
For reasons of comparability the annual energy production is calculated only in the wind speed range from 6 m/s and 15 m/s. The following picture shows the resulting change in annual energy production for the 6 different classes of wind gradient.

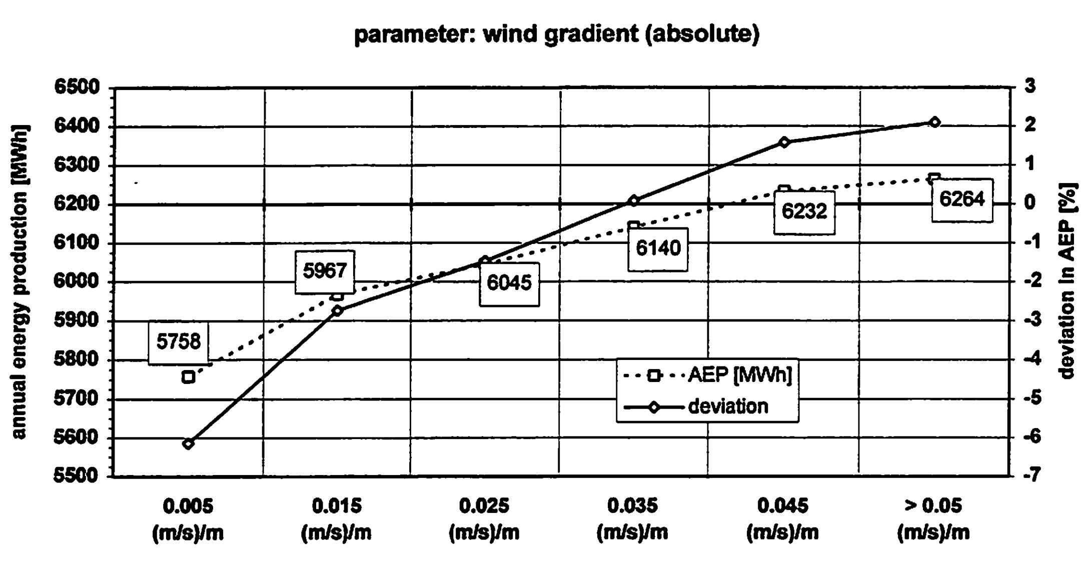


Fig. 13: Annual energy production at a site with the characteristics measured at "Jade Windpark", (Weibull parameters: A=8.9 , k=2.23). AEP calculated for the wind speed range from 6 m/s to 15 m/s.

Obviously for the applied wind speed distribution an increase of wind gradient leads to an increase of the AEP. This effect can be generally understood from the observations concerning the influence of turbulence intensity on the power performance discussed before , because high wind gradients correspond to high spatial variations in wind speed over the rotor height and thus result in a higher annual energy production similar to the effect of high turbulence. Otherwise the effects of wind gradients and turbulence are opposed, because usually a high wind gradient corresponds to a stable layer with low turbulence intensity.

Although the turbulence intensity decreases with increasing wind gradient, the interference of both effects lead to an increasing AEP. Therefore it can be expected that the deviation in AEP for different wind gradients will be higher when regarding only values with nearly the same temporal turbulence intensity. This examination is not done until now.

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ACKNOWLEDGEMENT

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Tilt angle sensitivity of different reference anemometers of MEASNET Instituts

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Presentation at IEA Experts Meeting
in Athens, 8 - 9.12.1997

1. Introduction

The aim of the investigations carried out by WINDTEST is to get information about tilt sensitivity of different anemometer types used by MEASNET Institutes. The wheels and especially the body of the test anemometers were of absolutely different shape. Interferences of body, neck and wheel are expected as the main reason for tilt sensitivity effects. WINDTEST performed several sensitivity tests of tilt effects on cup anemometers. The test showed that uncertainties and/or errors due to tilt sensitivity are sometimes higher than assumed by the expected cosine response. Over- (or under-) speeding induced by temporary vertical wind components (vertical turbulence characteristics) can occure and be more important than conventional overspeeding.

The following results are based on measurements performed on February 18/19th, 1997 in the wind tunnel of „Institut für Schiffbau, Universität Hamburg".

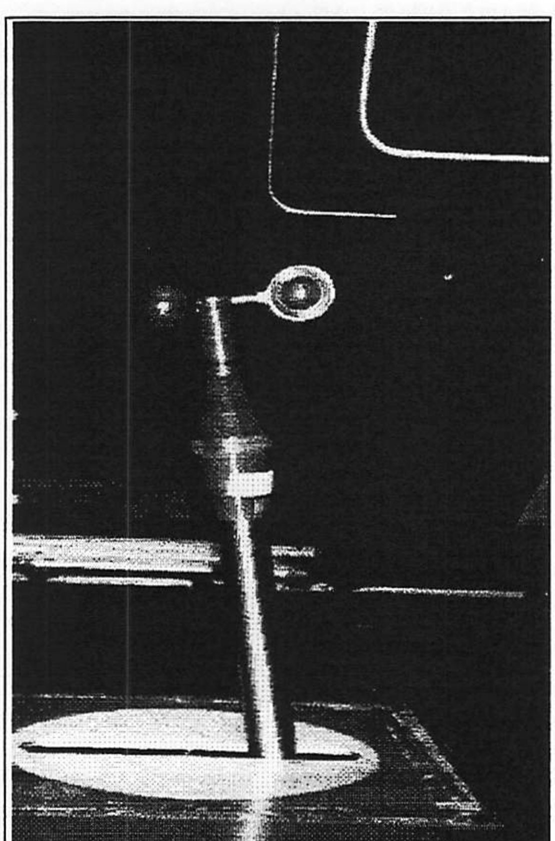

Figure 1: tilt tests using a rotating tube

2. Procedure

To adjust different tilt angles a computer controlled sliding board installed beneath the test section (figure 1) was used. For all tests the anemometer remained in the same position within the test section. To avoid asymmetrical effects of the wind tunnel, the test section is equipped with a second wall. Tilt sensitivity tests on seven reference anemometers of MEASNET Institutes (including NREL informally) have been investigated. The cups were:

- Climatronics 100075 (S-Nr. 1092189),
- Friedrichs 4032.1000 (S-Nr. WT 0107194),
- METone Instr. (NREL-Ref.),
- Mierij 0268/11043 (S-Nr. 012.0029),
- RISØ PFV 1115 (S-Nr. 0650 Ref. 200),
- SEAC NS.950./0/9, (S-Nr. 00.0002),
- Thies 4.3303 (S-Nr. 1092189),
- Vector Instr. A100 (S-Nr. 2901).

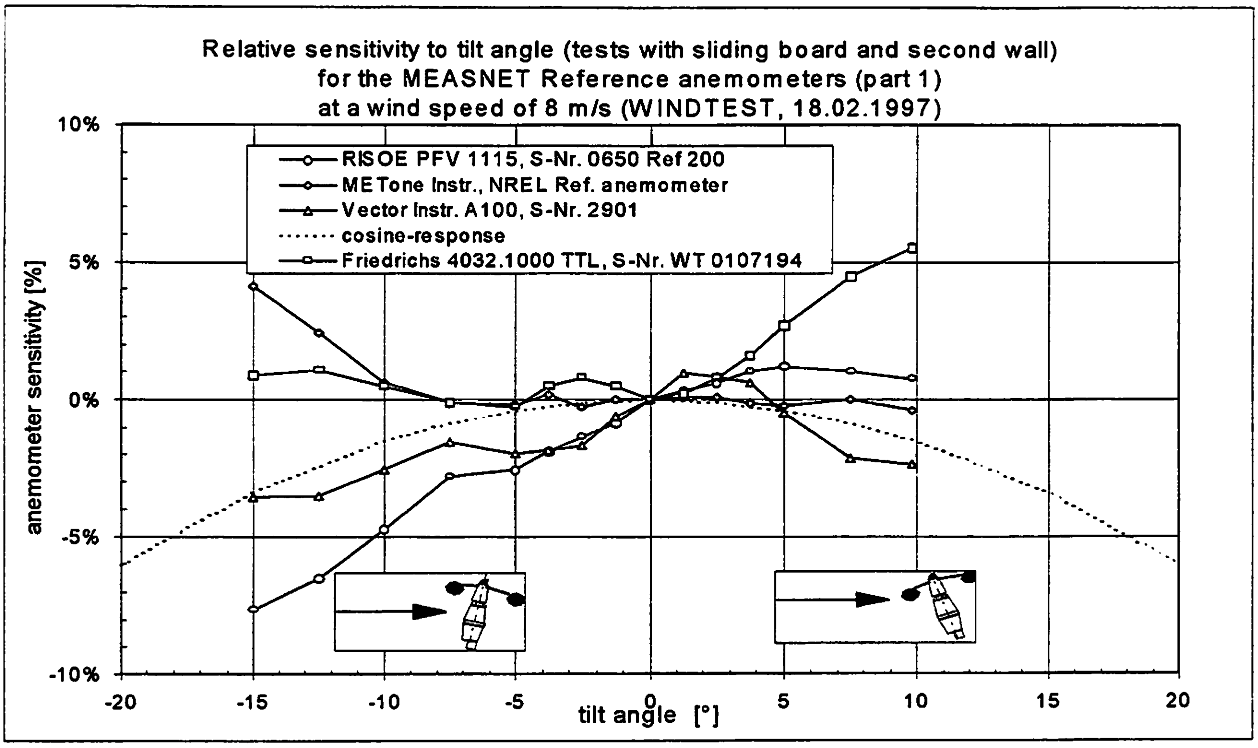

Figure 2: Results of tilt angle sensitivity test of eight anemometers (part 1)

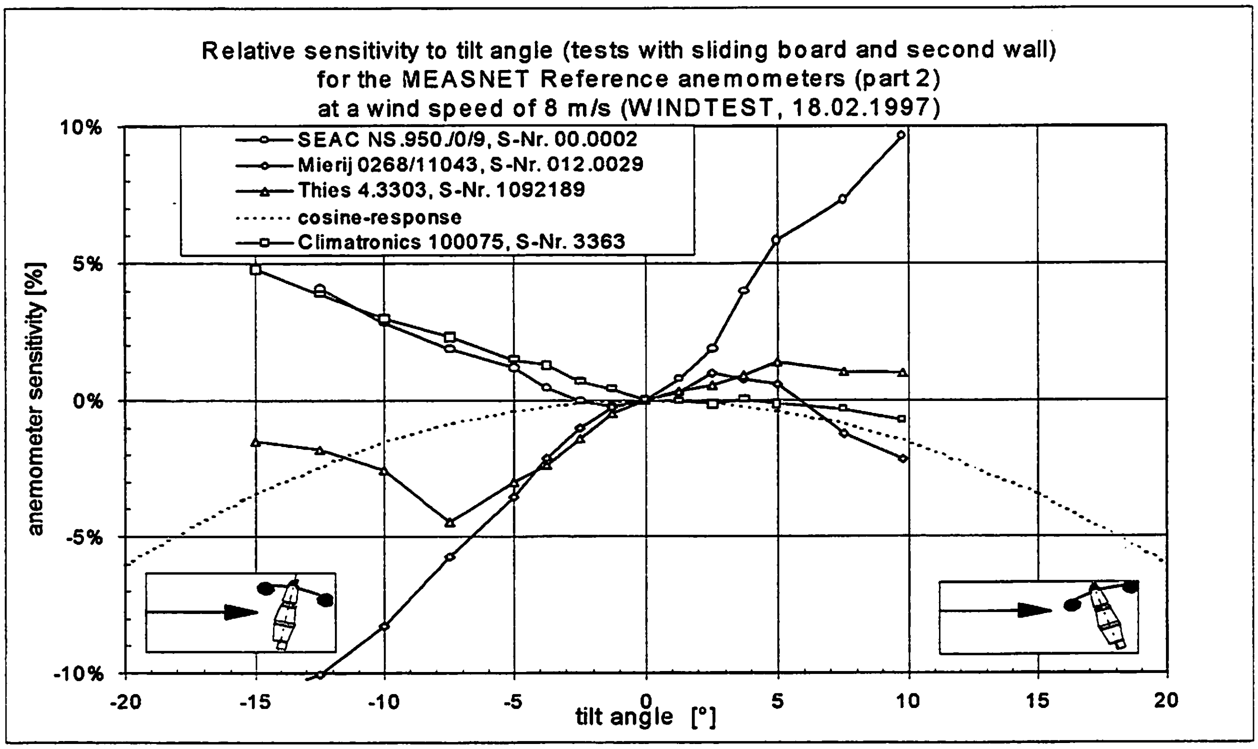

Figure 3: Results of tilt angle sensitivity test of eight anemometers (part 2)

3. Results

In figure 2 and 3 the results of tilt test of eight anemometers are shown. It is clearly visible that:

1. The tilt behaviour for all anemometer types is totally different to a cosine function.
2. Each anemometer has its own tilt characteristics.

3. Anemometers either can overestimate wind speed or underestimate wind speed both for positive elevation angles (upwind anemometer head) and negative elevation angles (downwind anemometer head).
4. A gradient can be seen at the 0°-position for some anemometers.

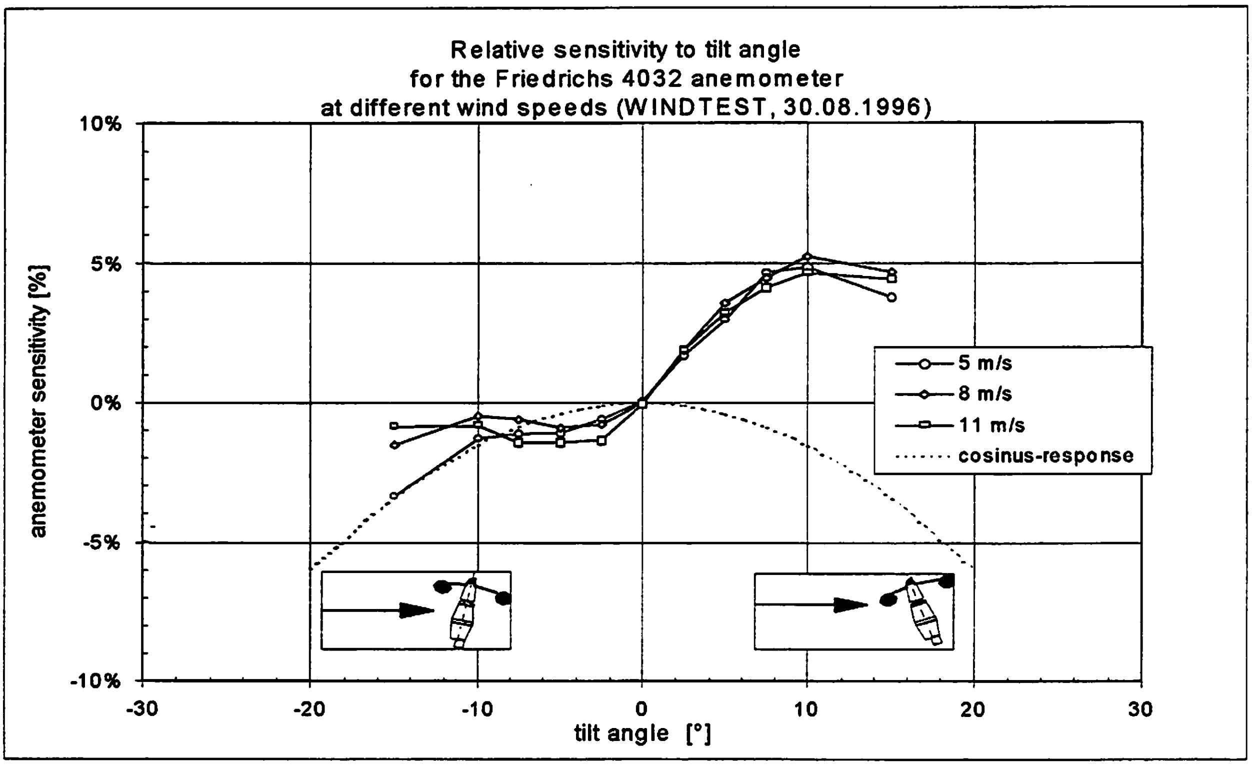

Figure 4: Relative tilt angle sensitivity for different wind speeds - Fiedrichs 4032.1000

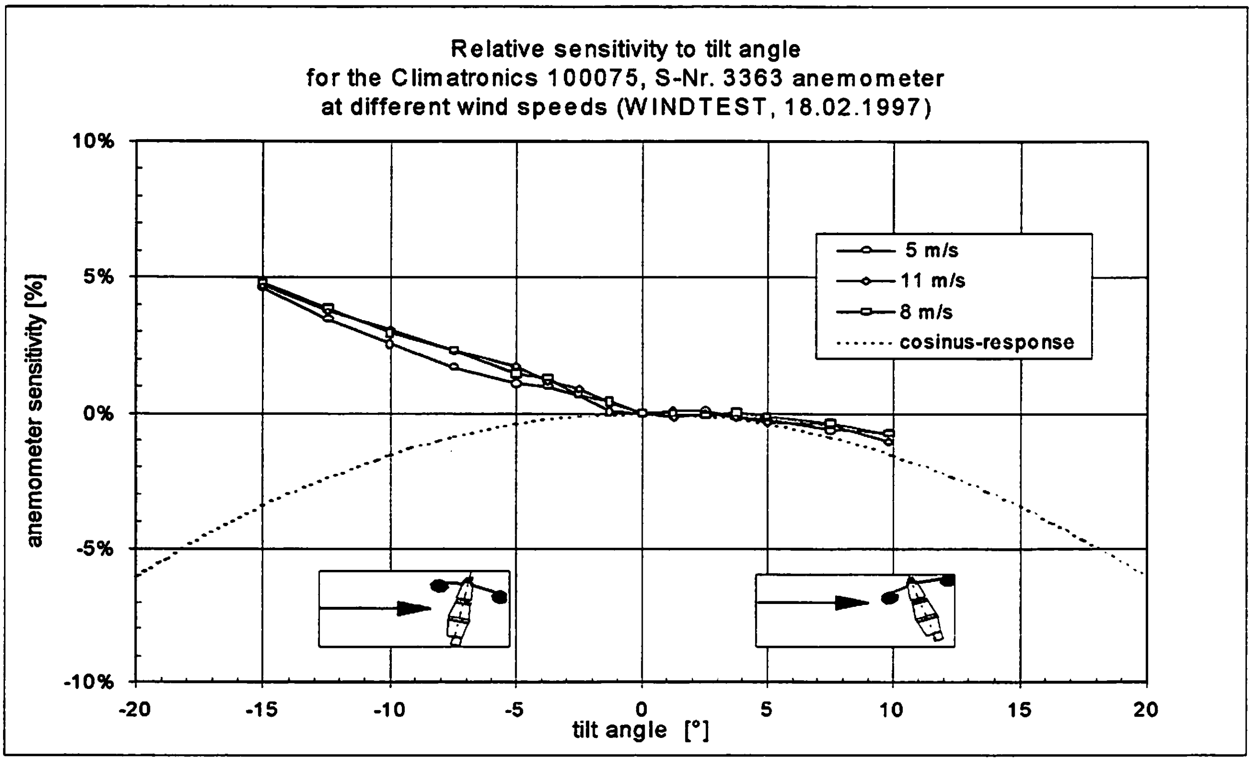

Figure 5: Relative tilt angle sensitivity for different wind speeds - Climatronics 100075

In figure 4 and 5 is shown, that tilt sensitivity for the two tested anemometers is similar for different wind speeds (5, 8 and 11 m/s). This test has been performed with a Friedrichs 4032.1000 and a Climatronics 100075 anemometer.

4. Conclusions

Operational characteristics with respect to tilt sensitivity can play a significant role during anemometer calibrations and wind measurements. Anemometers are in most cases more sensitive to tilt angles than expected from a cosine-function. As a consequence tilt effects should be known for all sensor types used for power performance measurements. Especially for site calibrations in complex terrain care should be taken when selecting suitable sensors.

Performing wind tunnel calibrations and field measurements the anemometer has to be aligned rectangular to the flow field in the test section as accurate as possible.

Further effects can be expected by turbulence characteristics of the wind flow. With respect to tilt this will induce an over- or underestimation of the anemometer signal.

In addition the tilt sensitivity has to be taken into account for measurements using a nacelle anemometer. Relative power curves and correlation results are depending on the used sensor and its tilt characteristics. Verification of the relative power curve therefore is only possible when using the same anemometer types for the reference and verification tests.

6. Literature

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Influence of various meteorological conditions on the annual energy production of Näsudden II (Ø=80 m)

IEA meeting
Athens, Greece
971208-971209

Göran Ronsten

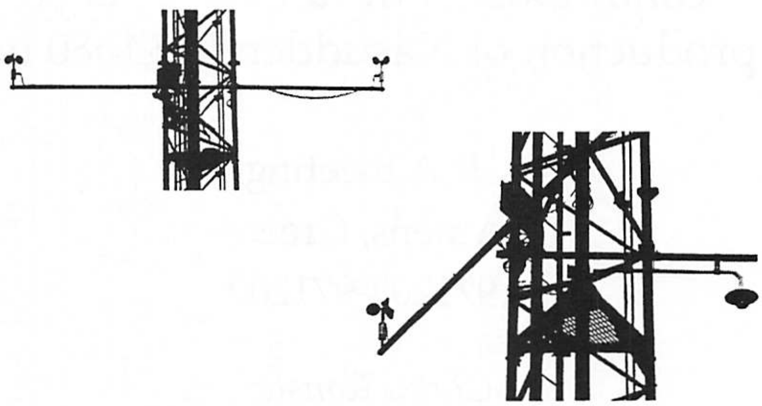
FFA

Objective

- Find the influence of meteorological and operational conditions on the annual energy production of Näsudden II
  - Mast influence
  - Turbulence intensity
  - Wind gradient
  - Nacelle wind direction

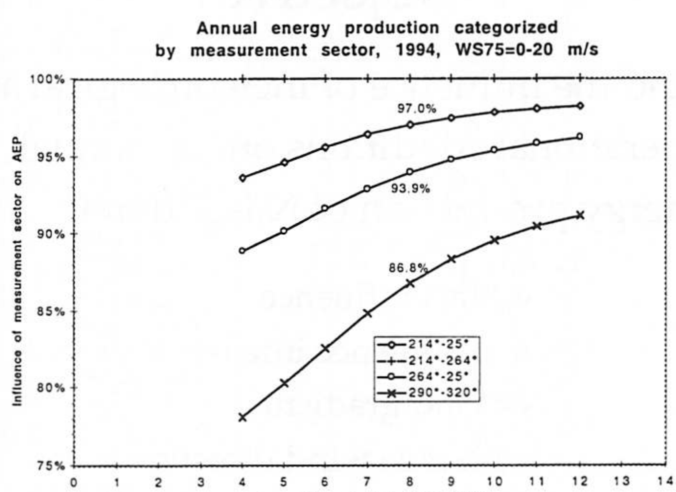
FFA

Mast influence



Mast influence on AEP

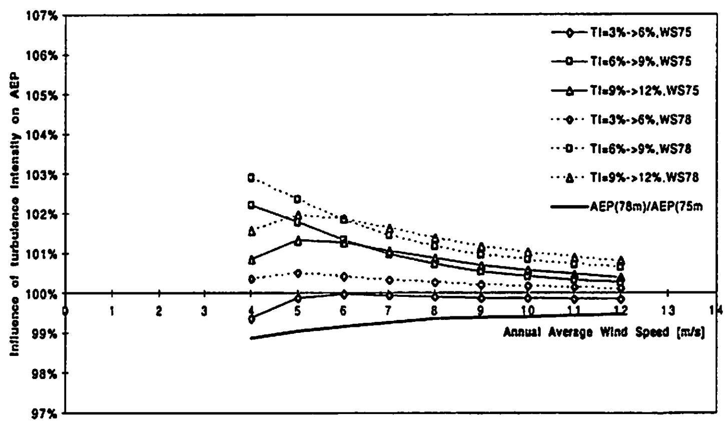
All sectors OK according to IEC



Turbulence intensity influence on AEP

WS78 was calculated using WS75 and the measured wind gradient

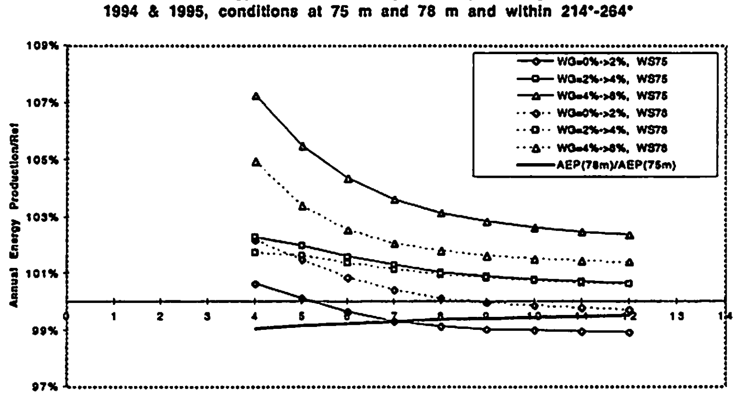
Annual energy production categorized by turbulence intensity, 1994 & 1995, conditions at 75 m and 78 m and within 214°-264°



Wind gradient influence on AEP

WS78 was calculated using WS75 and the measured wind gradient

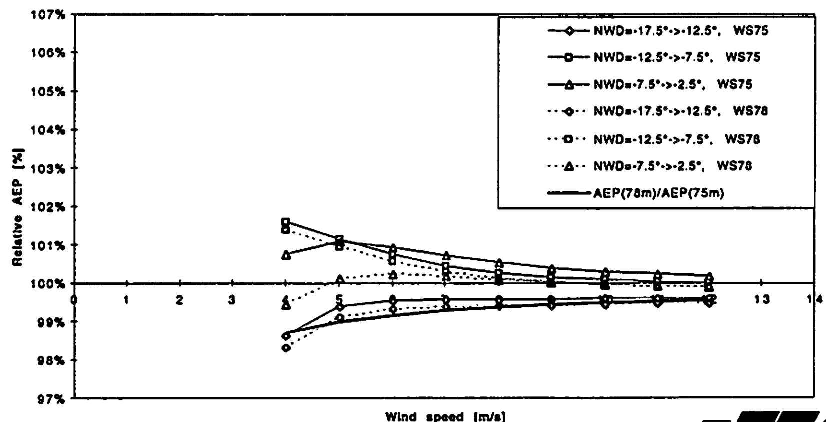
Annual Energy Production categorized by wind gradient, 1994 & 1995, conditions at 75 m and 78 m and within 214°-264°



Nacelle wind direction and its influence on AEP

WS78 was calculated using WS75 and the measured wind gradient

Annual energy production categorized by nacelle wind direction, 1994 & 1995, conditions at 75 m and 78 m and within 214°-264°



Conclusions

- Severe mast influence on the measured wind speed due to short horizontal and vertical booms
- 2% increase in AEP (at 8 m/s) as turbulence increases from 3-6% to 9-12%
- 2% increase in AEP (at 8 m/s) as the wind gradient increases from 0-2% to 4-8%
- 1% drop in AEP (at 8 m/s) at 15° offset between nacelle direction and wind dir.

How relevant, referring to power performance for large wind turbines, is the hub height wind speed?

IEA meeting
Athens, Greece
971208-971209

Göran Ronsten

FFA

Objective

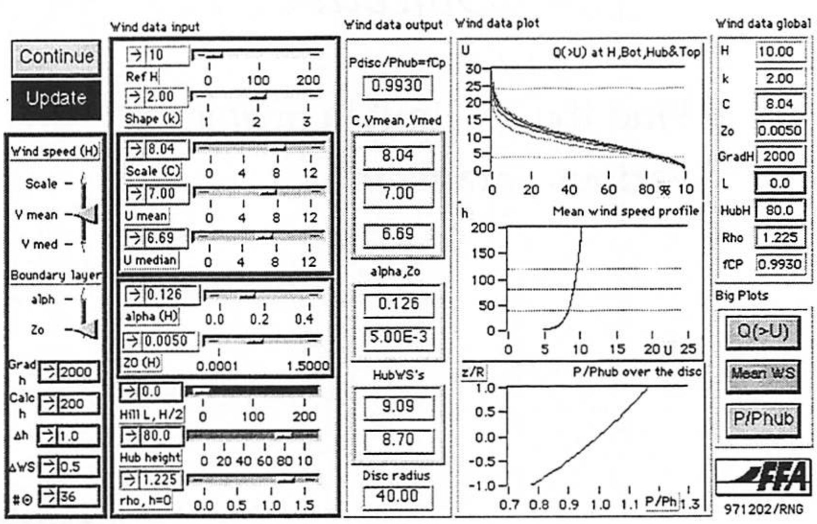
- Find the 1% limit in power for various parameters

FFA

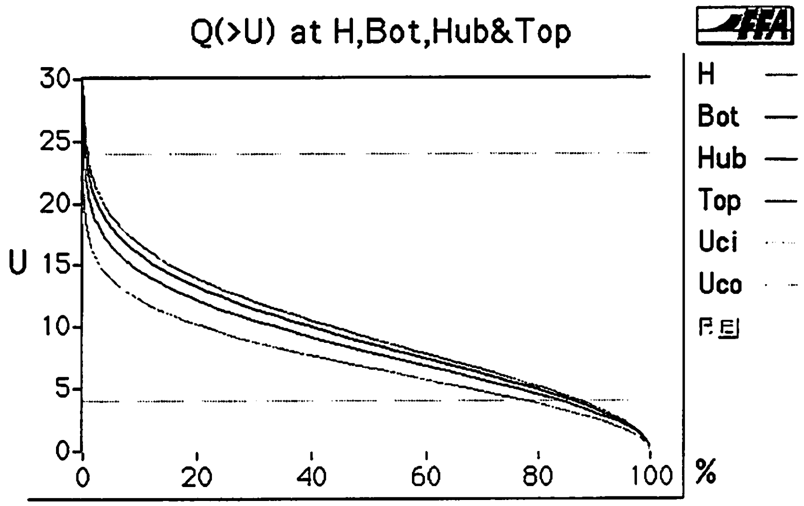
How to achieve the objective?

- Study of P/P_{hub} for a 3 MW, 80/80 m turbine and varying the :
  - Roughness length
  - Tower height
  - Radius

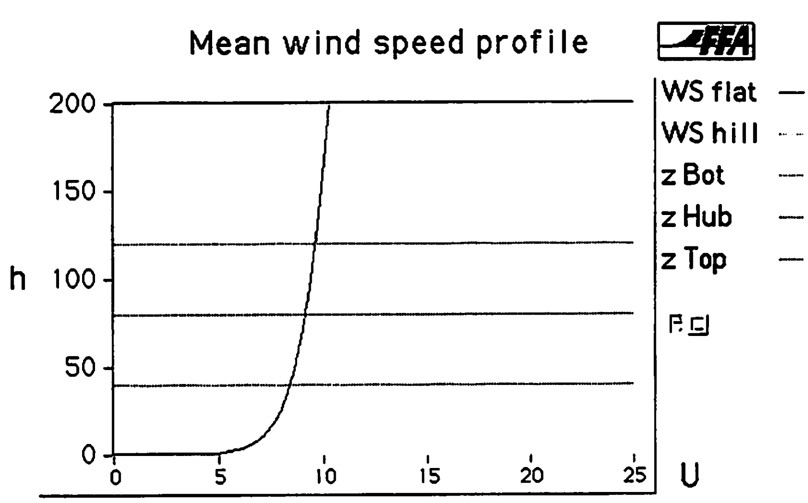
Example of input and output



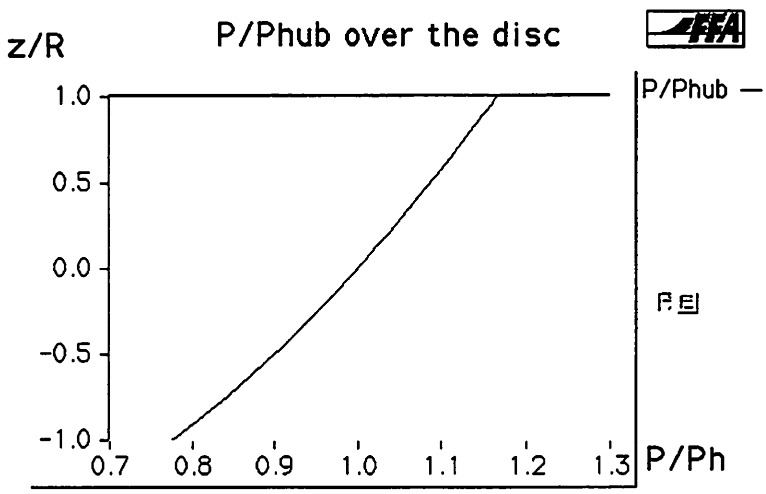
Wind speed duration



Vertical wind speed



Power ratio



Roughness length

- h=80m, r=40m

	P/P_{hub}
z_0=1e-10m	99.7%
z_0=0.005m	99.3%
z_0=4.8m	99.0%

Tower height

- z_0=0.005m, r=40m

	P/P_{hub}
h=120m	99.7%
h=92m	99.5%
h=80m	99.3%
h=69m	99.0%

Rotor radius

- z_0=0.005m, h=80m

	P/P_{hub}
r=20m	99.8%
r=30m	99.6%
r=40m	99.3%
r=47m	99.0%

Results

- P/P_{hub} due to roughness:

z_0=0.005m	99.3%
z_0=4.8m	99.0%

- P/P_{hub} due to rotor radius

r=40m	99.3%
r=47m	99.0%

- P/P_{hub} due to tower height :

h=92m	99.5%
h=69m	99.0%

FFA

Comments regarding future power performance evaluation of an 80 m turbine:

- Power performance is generally slightly overestimated if only the hub wind speed height is used
- Power performance evaluation can be made more accurate if the average wind gradient is measured

FFA

Some aspects of power curve measurements in complex terrain

Troels Friis Pedersen, Department of Wind Energy and Atmospheric Physics, RISØ, Denmark

IEA R&D Experts Meeting
State of the Art of Power Performance Assessment for Wind Energy Conversion Systems
Athens 8-9 December 1997

Abstracts

The development of measurement procedures for power performance measurements is moving into a new phase. The key issue has now been set on the problems connected to performing power performance measurements on wind farms in complex terrain. Within this complex of verification of power performance, the performance of the individual wind turbine and its power curve is considered. In this respect, it is the measurement of the wind speed and the power produced by the wind turbine that is considered in this paper. This paper considers some definition aspects of the measurement procedures for power curve measurements in complex terrain.

Introduction

The state of the art of power curve measurements is well described in the IEC 1400-12 FDIS document "Wind Turbine Generator Systems, Part 12: - Wind Turbine Power Performance Testing". On the other hand, some aspects of power performance measurements in complex terrain and wind farms are not properly covered, and it has been found necessary to supplement the present measurement standard with an additional document. This paper will not deal specifically with this task, but will concentrate on some aspects in power performance testing in complex terrain.

Demands for power curve measurements

Power curve measurements are initiated by many reasons. Often, the goal is not very clear for the measurements, and it might be expected that measurements can be used for various purposes. In general, though, there seem to be three specific demands for power curve measurements, for which different ideal conditions are evident.

Power curve measurements in relation to certification

For certification purposes it is required to measure the power curve. In this case it is important to determine the performance of the wind turbine itself without interference with other wind turbines or terrain obstacles. The conditions should be well-defined, the terrain flat, and the flow homogeneous. These conditions are the most favourable for an objective determination of the performance and for the comparison of the performance of different wind turbines. In measurement procedures such conditions are referenced as ideal test sites. The advantage of such ideal sites are, that the measurements are simple, the measurement procedures are reasonably robust, flows are well-defined, very detailed evaluation of the wind turbine can be made, and the uncertainties connected with the measurements are low.

Verification of power curves of single wind turbines

An owner often wants the power curve of a wind turbine verified at the individual site. Often the intention is to verify the power curve, which the manufacturer claims for the wind turbine. In this case, a power curve measurement is very site specific, and the influence of the surroundings is part of the task to include in the power curve measurement. Varying topography, obstacles, other wind turbines and roughness influences the power curve. These influences might cause the airflow to have wind shears in the vertical and horizontal planes very different from homogeneous terrain. In these cases, the power curves must be expected to be different from power curves, measured at ideal test sites in homogeneous terrain, and they are not necessarily comparable. On the other hand, site specific power curves are useful for the owner as an actual verification of the performance of "his" machine at "his" site. Such a power curve is often called a "verified power curve", relating to the manufacturers "guarantied power curve".

Other problems of verification of power curves in complex terrain are the bad correlation between the one point measured wind speed at a meteorology mast, positioned some rotor diameters away from the wind turbine, and the wind speed at the centre of the wind turbine. Site calibration procedures have been introduced, in which an intermediate meteorology mast is erected at the position of the wind turbine, to verify the wind correction factor from different wind directions. These site calibrations are by some parts of the wind energy community not yet recognised to be appropriate. The cause is, that the wind turbines are often erected before a power curve measurement is undertaken, leaving very substantial problems to the undertaker of the power curve measurement. Leaving out the site calibration, the uncertainties in the measurement are increased substantially.

Verification of power curves of wind turbines in wind farms

In wind farms, the verification is also very site specific, but the process becomes much more complicated. One could consider each wind turbine individually, and follow the verification of single wind turbines for all of the wind turbines in the wind farm, as described above. In this case, the influence of the surrounding wind turbines becomes very significant. This procedure is not practicable, though, but often at least one of the wind turbines are selected for such a verification on a spot check basis, or for a basic reference. In wind farms, it is the overall performance that has the main interest, but for warranty issues and for optimum performance, the "power curves" of the individual wind turbines is essential.

Requirements for Harmonisation and Metrology

The wind energy community is developing, and the requirements to different performers changes. To day, it is the market force that has the strongest incentives for this development. Market forces are driven by the customers: developers, investors, utilities, banks, etc. But for the market to work well, there are also requirements for certification, harmonisation and third party interaction.

International standards are of increasing importance. At present, the IEC power performance procedure has an FDIS status, but it will be an international standard in the beginning of 1998 if the last voting is successful (all votes were positive in the previous stage). An additional standard, specific for wind farm and complex terrain applications, have been decided by the IEC committee to be prepared. This work should, among other work, be based on some research projects POWASS (a JOULE project) and an SMT project. Other work includes the project EWTS-II (a JOULE project) and work by the CENELEC BTTF working group.

The requirements of the knowledge and capability of the performers that are using the international power performance standards are increasing. Institutes that perform power curve measurements will in the future need accreditation in accordance with the standard EN45001 or the ISO 25 Guide to assure the quality of work. The institutes that are allowed to measure power curves for certification purposes are put on "acceptance lists". All power curve measurements need to be traceable, which means that they shall be absolute "true" values (including mean values and uncertainty estimates), related to the definitions of the fundamental physical units in the MKSA system, defined by "Bureau International de Poids et Mesure" in Paris. The principle of traceability in measurements is a rather strong requirement and specifies a rather advanced chain of calibrations, in which increasing uncertainties document objective and "true" measurements. Traceability in measurements requires quite detailed knowledge of statistics and uncertainty analysis.

The increasing requirements to the measurement procedures and to the performers of power curve measurements put the question, whether the measurement standards, when describing the complex procedures to verify wind turbine power performance in complex terrain, can be made simple enough, so that they are accessible to others than the expected performers, for whom accreditation, traceability and uncertainty analysis are well-known terms.

Is a power curve well defined?

The reason to raise this question is that power curves must be expected to be different when measured in homogenous terrain and complex terrain. The standards, used in the past, define power curves as described in Table A.

From the table it is seen that the power curve is well-defined from a relation between net power and wind speed, where the wind speed is defined as a point measurement. In the IEA, ECN and IEC procedures the point is defined at hub height, and when looking at the other requirements regarding the positioning of the mast, the point is defined at a distance of several rotor diameters away. For some reason one could argue that this is satisfactory, but when going into complex terrain, deviations might be very high, and this is the reason why site calibrations are taken into account. The definition of the power curve and measured wind speed in the ENS procedure is very specific, and the requirement of the site calibration is straight forward.

For verification of power curves in complex terrain, where vertical and horizontal wind shears can vary substantially from the wind shears in homogeneous terrain, it might be advantageous to define power curves differently by defining the wind speed as an integrated wind speed over the swept area of the rotor. The advantage of this is to include the varying wind shears, thereby getting a power curve which is more comparable to a power curve measured at a homogeneous site. The disadvantages of such a procedure is that, for an integration over the swept area, one needs higher meteorology masts and more masts to measure the horizontal wind shear. This increases the uncertainties due to mast and boom effects on the anemometer measurements. It is doubtful whether the additional costs of masts, booms and sensors to get a detailed knowledge of the wind flow will decrease the uncertainties enough to make this procedure attractive in the market place.

Table A Power curve definitions

Measurement procedure	Power Curve Definition
ECN-217, 1989 Ref. 1	Definition: • Power Curve - A characteristic which depicts the mean net power output of a WT as a function of the undisturbed wind speed at hub height • Net Power - The power available to the user, 10-minute values • Wind Speed - Speed of the undisturbed air flow, 10-minute averaged value
IEA 2. Edition, 1990 Ref. 2	Definition: • Power Curve - A graph which depicts the net power of a WT as a function of wind speed • Net Power - The power available to the user, 10-minute values • Wind Speed - The 10-minute average wind speed, unless otherwise specified • The test anemometer shall be located at a height above the terrain surface, equal to the hub height
ENS, Denmark, 1992 Ref. 3	Definition: • Power Curve - The power curve is defined as a table of data, consisting of connected values of net electric power from the wind turbine and the wind speed • The wind speed, and other meteorological parameters, are referred to the center of the wind turbine rotor, as they would be, if they were not disturbed by the presence of the wind turbine
IEC, FDIS, 1997 Ref. 4	Definition: • Table and graph that represents the measured, corrected and normalized net power output of a WTGS as a function of measured wind speed, measured under a well-defined measurement procedure • The measured power curve is determined by collecting simultaneous measurements of wind speed and power output at the test site for a period that is long enough to establish a statistically significant database over a range of wind speed and under varying wind conditions • Net Power - Measure of the WTGS electric power output that is delivered to the electrical power network • Wind Speed - Wind speed measurements shall be made with a cup anemometer that is properly installed at hub height on a meteorology mast, at a point that represents the free stream wind flow that drives the WTGS

The term "power performance measurement" is broader than the term "power curve measurement". The difference is, that "performance measurement" is not defined from a relation between a well-defined wind speed and power. One might say that performance measurements are measurements made to verify calculation tools that calculates the flow, and estimates the power from a number of wind turbines. Verification of calculation tools for very specific conditions (for instance a few wind turbines in a wind farm) makes it possible to extrapolate to the whole wind farm. Such a procedure is very much used in certification of wind turbines. All load cases can normally not be measured and verified because they are too rare. Therefore, the calculation codes are verified for specific load cases (calibrated), and then used for extrapolation into rare load cases.

Concluding, it can be said that power curves should be defined as precise as possible (for instance as in the ENS procedure), and that they should be defined different from the present definitions if procedures to measure and integrate wind speeds over the whole swept area becomes feasible. When performing verification of performance of wind farms in complex terrain, it might not even be necessary to consider power curves of individual wind turbines, which relates point wind speed measurements with power.

Is the wind speed well defined?

The reason to raise this question is some investigations into the operational characteristics of cup-anemometers, Ref. 5. These investigations showed that there is a difference in a power curve measurement whether the measured wind speed is the averaged vector wind speed or the averaged horizontal wind speed. Furthermore, the operational characteristics showed much higher deviations than has been anticipated earlier.

The following tables list results of calculations made on an artificial wind: the response of a cup-anemometer on the 8m/s wind, using a 3D cup-anemometer model of the RISØ cup-anemometer, and the response of a 225kW wind turbine on the same wind using a 3D wind turbine model, HAWC.

Table B Wind speed (m/s), 10-minute mean values

	turbulence 0%	**turbulence 10%**	**turbulence 20%**
u (U_{1D})	8.0000	8.0000	8.0000
v	0.0	0.0	0.0
w	0.0	0.0	0.0
U_{2D} (horiz.)	8.0000	8.0258	8.1060
U_{3D} (vector)	8.0000	8.0361	8.1494
anemometer resp.	8.0000	8.0050	8.0603

Table C Electric power (kW), 10-minute mean values

Flow field on wind turbine	turbulence 0%	turbulence 10%	turbulence 20%
3D	78.195	79.484	82.181
2D	78.195	79.541	82.390
1D	78.195	79.568	82.464

It is seen (Table A) that there is a difference of 0.5% for 20% turbulence intensity between the mean vector wind speed, U_{3D}, and the horizontal wind speed, U_{2D}. The difference between the axial wind speed, U_{1D}, and the vector wind speed, U_{3D}, is 1.9% at 20% turbulence. Omitting a definition of the wind speed will therefore account for up to 1.9% of uncertainty in the measurement of the wind speed, and it will increase at lower wind speeds. For the energy content in the wind or the C_P value of a wind turbine, the difference is 5.7%, which is quite significant.

The difference in mean power (Table C) from 0% to 20% turbulence intensity is seen to be 5.1% for the 3D wind. This relative increase in power with the turbulence (1.051)is found to be proportional to the relative increase, 1.019, in vector wind speed, U_{3D}, raised to a power of 2.7, and to the relative increase, 1.013, in horizontal wind speed, U_{2D}, raised to a power of 3.8. This means, that if the wind speed is defined as the vector wind speed, the influence of turbulence intensity on the power curve is reduced, compared to defining the wind speed as the horizontal wind speed.

Inadequacies of wind speed measurements

In Ref. 6, a classification procedure for cup-anemometers was proposed and it was found that the operational characteristics of a RISØ cup-anemometer varied surprisingly much for operational ranges including those for complex terrain, Table D:

Table D Summary of environmental operational ranges

Parameter	Range	
	Minimum	Maximum
Wind speed (10min)	4m/s	16m/s
Turbulence intensity	5%	(1,13m/s/V_{hub}+ 0,12) 100%
Air temperature	-10°C	40°C
Air density	0,90 kg/m³	1,35 kg/m³
Slope of terrain	-10°	10°

Additionally, it was found that there are substantial differences in the measurements, whether the wind speed is defined as a vector wind speed or a horizontal wind speed. The shown relative deviations of the cup-anemometer, see Fig. 1 and 2, are seen to be quite substantial. In the low wind speed range up to 15%, and 5% and high wind speeds. The cup-anemometer is seen to be a much better horizontal wind speed cup-anemometer than a vector wind speed cup-anemometer.

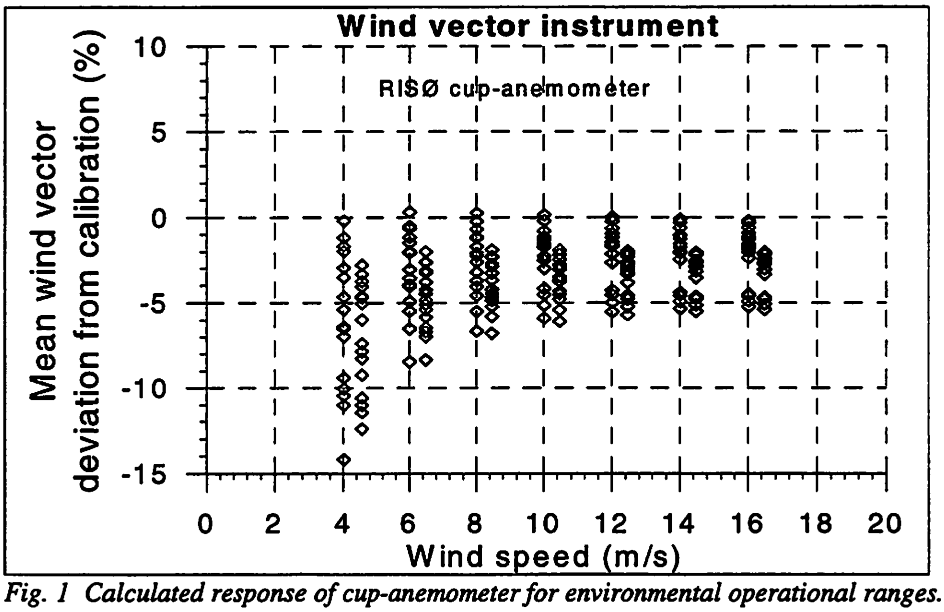


Fig. 1 Calculated response of cup-anemometer for environmental operational ranges. Relative deviations from linear calibration line for a vector wind speed instrument

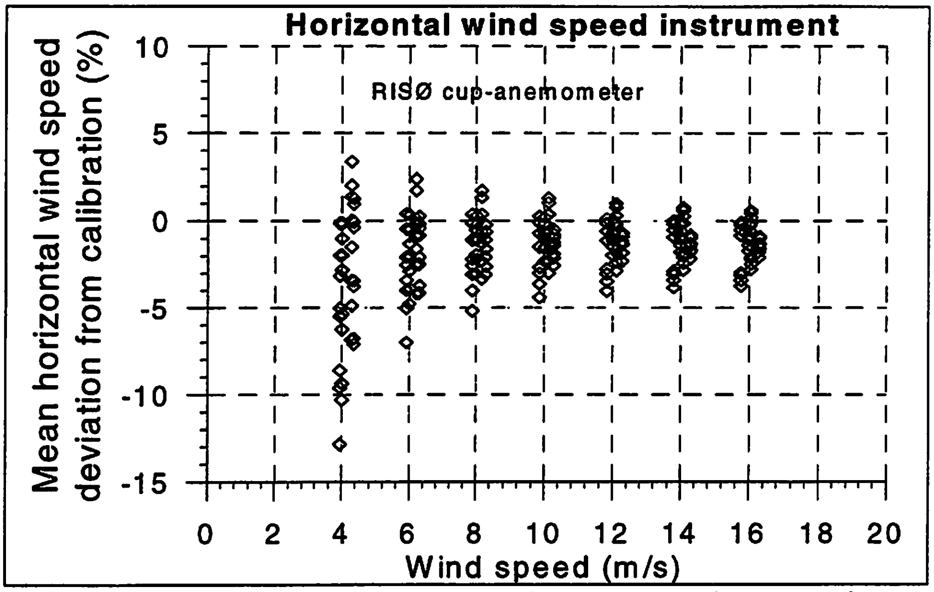


Fig. 2 Calculated response of cup-anemometer for environmental operational ranges. Relative deviations from linear calibration line for a horizontal wind speed instrument

The results of the investigations show that the deviations of cup-anemometers increase substantially when slope of terrain and turbulence increase, which are the conditions for complex terrain. It is therefore more important to be aware of the inadequacies of cup-anemometers when being used in complex terrain.

CONCLUSIONS

There seem to be three different demands for power curve measurements:

- power curve measurements for certification purposes
- site specific power curve measurements for verification of "guarantied power curves"
- verification of power performance of wind farms

When considering power curve measurements, it should be specified for which purpose the power curve is measured, and power curves for different purposes are not necessarily comparable.

The developments of the measurement procedures are getting more complex, and the requirements for the performers are substantially increasing. This might affect the "readability" of the more complex measurement procedures.

The power curves defined in the standards might be better defined. Additional definitions might be added if procedures for measurements of wind speed over the swept area of the rotor are successful. For wind farms in complex terrain the term power performance measurements might deviate from the traditional power curve measurement in homogeneous terrain.

Omitting the definition of the wind speed in measurements may account for 1.9% wind speed deviations at 20% turbulence intensity.

For power performance measurements, the vector-averaged wind speed seems to be the best definition of the measured wind speed.

In complex terrain the inadequacies of cup-anemometers become more important than in homogeneous terrain.

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POWER PERFORMANCE MEASUREMENTS IN COMPLEX TERRAIN

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ABSTRACT

During the last years the standardisation effort within the field of wind energy has been intensified. The main objective of the current research effort is the creation of technical background in order to facilitate the development of new or the extension of existing standards, recommendations or criteria on the issue of power performance measurements in complex terrain sites. This paper presents a review of the power performance measurement techniques for complex terrain WT operation..

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. Currently, several EU funded research projects as well as standardisation bodies are working on the different aspects of the issue.

The presented research effort intents to clarify the status of power performance verification and assessment and identify the future needs in terms of applications, research fields and standardisation actions, putting emphasis on the following items:

- *Power performance verification for wind turbines operating in complex terrain*. A significantly large amount of the most promising areas for wind energy exploitation are located in complex terrain. The topography characteristics along with the wind structure in those areas impose significant uncertainties in power performance verification. New procedures have been applied and verified, and by the aid of the future international or national standards the large scale integration into these areas will be strongly supported.
- *Assessment of the available international and national standards*. The urgency for the international standardisation bodies to encounter the issue is strong as the market needs are increasing.
- *Assessment of developed, applied and verified tools for WECS power performance*. Significant amount of experimental work has been done on the fields of power performance assessment, site calibration and site assessment. Procedures have been developed and tested whereas the needs for the use of sophisticated machinery is justified. Recent improvements in the field of simulation work reveal the potential of using analytic tools in assessment procedures.

The research effort regarded the following fields:

- assessment of site calibration techniques
- assessment of alternative site calibration techniques (nacelle cup anemometer on running machine)
- identification of parameters that affect the power performance
- assessment of the existing guidelines on power performance and identification of the drawbacks and their applicability for complex terrain measurements.

The conclusions drawn are based on the evaluation of the identified effect that complex terrain related parameters induce on power performance. Following the above evaluations the measuring practices, the calibration procedures as well as the uncertainty estimation methodologies have been assessed and final recommendations addressing the power performance in complex terrain are proposed.

2 STATE OF THE ART ON POWER PERFORMANCE MEASUREMENTS

The methodology for power curve measurements on wind turbines as well as extensive literature surveys are elaborated in various studies (Christensen C., 1986, Pedersen T.F., 1993, Van der Borg 1996). The following issues are prominent:

a) Topography effects on mean wind field. Topography variations induce strong effects on the mean wind field. By assessing the experimental and theoretical works on the issue it is clarified that the need of a method for estimating these effects is imperative when power performance in complex terrain is considered.

b) Effect of obstacles on mean wind field Extensive experimental and theoretical research has been performed on the operation of wind turbines within wakes. The assessment of the reported results gives a clear picture on the wake decay rate and supports the prescription of rules that would be applied for the avoidance of wake effects. The same apply for obstacles such as houses, vegetation etc. In all cases, atmospheric stability affects the wake decay and should be taken into account.

c) Site calibration Site calibration practices include modelling in wind tunnels, numerical modelling as well as field measurements. The latter may be performed either with a temporary meteorological mast prior to the wind turbine erection or with a mobile mast placed on the nacelle of the parked turbine. Wind tunnel modelling has been applied in a limited number of cases and its accuracy is assessed against open field measurements and numerical predictions. On the other hand, the utilisation of numerical models for site assessment and in some cases for site calibration is becoming popular (Glinou G., 1997). The models that can deal with the site calibration issue are: the *kinematic or mass consistent models* that are based on the solution of the continuity equation simulating inviscid flow fields, the *dynamic models* that are based on the solution of boundary layer equations and the *Navier-Stokes* equation solving models. Recently *hybrid models* have been introduced addressing the combination or nesting of different types of models. Evidently, depending on the underlying background theory each model presents specific possibilities and limitations. The wide use of the numerical models and the volume of the reported research allow the prescription of the basic prerequisites that a model should meet in order to be reliably used for site calibration purposes. The prerequisites may refer to 3D capabilities, turbulence modelling and stratification effects on one hand and applicability and cost effectiveness on the other. Field measurements by anemometer on a temporary meteorological mast in the place where the wind turbine under test is to be erected presents a solution that introduces the minimum amount of uncertainty; yet it lacks applicability in cases of already erected turbines. Experimental research has proved that certain aspects of the application of the method regarding measurement duration and wind direction sectoring may affect the reliability of the method. The use of a nacelle cup, mounted on a temporary mast on the turbine nacelle has been applied as an alternative procedure. Different nacelle cup positions have been proposed, aiming to minimise the nacelle blockage effect on one hand and the displacement from the hub on the other. In cases where the displacement from hub is large an estimation of the incoming wind shear increases the accuracy of the method.

d) Alternative power curve measurement procedure An alternative methodology for power measurements have been proposed recently known as nacelle anemometry. The relation between the average undisturbed wind speed at a meteorological mast and the average wind speed reading of the nacelle mounted anemometer is measured on a site and is assumed to be applicable for the power curve measurements of another turbine of the same make and model at another site. The applicability of the method is related with aspects such as turbine type, instrumentation and terrain type (Hinsch C., 1996, Antoniou I., 1997).

e) Power curve sensitivity to terrain characteristics Effects of turbulence, wind shear and stratification on the power performance are primarily theoretically and secondly experimentally investigated. The magnitude of the combined effect suggests that the recording of these parameters may be used for normalisation of the power curve to specific conditions.

f) Sensor characteristics The mean wind speed is in the majority of cases measured by a cup anemometer. Two phenomena of major importance are related to cup anemometer measurements namely anemometer over-speeding and sensitivity to inclined flow (Glocker S., 1997). Both phenomena may introduce a significant uncertainty in power measurements. Theoretical and experimental research results are available presenting a means for correcting the mean wind speed measurements, but none has yet been utilised in power performance measurements.

3 SITE CALIBRATION ASSESSMENT

Various methodologies involving physical or numerical modelling or field measurements have been utilised for site calibration. The IEC 1400-12 (1997) document gives the possibility to perform a site calibration by numerical modelling and by field measurements using a temporary meteorological mast. The minimum allowed associated uncertainties are related, in terms of percentage, to the maximum correction found in the total measurement sector. More information found in the literature is presented in the following paragraphs.

- Physical modelling may be utilised in various cases for site calibration. Numerous applications have been reported regarding either typical hill or ridge configurations or real sites (Veenhuizen S., 1987, Sierputowski 1995, McCarthy E., 1993).
- Numerical models have been developed and extensively used for site assessment purposes. State of the art reviews are found in the work of (Glinou G., 1997, Van der Borg, 1996). Three basic categories exist and these are: a) kinematic or mass consistent models (i.e NOABL, AIOLOS, WINDS e.t.c) b) dynamic models based on the solution of boundary layer equations (i.e WASP and MS3DJH) and c) full Navier-Stokes equations based models (typical applications are found in Tryfonopoulos D., 1989 and Bergeles G., 1996). Recently, hybrid models have been introduced allowing for the nesting of models with different spatial resolutions (i.e. WAsP/local scale with KAMM or HIRLAM / meso scale (Landberg L., 1996, Lalas D., 1994) and the combination of models with different principles (i.e WAsP with Navier Stokes solvers and mass consistent models with Navier- Stokes solvers). Specific applications for site calibration are

found in the works of (Hassan U., 1982, Sandstrom S., 1994, Watson R., 1994, Weng W., 1994 and Smedman A., 1996).

- Field measurements by anemometer placed on a temporary meteorological mast is the procedure recommended by the IEC 1400-12 (1997) document. A temporary mast is erected in the place of the wind turbine prior to its installation. The ratio between the average reference wind speed and the turbine hub is measured during a certain period. The practice of this procedure in terms of wind speed ranges that are considered, definition of wind direction sectors as well as minimum number of collected data are prescribed within the existing standard..
- Field measurements by anemometer on parked wind turbine is a procedure that overcomes the necessity of performing site calibration prior the turbine erection or after dismantling it. A cup anemometer is placed on the wind turbine nacelle, by means of a mobile mast, while the turbine is turned downwind. Applications of this procedure are found in the works of Jamieson N. (1988), Nielsen M. (1994) and Morfiadakis E. (1994) where the anemometer is positioned on a vertical boom (length 3 or 4m) attached to the rear end of the nacelle while the turbine rotor was turned downwind.

In this chapter the following techniques are experimentally assessed:

- site calibration with a hub height meteorological mast placed at the wind turbine location prior to machine erection
- site calibration with a mobile meteorological mast placed on the wind turbine nacelle, while the machine is at stand still and turned to downwind direction
- site calibration using the upwind rotor mean wind speed.

The results obtained from the application of the different site calibration procedures are presented and discussed focusing on the applicability and reliability of the techniques.

3.1 Experimental research on site calibration practices

3.1.1 Site calibration for WINCON 110XT

The anemometer used for the site calibration procedure was installed at 32.4m height at the location of the wind turbine, using a mobile meteorological mast erected on the nacelle of the wind turbine (Morfiadakis E., 1996c). Data was collected for a period of approximately 2 months. During this period the wind turbine was at stand-still, in the downwind position and the wind speed varied from 2m/s to 14m/s. Wind shear was estimated from measurements collected from the upwind erected masts. The wind speed at the turbine location and at hub height is estimated from the nacelle cup measurement after correction for wind shear. The correction factors to be applied to the measured reference wind speed were estimated by applying linear regression, with no intercept, of the estimated wind speed values at wind turbine location at hub height against the measured reference wind speed. The use of the rotor mean wind speed as the reference value for power curve estimation was also examined, by means of the upwind wind speed measurements performed on the three masts. AEP estimations for three cases, namely without correction, rotor mean reference and nacelle cup correction are presented in table 1.

AEP estimation with corrected reference wind speed			
Mean annual wind speed [m/s]	Annual Energy Production [MWh] (Uncertainty)		
	Wind direction sector		
	330°-30°	350°-10°	10°-30°
5	112,6 (4,11)	111,93 (4,12)	113.89 (4,12)
7	264,3 (7,13)	263.30 (7,15)	265,97 (7,23)
9	390,5 (8,38)	389.55 (8,40)	392,10 (8,66)
11	459,2 (8,50)	458,50 (8,49)	460,48 (8,92
AEP estimation without correction for reference wind speed			
Mean annual wind speed [m/s]	Annual Energy Production [MWh] (Uncertainty)		
	Wind direction sector		
	330°-30°	350°-10°	10°-30°
5	116,22 (8,35)	115,32 (8,56)	117,21 (7,85)
7	270,00 (14,49)	268.86 (14,68)	271,26 (14,37)
9	396,36 (16,59)	395.07 (16,69)	397,40 (17,24)
11	464,47 (16,32)	462,98 (16,34)	465,20 (17,56)
AEP estimation with rotor mean reference wind speed			
Mean annual wind speed [m/s]	Annual Energy Production [MWh] (Uncertainty)		
	Wind direction sector		
	330°-30°	350°-10°	10°-30°
5	117,3 (8,57)	116,3 (8,54)	118,6 (8,57)
7	271,8 (14,70)	270,6 (14,67)	273,6 (14,83)
9	398,4 (16,79)	397,2 (16,75)	400,4 (17,20)
11	466,5 (16,54)	465,4 (16,47)	468,3 (17,18)

Table 1. Annual energy production estimations for W110XT.

The main conclusions are the following:

- due to the small correction factors the differences between AEP estimations based either on corrected or on uncorrected data are less than 3%
- the use of the rotor averaged wind speed leads to estimations close to those without any correction; this is attributed to the fact that wind shear on the turbine location is flat and therefore the rotor centre wind speed value is close to the averaged one
- insignificant differences, less that 2% were found to exist for AEP estimations for different wind direction sectors

3.1.2 Site calibration for VESTAS V27

The anemometer used for the site calibration procedure was installed at 40m height at the location of the wind turbine, using a mobile meteorological mast erected on the nacelle of the wind turbine (Morfiadakis E., 1994, 1996b). The correlation coefficient calculated for the anemometers at 40m, on the reference mast and the nacelle, was applied also to the anemometers mounted at 31.5m height, under the assumption that wind shear deformations are not sensitive to wind direction. Using a 5-15m/s wind speed bin for the whole wind direction sector the average and the maximum correction factor was found equal to 1.015 for the used wind direction sector. The reference mast was erected side on the side of the turbine at 1.6D distance. AEP estimations for two cases, namely nacelle corrected and without correction at upwind reference are presented in table 2.

AEP estimation with corrected reference wind speed			
Mean annual wind speed [m/s]	Annual Energy Production [MWh] (Uncertainty)		
	Wind direction sector		
	345°-15°	345°-360°	0°-15°
5	272,81 (10,95)	270,98 (10,95)	295,69 (11,06)
7	603,55 (17,98)	603,58 (18,12)	619,78 (17,98)
9	857,19 (20,54)	859,54 (20,76)	867,49 (20,48)
11	964,59 (20,09)	968,17 (20,32)	971,06 (20,02)
AEP estimation without correction for reference wind speed			
Mean annual wind speed [m/s]	Annual Energy Production [MWh] (Uncertainty)		
	Wind direction sector		
	345°-15°	345°-360°	0°-15°
5	303,63 (15,88)	281,69 (15,95)	307,18 (15,96)
7	634,49 (25,86)	620,24 (26,19)	637,14 (25,76)
9	884,78 (28,83)	876,68 (29,35)	885,86 (28,65)
11	987,89 (27,56)	983,45 (28,14)	987,92 (27,38)

Table 2. Annual energy production estimations for V27.

The main observations are the following:

- the differences between AEP estimations based either on corrected or on uncorrected data are less than 5%
- the reference mast selection (erected side to the turbine) led to small correction factor; if the upwind mast was used the resulting AEP differences would exceed 30%
- the differences encountered in AEP estimations for different wind direction sectors indicate the need for using correction factors for narrower wind direction sectors; this was apparent for the side reference mast whereas the differences when using the upwind mast were lesser

3.1.3 Site calibration for NORDTANK 500/37

Prior to the installation of the wind turbine a meteorological mast was erected at the location of the WT (Morfiadakis E., 1996a). The mast was equipped with cups and vanes at three heights, i.e. 16.5m, 35m and 39m. Data was collected for a period of 13 days (15 to 28/12/1994). The measured wind speed at the wt location at hub height was compared with the corresponding measurement from the reference mast. The correction factors were estimated using 10° wind direction bins, for the wind speed range of 5-15m/s. In addition, a brief site calibration with a mobile mast placed on the wt nacelle while the machine was at stand still has been performed. Wind speed measurements were collected for a short period of two days from the nacelle cup as well as from the reference mast. With the applied technique the correlation between the wind speed at the wind turbine location at a height of 43.5m agl and the one measured at the hub height (35m agl) at the reference mast was measured. The calculation of the correlation at the same height, was feasible through the wind shear estimation. In figure 1 the comparison of the results from the two site calibration techniques is presented (Mouzakis F., 1997a).

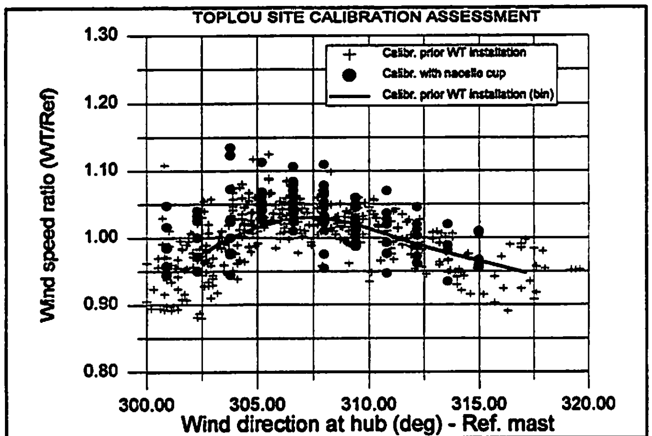

Figure 1. Comparison of calibration practices for NTK500/37.

Although applied for a short period the alternative site calibration technique yields results which are in fairly good agreement with these of the conventional site calibration. The variation of the wind speed ratio with wind direction, observed within a narrow sector of 15°, is captured satisfactorily by the nacelle anemometer.

3.2 Conclusions

Different site calibration techniques have been experimentally assessed. When AEP estimation was used as a tool for the assessment all the differences encountered were well within the uncertainty limits of the measurements. The site calibration technique using a mobile meteorological mast placed on the wt nacelle while the machine is at stand still when applied on a NTK500kW at Toplou yielded results which were in fairly good agreement with these of the conventional site calibration. Power curve estimations based on rotor mean wind speed do not necessarily lead to higher accuracy; especially in complex terrain cases where uniform wind profile shapes are common.

The main conclusions were:

- the position of the reference masts are quite suitable as the mean corrections applied to reference wind speeds were limited (up to 3%)
- the maximum observed speed-up within a wind direction bin reached 9% to 11%
- the only case where significant corrections would have been applied is in the case of V27 operating at Andros site, if the upwind mast is chosen as the reference one (the mean bin corrections well exceed 5%)
- the site calibration technique using a mobile meteorological mast placed on the wt nacelle while the machine is at stand still was validated and fairly good agreement was found with these of the conventional site calibration
- power curve estimations based on rotor mean wind speed do not necessarily lead to higher accuracy; especially in complex terrain cases where uniform wind profile shapes are common.
- although the wind speed corrections are of limited magnitude the turbulent characteristics may present significant variation between the reference point and the turbine location

The experience from the extensive application of site calibration techniques leads to the following advises for good practice:

- in cases where the site calibration can be performed without the presence of the wind turbine the use of a temporary mast should be preferred
- flow distortion correction factors should be established for each wind direction sector, by regressing the wind data generated from the above procedure, (on site measurements prior to the installation of wt or nacelle measurements and assumed wind velocity gradient) referring to the hub height wind speed at wt location, on the measured wind data from the reference mast
- alternative site calibration of a test site may well be performed by placing an anemometer above the nacelle of the wt at a separation distance carefully selected with respect to the nacelle cross section so that the disturbance caused by the presence of it does not exceed 1% of the free stream wind speed. This should be verified by means of physical or theoretical modelling of the flow field around the nacelle of the wt. Any additional corrections which are applied to account for the spatial and vertical variation of the wind speed measured at the wt location and the wind speed driving the wt have to be reported clearly and the associated uncertainty has to be taken into account.

4 EXPERIMENTAL RESEARCH ON ALTERNATIVE METHODS FOR POWER PERFORMANCE ASSESSMENT

From the existing experimental research, that followed the recommendations of Pedersen T. (1994) regarding medium and large wind turbines (Antoniou I., 1997, Hinsch C., 1996) the following conclusions were drawn:

- the methodology is feasible presenting significant advantages regarding its applicability
- the relation between the mast anemometer and the nacelle anemometer may be approximated either by a linear model or by a higher order polynomial
- the factors that should by unchanged in order to maintain the validity of the calibration formula are the wind turbine rotor settings, the yaw control strategy, the nacelle anemometer position and the terrain type
- change in upwind terrain characteristics may inhibit erroneous results
- the method presents significant advantages for application on wind turbines operating within wind farms.

The methodology is furthermore experimentally investigated by its application on a 110kW stall regulated wind turbine operating at complex terrain.

4.1 Nacelle cup anemometry on WINCON 110XT

A cup anemometer was placed on the nacelle according to the practice found in Pedersen T. (1994). The horizontal distance of the cup from the blade root was 2.5 times the blade root diameter while the vertical distance from the nacelle was set to 1m. The experiment lasted one month (Mouzakis F., 1997b). In order to assess the performance of nacelle anemometer technique the whole data set was divided to two wind direction sectors, i.e. 315°-360° and 0°-45°. Moreover, the correlation of nacelle cup measurement against the reference cup were estimated for both sectors. Finally, the power curves for each sector using the corrected nacelle cup measurements from the correlation provided from the other sector measurements are drawn. The assessment of the site calibration technique was performed via annual energy production estimations. The AEP estimations were made for the power curves calculated from the following data sets and the results are given in table 3:

- total data set (i.e. sector 315°-45°)
- western directions (i.e. sector 315°-360°), reference cup measurements
- eastern directions (i.e. sector 0°-45°), reference cup measurements
- western directions (i.e. sector 315°-360°), nacelle cup (correlation from eastern directions)
- eastern directions (i.e. sector 0°-45°), nacelle cup (correlation from western directions)

Although the AEP estimations are almost identical for the three cases based on the reference mast, differences are depicted in the nacelle cup based estimations. The differences are attributed to the statistical error induced to the power curve calculations from the nacelle cup correlation as well as to the sensitivity of the correlation to parameters that are not seen by the wind turbine as far as the mean power output is regarded.

	AEP estimation		
Method/Sector	6m/s	8m/s	10m/s
Reference wind speed (reference case) 315°-360°	184.1	260.5	271.1
Reference wind speed, 0°-45°	184.8	260.8	271.3
Reference wind speed, 315°-45°	184.3	260.4	270.9
Nacelle cup (calibration from 0°-45°) 315°-360°	187.7	264.3	273.9
Nacelle cup (calibration from 315°-360°) 0°-45°	180.9	254.9	264.9

Table 3. AEP estimations for different wind direction sectors using nacelle cup calibration.

The main conclusions are:

- although the AEP estimations are almost identical for the three cases based on the reference mast, differences are depicted in the nacelle cup based estimations
- the differences are attributed to the statistical error induced to the power curve calculations from the nacelle cup correlation as well as to the sensitivity of the correlation to parameters that are not seen by the wind turbine as far as the mean power output is regarded

5 PARAMETER IDENTIFICATION OF WIND TURBINE POWER PERFORMANCE

The scope of the parameter identification procedure is to identify the statistically significant parameters and to quantify their composed effect on power performance. The parameter identification procedure was applied for V27, W110XT and NTK500/37 addressing the field of power performance evaluation of wind turbines operating at complex terrain. The power performance evaluation was attained by regarding the basic statistics of power measurements namely the mean value as well as the standard deviation within each 10 minute measuring session. In the case of the pitch regulated machine, the response of the power control system was also examined. The utilised analytic tool is based on multivariate regression analysis with a backward parameter elimination technique in order to account for the statistically insignificant parameters. The proposed analytic tool is considered as a highly promising engineering method for reliable and efficient parameter identification tasks based on experimental results.

The wind field characteristics of complex terrain are extensively investigated in Glinou G. (1996). Qualitatively speaking the main effects that complex terrain induces to wind turbine power performance are related to the uncertainty of wind speed measurement (i.e. wind inclination effect), the uncertainty of determination of reference wind speed (i.e. large spatial variation of wind speed) as well as the effect of turbulence, shear deformations and wind speed distribution to the response of the machine and particularly to the control systems.

In the following paragraphs an extensive presentation of the parameter identification procedure is given. In the sequel, the application of the procedure to three large power performance measurement campaigns is presented and finally the main conclusions are drawn.

5.1 Parameter identification practice

The scope of a parameter identification procedure is to identify the statistically significant parameters and to quantify their composed effect. Multivariate regression analysis methods present significant advantages, under the restriction of the availability of large amounts of data, when the goal is to capture the effect of different parameters that are not supposed and most importantly do not need to be uncorrelated. The topics that are discussed herein are related to the regression analysis application and assessment as well as to the parameter identification procedure. Detailed description of the method and sample applications are found in the work of Mouzakis F. (1996b).

Multivariate regression analysis

The used multivariate regression analysis is based on least square fitting process as a maximum likehood estimator of the fitted parameters (Kleinbaum K., 1985). It is assumed that the measurement errors are independent and normally distributed with constant standard deviation.

The scope of the regression is the estimation of the coefficients (a_k,k=1,M), for the expression of the dependent variable (y) as follows:

$$y(x_i) = \sum_{k=1}^{M} a_k X_k(x_i) + E(x_i)\ ,\ i=1,N \qquad (1)$$

where $X_k(x_i)$ is the value of the k^{th} independent variable at point x_i and $E(x_i)$ is the associated error at the same point. Chi-square fitting is applied as the weighted least square fitting process, in which the magnitude χ^2 defined as:

$$\chi^2 = \sum_{i=1}^{N}\left(\frac{y_i-\hat{y}_i}{\sigma_i}\right)^2\ ,\ \hat{y}_i = \sum_{k=1}^{M} a_k X_k(x_i) \qquad (2)$$

is minimized. The magnitude σ_i presents the measurement standard error at point ($y(x_i)$,x_i). If the measurement errors are not known (as in the present practice) they are all set equal to unity. The number (n=N-M) represents the fitting degrees of freedom.

The minimum of χ^2 occurs where its derivatives with respect to parameters (a_k,k=1,M) vanish. The resulting linear equations are solved by the Gauss-Jordan elimination technique, yielding the coefficients (a_j,j=1,M):

$$a_j = \sum_{k=1}^{M} C_{jk}\left[\sum_{i=1}^{N}\frac{y_i X_k(x_i)}{\sigma_i^2}\right]\ ,\ C_{jk} = \left[\sum_{i=1}^{N}\frac{X_j(x_i)X_k(x_i)}{\sigma_i^2}\right]_{jk}^{-1}\ ,\ j=1,M \qquad (3)$$

where the standard deviation related to the estimate of a_j is given by the equation:

$$\sigma(a_j) = \sqrt{\left(\sum_{i=1}^{N}\sigma_i^2\left(\frac{\partial a_j}{\partial y_i}\right)^2\right)} = \sqrt{C_{jj}} \qquad (4)$$

Assessment of the accuracy of the multivariate regression

For the assessment of the accuracy of the regression analysis, the following magnitudes were considered:

a) total sum of squares SSY, sum of squares due to error SSE, sample squared correlation coefficient R^2 as well as fitting standard deviation σ_y, defined as follows:

$$SSY = \sum_{i=1}^{N}(y_i - y_{mean})^2\ ,\ SSE = \sum_{i=1}^{N}(y_i-\hat{y}_i)^2\ ,\ R^2 = \frac{SSY-SSE}{SSY}\ ,\ \sigma_{\hat{y}} = \sqrt{\frac{\sum_{i=1}^{N}(y_i-\hat{y}_i)^2}{N-M}} \qquad (5)$$

b) F-test statistic, describing the hypothesis "H0 : there is no significant overall regression using the M independent variables", is defined as follows:

$$F = \frac{SSY - SSE}{SSE}\left(\frac{N-M}{M-1}\right) \quad (6)$$

Consequently the p-value for the above defined F-test is calculated from Fisher's F sampling distribution with M-1 and N-M degrees of freedom ($p_{F/M-1,N-M}$). For the quantitative assessment of the relation of the dependent variable on each of the independent parameters X_k, various magnitudes were considered, namely the regression coefficients a_k themselves, the relative per sigma dependence coefficient S_k or the t-test statistic for each parameter.
The relative per sigma dependence or dependence coefficient S_k, is defined as:

$$S_k = a_k \frac{\sigma_{X_k}}{y_{mean}}, \quad \sigma_{X_k} = \sqrt{\frac{\sum_{i=1}^{N}\left(X_k(x_i) - \overline{X_k}\right)^2}{N-1}} \quad (7)$$

The magnitude S_k represents the relative change of the dependent variable induced by the increase of the value of parameter X_k by its standard deviation σ_{Xt}, within the regression domain. Assuming that the probability of that change is expected to be comparable for all independent variables, the relativistic assessment of the effect of each variable X_k on y can be attained. Although the above assumption is not valid in cases where the distribution of X_k, within the regression domain, differs significantly from normal, still the magnitude S_k offers a valuable means for weighting the dependence of each X_k on the dependent magnitude. The t-test statistic, describing the hypothesis "H_0 : the regression coefficient a_k is zero", is defined as $t=a_k/\sigma(a_k)$ and consequently the p-value for the above defined t-test is calculated from Student's t sampling distribution with N-M degrees of freedom ($p_{t/N-M}$).

Parameter identification procedure
The introduced procedure comprises the following phases:

I. Identification of potential causative processes: The deterministic wind characteristics, wind turbulence and the wind speed distribution are regarded as the main causative processes as far as wind turbine power performance is considered.
II. Determination of candidate independent variables for each process: Upon recognition of the potential causative processes, a set of independent variables are selected in order to describe each process. The term independent is used according to the regression analysis nomenclature and does not imply that the predictive variables should be uncorrelated. For the present application, for instance, the deterministic wind characteristics are described by the mean wind speed, the air density, the shape of the wind shear and the wind mean inclination.
III. Application of the full model: The regression analysis is performed for the selected full model as described in the above paragraphs.
IV. Iterative application of evaluation criteria and model reforming: The evaluation criterion is based on the p-values of the t-ratios of each independent variable. Large values for the p-value indicate that the rejection of the hypothesis "H_0: the regression coefficient a_k is zero" is questionable, and consequently the parameter is rejected from the model and the regression analysis is performed again. The rejection threshold, set to 5%, is defined after numerical experimentation.
V. Final selection and assessment: After the completion of the iterative process, the assessment of the regression findings is attained through descriptive magnitudes namely the dependence coefficients.

5.2 Parameter identification for power performance assessment

Three different power performance measurement campaigns were used for applying the parameter identification procedure described in the previous paragraphs. The campaigns regarded measurements performed on VESTAS V27/225kW, operating at Andros site, on WINCON 110XT, operating at C.R.E.S. test station and NORDTANK NT500/37, operating at Toplou site in Crete (Mouzakis F., 1997c). In tables 4 to 6 the variability of the selected parameters that comprise the basic set are presented by means of their mean value and standard deviation within the regression domain. It must be noted that the standard deviation comprises the increment upon which the response, in percentage, of the dependent variable is estimated. In figures 3 to 6 the dependence coefficient charts for the three applications are given.

For the case of the pitch controlled wind turbine V27 the following are observed (figure 3):
For the mean power output:

- the predominant parameter for all wind speed ranges is the mean wind speed; the results follow the power curve slope
- the standard deviation of wind speed induces a positive effect under 13m/s and an adverse effect for higher wind speed ranges
- the wind direction standard deviation has an adverse effect more pronounced under 13m/s
- wind speed distribution skewness has a limited positive effect for the upper ranges
- air density effect is insignificant due to the small variation of the parameter

For the power standard deviation:

- the predominant parameters for all wind speed ranges are the turbulent components namely the standard deviations of wind speed and wind direction
- wind speed effect is positive in lower wind speeds and adverse in higher ranges
- wind speed distribution skewness has a significant adverse effect in high wind speed ranges
- the limited air density positive effect is present within the middle wind speed ranges

For the mean pitch angle (control system response):
- the predominant parameter for all wind speed ranges is the mean wind speed
- the standard deviation of wind speed and wind skewness induce a positive effect; the opposite holds for the standard deviation of wind direction
- the turbulence length scale induces an adverse effect in the 11-13m/s range

For the standard deviation of pitch angle (control system response):
- the predominant parameters for all wind speed ranges are the mean and the standard deviation of wind speed
- the positive effects of air density, standard deviation of wind direction and wind speed distribution skewness are detected in nearly all ranges
- the turbulence length scale induces an adverse effect in middle wind speed ranges

Wind speed bin	U=6-8m/s		U=8-11m/s		U=11-13m/s		U=13-16m/s	
Parameter	mean	SDV	mean	SDV	mean	SDV	mean	SDV
Mean wind speed - U (m/s)	7.1	0.57	9.53	0.83	12.0	0.578	14.1	0.84
Air density - ρ (kgm^{-3})	1.15	0.008	1.15	0.007	1.15	0.007	1.15	0.007
Wind shear exponent - α	0.04	0.049	0.048	0.047	0.043	0.038	0.039	0.033
SDV wind speed - σ_u (m/s)	0.785	0.192	0.964	0.178	1.21	0.221	1.42	0.302
SDV wind direction - σ_φ (deg)	6.69	2.29	5.98	1.48	5.67	1.2	5.33	0.986
Wind speed skewness - U_{sk}	-0.045	0.253	-0.046	0.268	-0.063	0.292	-0.136	0.286
Wind speed kurtosis - U_{ku}	-0.192	0.366	-0.123	0.404	-0.157	0.443	-0.22	0.346
Turbulent length scale - L_u (m)	65.29	32.31	58.37	25.37	55.2	21.8	57.6	20.0

Table 4. Independent parameter variation for the V27 data base.

For the case of the stall controlled W110XT wind turbine the following are the main observations (figure 4):

For the mean power output:
- the predominant parameter for all wind speed ranges is the mean wind speed; the results follow the power curve slope
- air density positive effect is captured for all ranges; this is due to the fact that the parameter values covered a significant domain within the data base
- the standard deviations of the wind speed components are inducing an adverse effect for all wind speed ranges
- wind speed inclination induces an adverse effect that is present for all wind speed ranges

For the power standard deviation:
- the predominant parameter for all wind speed ranges is the standard deviation of longitudinal wind speed component
- wind speed effect is positive in lower wind speeds and adverse in the higher ranges
- standard deviation of the vertical wind speed component is significant and positive for the upper ranges whereas the lateral component effect is present in the higher wind speed range
- wind inclination effect is positive and pronounced in higher wind speed ranges whereas wind shear effect is insignificant
- air density effect is positive in all ranges
- wind speed distribution estimators have adverse effect; skewness effect is pronounced in higher wind speed ranges

For the case of the stall controlled NTK500/37 wind turbine V27 the following are observed (figure 5):

For the mean power output:
- the predominant parameter for all wind speed ranges is the mean wind speed; the results follow the power curve slope
- the longitudinal component of turbulence induces a significant positive effect under 11m/s
- the wind direction standard deviation has an adverse effect more pronounced under 11m/s
- wind speed distribution skewness has a positive effect pronounced in the lower wind speed ranges
- the adverse effect of wind shear is significant in the lower wind speed range
- air density effect is insignificant
- turbulent length scale effect is limited and adverse

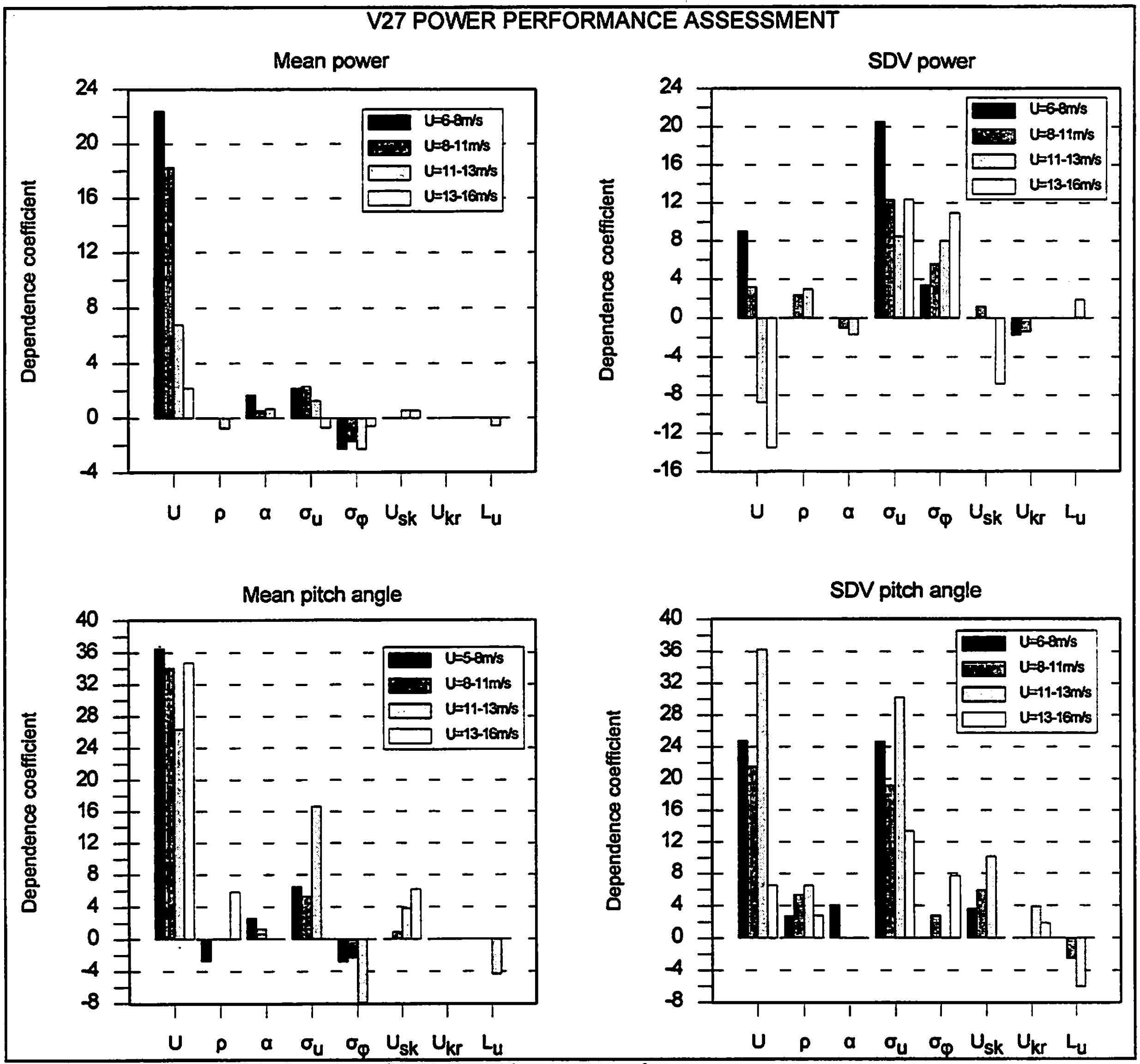

Figure 2. Dependence coefficient charts for V27 at Andros power performance.

Wind speed bin	U=6-8m/s		U=8-11m/s		U=11-13m/s		U=13-16m/s	
Parameter	mean	SDV	mean	SDV	mean	SDV	mean	SDV
Mean wind speed - U (m/s)	7.23	0.514	9.33	0.82	11.9	0.59	14.2	0.82
Air density - ρ (kgm^{-3})	1.19	0.027	1.19	0.029	1.18	0.020	1.19	0.018
Wind shear exponent - α	0.029	0.034	0.023	0.028	0.024	0.027	0.03	0.024
Wind inclination - θ (deg)	3.45	1.38	3.49	1.26	3.14	0.984	3.5	0.90
SDV wind speed - σ_u (m/s)	0.97	0.196	1.33	0.27	1.64	0.299	2.07	0.397
Lateral turbulence component σ_v	0.95	0.25	1.21	0.28	1.40	0.30	1.69	0.34
Vertical turbulence component σ_w	0.78	0.20	1.01	0.22	1.16	0.19	1.39	0.24
Wind speed skewness - U_{sk}	-0.087	0.289	-0.13	0.30	-0.255	0.295	-0.20	0.295
Wind speed kurtosis - U_{ku}	-0.054	0.53	-0.071	0.47	-0.025	0.466	-0.063	0.448
Turbulent length scale - L_u (m)	35.7	16.6	40.1	16.3	46.4	18.4	50.6	17.9

Table 5. Independent parameter variation for the W110XT data base.

For the power standard deviation:

- the predominant parameters for all wind speed ranges are the turbulent components namely the standard deviations of wind speed and wind direction
- wind speed effect is positive in lower wind speeds and adverse in higher ranges
- wind speed distribution skewness effect is positive for the lower ranges whereas adverse for the high range
- the air density effect is positive in 8-11m/s range and adverse in the high wind range

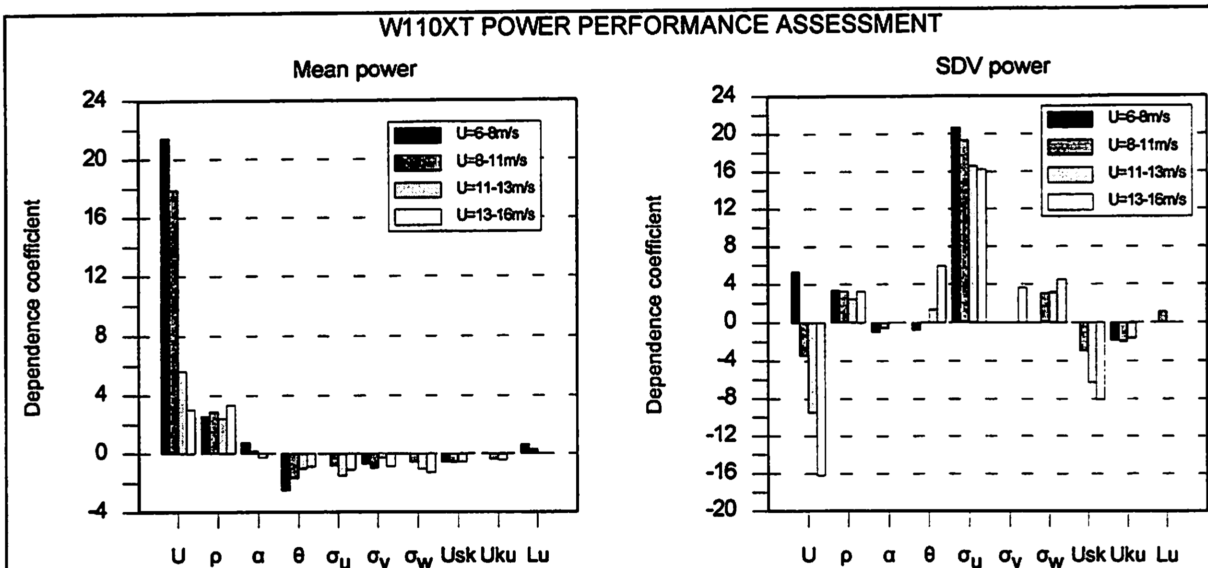

Figure 3. Dependence coefficient charts for W110XT at Lavrio power performance.

5.3 Conclusions

An analytic method is introduced covering parameter identification tasks. The developed tool is based on multivariate regression analysis with a backward parameter elimination technique in order to count for the statistically insignificant parameters. The method is applied for the parameter identification of the power performance of wind turbines operating in complex terrain and the results support that it comprises a promising method for reliable and efficient parameter identification tasks based on experimental results. 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 captured and quantified. It was revealed 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 results of the parameter identification also reveal the inefficiencies of the present standardisation documents that are related to complex terrain. It is concluded that the 3D structure of mean wind speed and turbulence should be reported and optionally introduced in the correction procedures by the application of the proposed method.

Wind speed bin	U=6-8m/s		U=8-11m/s		U=11-13m/s		U=13-16m/s	
Parameter	mean	SDV	mean	SDV	mean	SDV	mean	SDV
Mean wind speed - U (m/s)	6.97	0.59	9.41	0.845	12.0	0.587	14.7	0.85
Air density - ρ (kgm^{-3})	1.23	0.009	1.23	0.007	1.23	0.009	1.23	0.011
Wind shear exponent - α	-0.017	0.019	-0.015	0.016	-0.019	0.011	-0.024	0.009
SDV wind speed - σ_u (m/s)	0.739	0.219	1.06	0.273	1.43	0.234	1.76	2.47
SDV wind direction - σ_φ (deg)	5.56	2.14	6.25	1.92	6.22	1.37	6.19	0.99
Wind speed skewness - U_{sk}	0.094	0.315	-0.053	0.269	-0.026	0.26	-0.039	0.22
Wind speed kurtosis - U_{ku}	0.388	1.22	-0.152	0.498	-0.343	0.299	-0.42	0.27
Turbulent length scale - L_u (m)	29.9	14.1	36.1	18.6	45.2	21.2	50.0	21.2

Table 6. Independent parameter variation for the NTK500/37 data base.

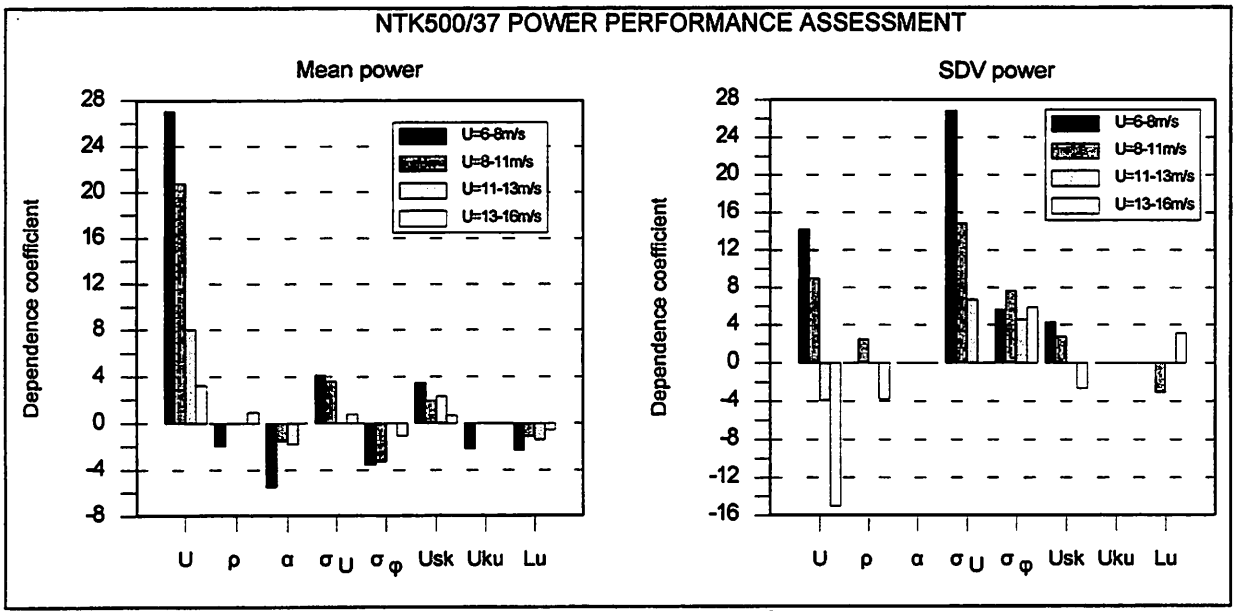

Figure 4. Dependence coefficient charts for NTK500/37 at Toplou power performance.

6 ASSESSMENT OF EXISTING GUIDELINES AND TECHNICAL BACKGROUND IN RELATION TO COMPLEX TERRAIN

The assessment is focused on the recommendations of IEC 1400-12 (1997). Critical points, related to site calibration and uncertainty estimation procedures, were identified. Reviewing the main effects that complex terrain induces to power performance the following are noted:

- uncertainty of determination of reference wind speed (i.e. large spatial variation of wind speed)
- uncertainty of wind speed measurement via cup anemometers (i.e. wind inclination effect, anemometer overspeeding effect)
- effect of turbulence, shear deformations and wind speed distribution
- response of control systems

The critical points on the existing recommendations in relation to complex terrain are the following:

A. Wind speed measurements
  - wind inclination due to upwind terrain
  - reporting 3D, wind shear and turbulence characteristics

B. Site calibration techniques application and assessment
  - site calibration prior to turbine installation (wind direction sector range, duration etc.)
  - description of alternative site calibration technique for cases where the wind turbine is already erected
  - uncertainty estimation

C. Response of wind turbine
  - the response of the control systems (i.e. yaw, pitch or rotational speed)

D. Contractual aspects
  - determination of accuracy level of verification and assessment procedures
  - wind farms

The developed technical background regards the following issues:

- Site characterisation
- Wind speed measurements
  - definition of reference wind speed (i.e. normal or longitudinal wind speed component)
  - utilisation of 3D wind speed measuring devices or compensation for inclined wind speed and/or cup overspeeding
  - reporting of 3D mean as well as stochastic wind speed characteristics
- Site calibration application and assessment
  - define rules of application of prior WT installation site calibration that take into account complex terrain characteristics (i.e. direction sectors, duration etc.)
  - definition of the framework of application of alternative site calibration technique for already erected wind turbines
  - utilisation of a suitable uncertainty estimation procedure

- Extended normalisation of power performance measurements including all measured site related parameters
- Measurement and reporting of wind turbine control system response

ACKNOWLEDGMENTS

The authors wish to thank EU and GSRT for funding the projects within the framework of which the presented measurements and analyses were performed as well as to the European Wind Energy Institutes that have participated. Thanks are also given for PPC for providing the wind turbines for measurements as well as to the CRES engineering and technical stuff for their contribution to the experiments.

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Experience with Power Performance Measurements in the US Wind Turbine Verification Program

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IEA Experts Meeting on Power Performance Measurements

Centre for Renewable Energy Sources
Athens, Greece

December 4-5, 1997

BACKGROUND

In 1992, the Electric Power Research Institute (EPRI) and the US Department of Energy (DOE) initiated the Utility Wind Turbine Verification Program (TVP). The goals of the program are to help electric utility companies gain field experience with wind power, evaluate prototype advanced wind turbines at several US sites, and transfer the experience to the wind power community.

The first wind project to be implemented under the TVP program is a 6 MW project owned by Central & South West (CSW) and installed at a site in the Davis Mountains near Fort Davis in West Texas. The project consists of 12 500 kW wind turbines. Plant construction and start-up occurred in 1995 and turbine acceptance testing was completed in July 1996.

The second project to be implemented under the TVP program is a 6 MW project owned by Green Mountain Power (GMP) and installed in a heavily forested ridgeline in Southern Vermont near the town of Searsburg. The project consists of 11 500-kW turbines and it began operating in July 1997.

In 1997, DOE and EPRI selected five more utility wind projects to be implemented under the TVP program. Two additional utility wind projects were also incorporated into the TVP as "associate projects" in 1997. These projects receive limited funding from the program but benefit from the information exchange and technical assistance. In return, the program sponsors receive performance data and other valuable information. Figure 1 shows the location of each of the wind projects included in the TVP program.

Figure 1

Distributed Wind Generation - TVP Phase III

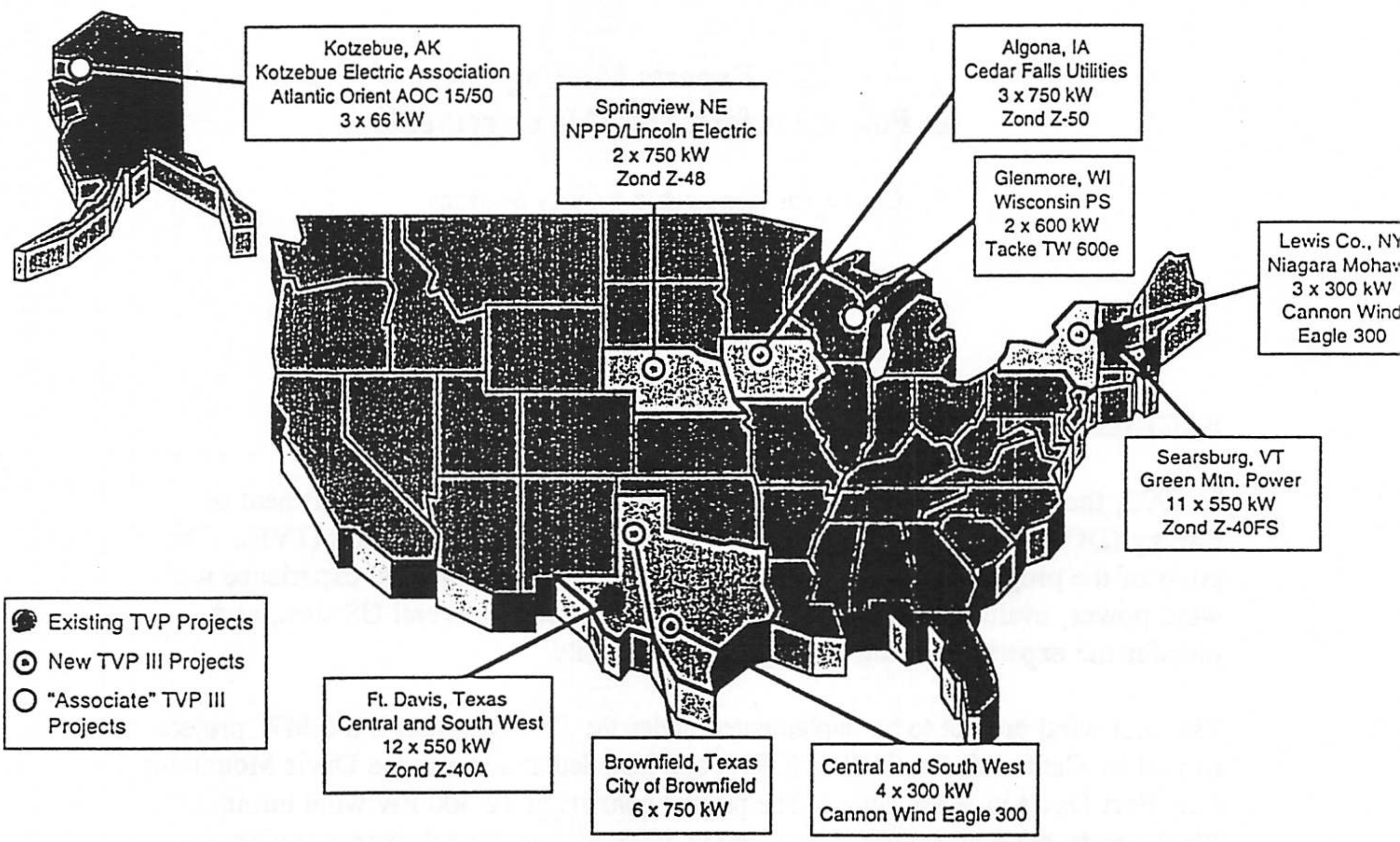

FIGURE 1.

Global Energy Concepts (GEC) is a private consulting company that serves as the technical support contractor for the TVP program.

EXPERIENCE TO DATE

One of the specific objectives of the TVP is to verify the performance, reliability, maintainability, and cost of new wind turbine designs and system components in a commercial utility environment. At the first TVP project (CSW), the responsibility for power performance testing was left to the turbine vendor and the utility. Figure 2 is a topographic map that shows the turbine and met tower locations at the CSW site. As shown in the figure, the project is located in complex terrain.

Both the utility and vendor collected data from sensors mounted on a boom extending upwind from the test turbine nose cone in an attempt to develop a site correlation between the met tower and the turbine. They received poor results due to the impact of the nacelle on the wind flow.

As an alternative, both parties agreed to install sensors on a boom extending from the turbine's lattice tower at a height of 30 meters (the hub height of the turbine is 40 meters) to develop a correlation with the 30 meter sensors on the met tower. For analysis purposes, the wind shear was assumed to be the same as measured at the met tower. Although the inaccuracies of this approach were acknowledged by the participants, it represented an acceptable compromise in terms of the cost and resources both parties were will to commit to the process.

Because of the difficulties in conducting power performance testing at the CSW site, the TVP program strongly recommended that GMP conduct site calibration work prior to the turbine installation. This project is also located in very complex terrain. Unfortunately, the project construction schedule did not allow sufficient time to conduct this activity. Due to severe winter weather, it was not possible to delay the schedule to accommodate this testing. GMP did install an anemometer on the turbine tower and collect data for a period of several weeks before the turbine nacelle was installed; however, the winds were fairly low during this period. Additional plans for power curve testing are currently under consideration.

FUTURE PLANS

In response to the experience at the first two projects, the TVP is formulating plans to conduct performance testing for the host utilities, in accordance with the IEC standards, on all the new TVP sites to ensure a consistent methodology and the documentation of results. The TVP projects offer an opportunity to collect test data from a variety of different turbines installed in different climates and topographic conditions. Such testing activities will provide a trial of the analysis procedures and techniques in the IEC standard as well as providing an opportunity to compare the results of alternate approaches to performance testing that may be proposed.

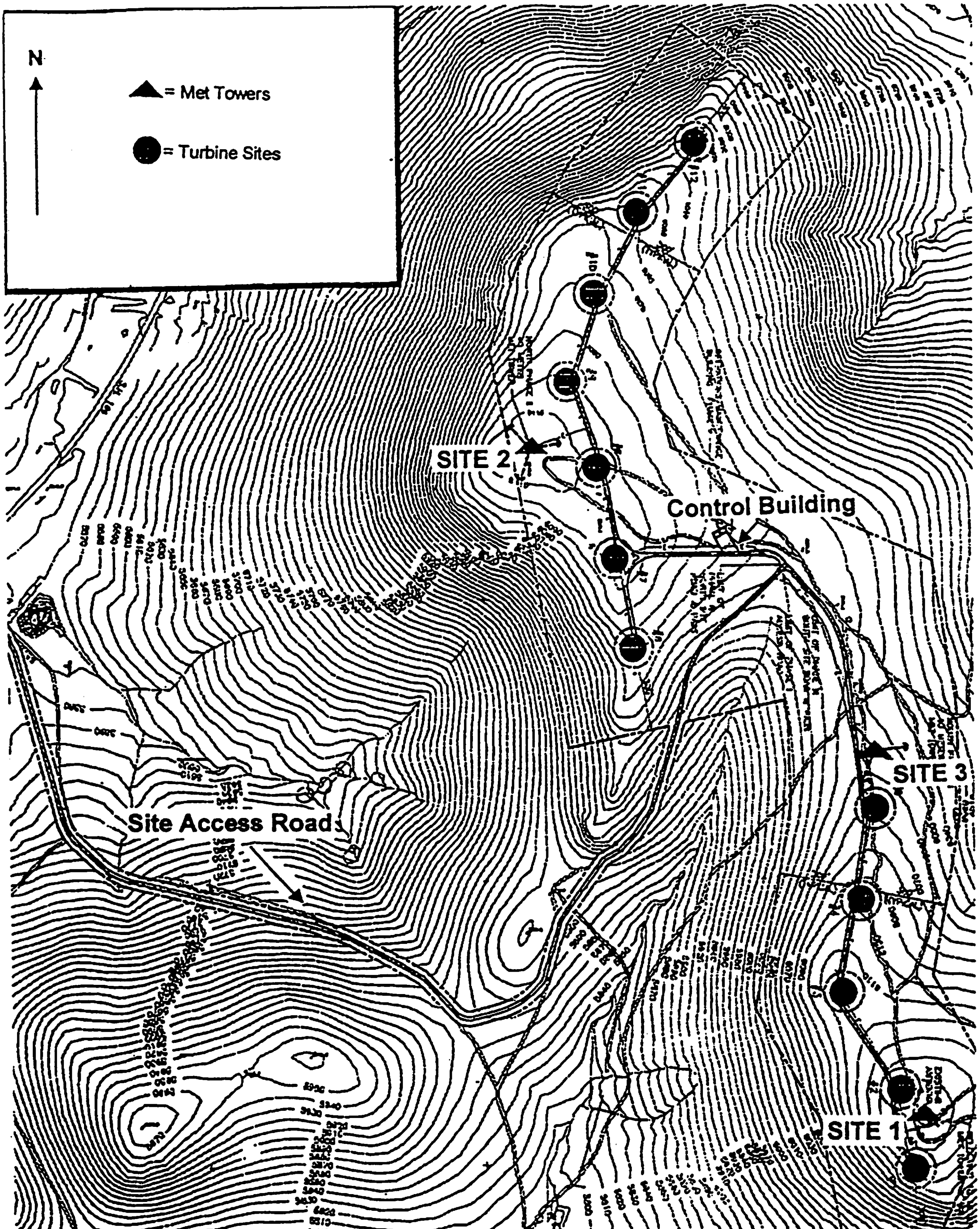
N
= Met Towers
= Turbine Sites
SITE 2
Control Building
SITE 3
Site Access Road
SITE 1

FIGURE 2.

30th IEA Experts Meeting
December 8 and 9, 1997
C.R.E.S, Greece

Investigation into the Sufficiency of Data in Wind Turbine Power Performance Testing

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April 26, 1998

Background

The International Electrotechnical Commission's draft standard, IEC 1400-12, requires that a minimum of 180 hours of power curve data be obtained in the assessment of wind turbine performance. While this quantity of data may suffice for many purposes, additional data may provide a better assessment of turbine performance. This paper suggests that relatively easy analyses can provide valuable information on the trade-off between testing time and accuracy of performance assessment.

Approach

The key to evaluating the potential to improve results by continuing to obtain test data is to examine how key parameters change as a function of the amount of power curve data that have been obtained. Annual energy production (AEP) is one parameter that should be considered. The IEC draft standard requires that AEP be projected for sites with average wind velocities ranging from 4 to 11 meters per second. In this paper, the author projected AEP for three sites. These sites have average wind speeds of 4, 7, and 11 meters per second.

AEP is calculated for each average wind speed using the method specified in the draft standard, IEC 1400-12 except that every wind speed bin that contains data is used in the calculation. For those bins that contain no data, a power output of zero is assumed. At the beginning of the data record, therefore, only one wind bin has any data (the first 10-minute average obtained). The AEP calculated based on this single datum is quite low compared to the final value it would be expected to reach. As more wind bins are filled, the projected AEP increases until, when all the required wind bins are filled, AEP is close to its final value. A plot of AEP versus the quantity of data obtained indicates how much this parameter continues to change after the wind bins are filled. If it continues to change a lot, additional test time is warranted.

Example Case

The author investigated a data set obtained on a new wind turbine in the U.S. The data set has over 1000 hours of data where wind speeds are from the allowable wind directions and of appropriate wind speeds. (The IEC draft standard defines the limits of wind speeds for the power curve as 1 meter per second below cut in to 1.5 times the wind speed at 85% of rated power.) A simple program calculated AEP for the three sites for each data point. Figure 1 shows the results obtained. AEP starts at zero and increases as each wind bin is filled. The last empty bin, 17 m/s, obtained a point at 263 hours and shows up as a jump on the 7 and 11 m/s lines. After this time, the plots are relatively flat and stable appearing.

Figure 2 shows the results in close up. In this case the plots are normalized to the final values obtained so one can quantify changes in terms of a percentage. This figure indicates that, even after 263 hours, projected AEP continues to change slightly at the higher wind speed sites. At the 4 m/s site, a significant change is noted at 506 hours. However, after 600 hours, the plots show a stability that suggests that no additional changes would be expected.

Wind Bin Data

One might question whether the turbine and/or operating conditions changed during the test so as to affect AEP projections. Another way to view the data is as a "time history" of power measured in each wind bin. With 29 wind bins, a single plot of all bins becomes too confusing. Figures 3 and 4 show the data from several wind bins. While the plot shows a fairly wide scatter of data at each wind speed, there are no obvious jumps or trends in the data.

Conclusions

In the example case, 180 hours was not enough to provide a good characterization of the turbine's performance. Projected annual energy production based on the data obtain to that time would be 5-8% low. Even after obtaining data in all the bins at 263 hours, the results would have been low. Almost 600 hours were required in this case to reach a good level of stability of results.

The relatively simple analysis method described here can provide a better assessment of the quality of test results than the assumption that any single criteria, such as the IEC standard's 180 hours, is sufficient.

Figure 1. Change in AEP during Testing

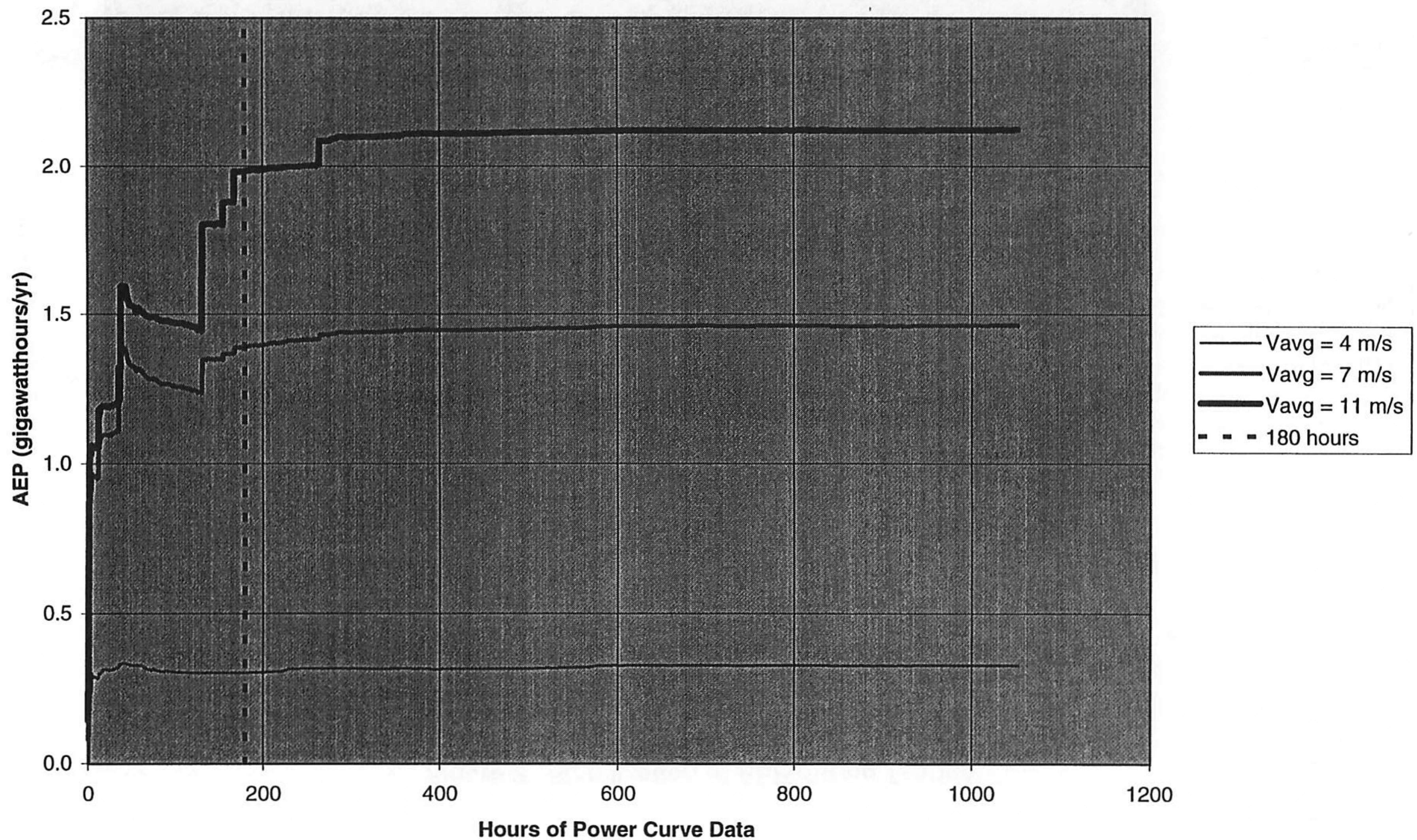


Figure 2. Stabilization of AEP during Testing

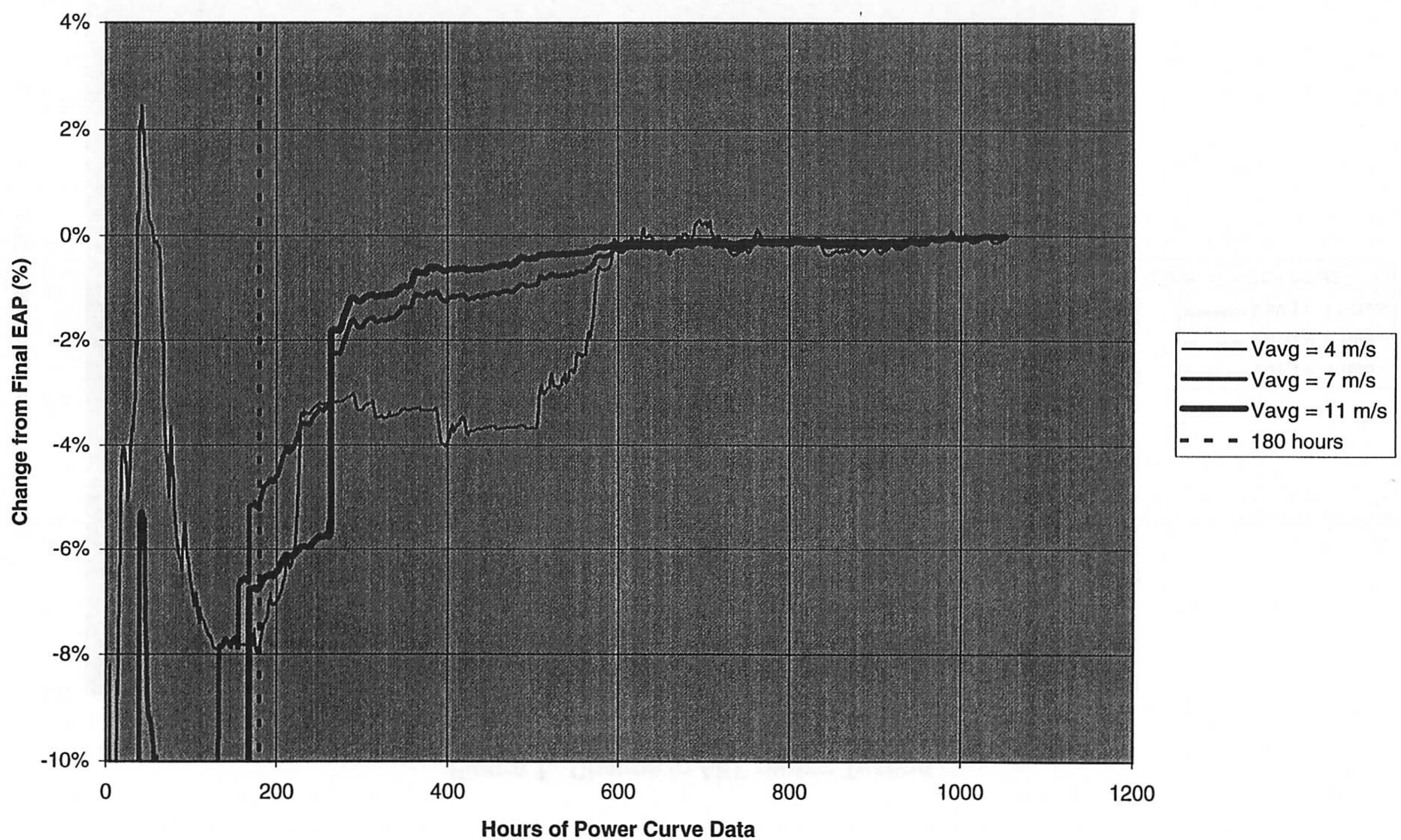


Figure 3. Wind Bin Data, 3-17 m/s Bins

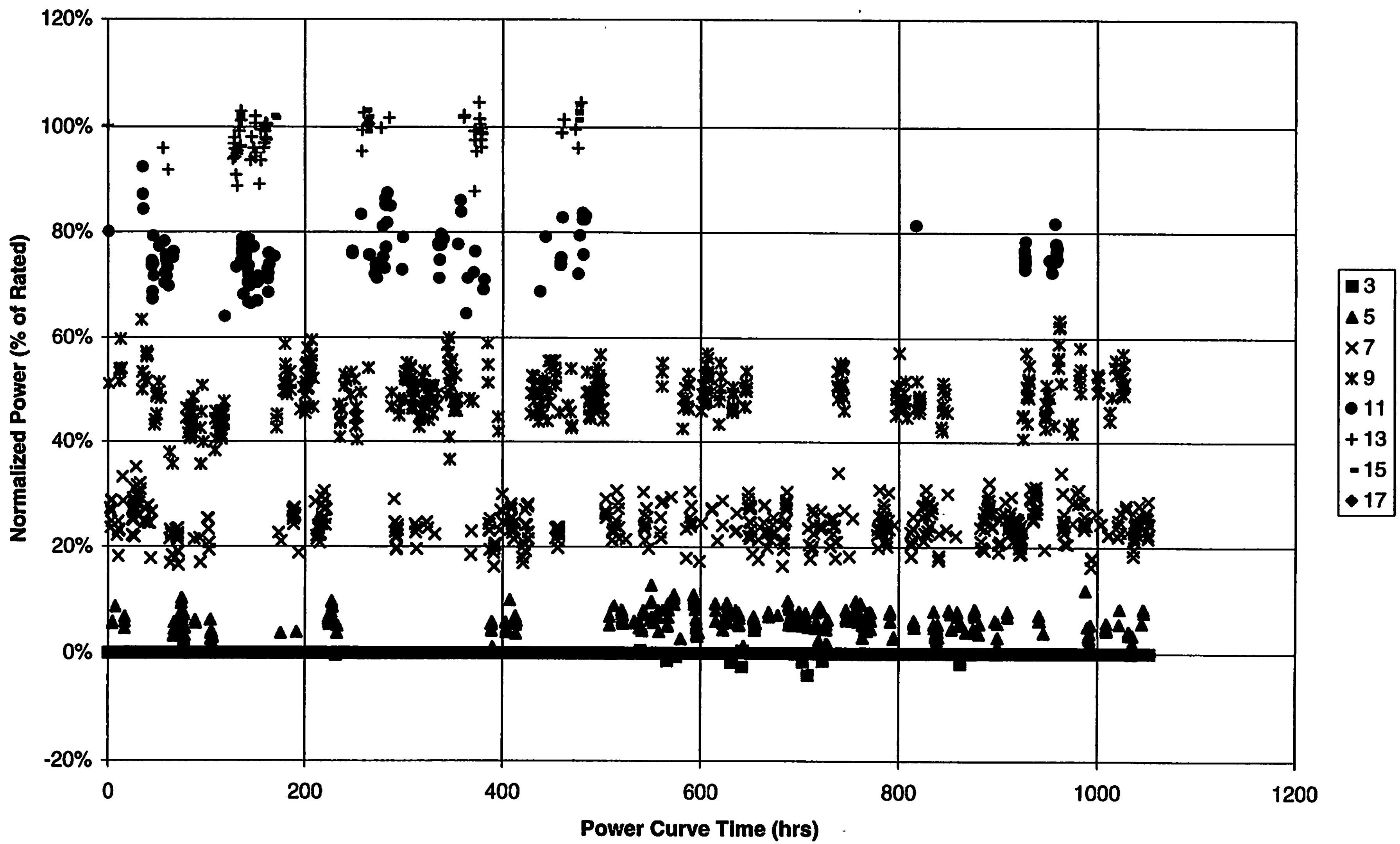
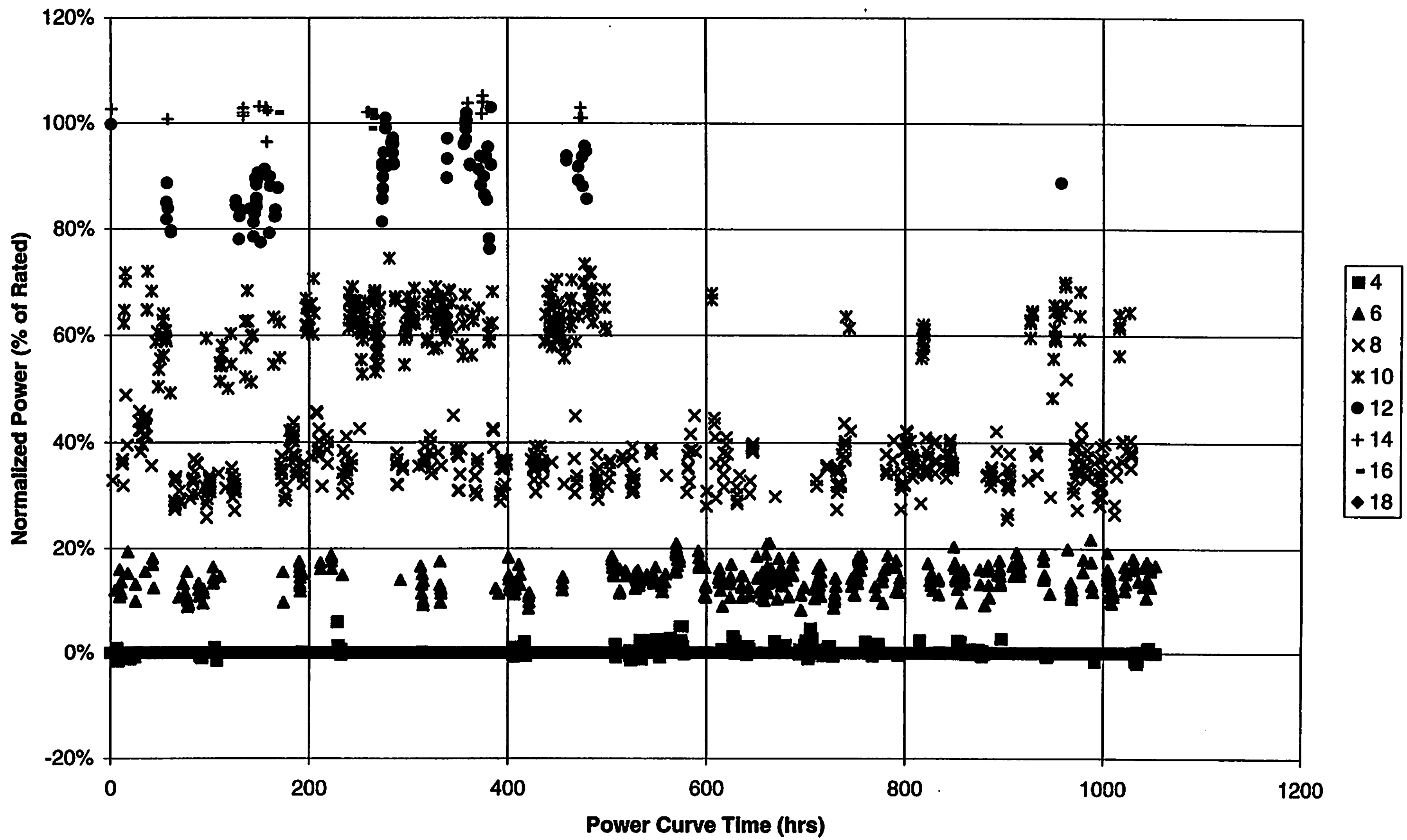


Figure 4. Wind Bin Data, 4-18 m/s Bins



Measurements on large wind turbines

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Presentation at IEA Experts Meeting
in Athens, 08 - 09.12.1997

1. Introduction

In the following an overview about the activities of WINDTEST concerning power performance measurements on wind energy converters (WEC) of the MW-class is given. In addition wind measurement with cup anemometers and a sodar system are compared.

2. Measurements on MW Turbines

In the last years Windtest has gained some experience with power performance measurements on large wind turbines. So far performance tests were carried out on the following turbines:

Type of turbine	Hub height [m]	Rotor diameter [m]
Autoflug A100	60	61
HSW 1000/54	55	54
HSW 1000/57	55	57
Micon M2300-1000/250kW	59	54
Nordex N52	60	52
Nordex N54	60	54
Nordtank 1500	68	64
Tacke 1.5	68	64
Vestas V63-1.5MW	65	63

As demanded by the recommendations (IEA, ECN-217, etc.) WINDTEST carries out the wind speed measurements with cup anemometers. These are installed on a met mast corresponding to the hub hight of the tested WEC. The MW-turbines now have hub hights of more than 60m - and the heights will increase up to 90m. As the formerly used guy wired masts with heights of more than 40m are hardly available WINDTEST shifted to climable lattice mast systems. The installation of the sensors on these masts is easy. But the masts themselves are quite expensive - especially for short term measurements. In addition to that the erection is difficult depending on the location.

Best would be a wind monitoring system which can do without any mast, based on the ground level.

Since several years such a system is known as 'sodar'. As the Sodar can not be calibrated in a wind tunnel it was decided to do a comparison of wind measurements between cup anemometers and the Sodar on the test station of WINDTEST.

3 Sodar Technique

Sodar is an acoustic system which is able to determine wind speed and wind direction gradients in heights from 15 to 200m in 5m increments.

The sodar operates by generating sound pulses at a frequency of 4500 Hz broadcasted streight upward at an angle of 16 degrees below zenith in two orthogonal directions. The pulses are scattered by thermal fluctuation in the atmosphere. Assuming a constant speed of sound, the time between the pulse output and the signal returned represents the height at which the signal was scattered. The doppler shift of the returned signal is an indication of the wind speed at that height. The strength of the signal returned is an indication of the stability of the layer. Figure 1 shows an example of a profile recorded with a sodar. The determined profile gives much more information particularly for the of the check of the control system during the power performance measurements.

The Sodar has an array of 32 piezo ceramic speakers and electronics that transmit the pulses steer the beam and control the reception the signal returns.

The typical sampling rate is one full scatter in app. 5-8 seconds. The manufacturer gives wind speed accuracy of less than 0.25 m/s and for wind direction of ±2 degrees.

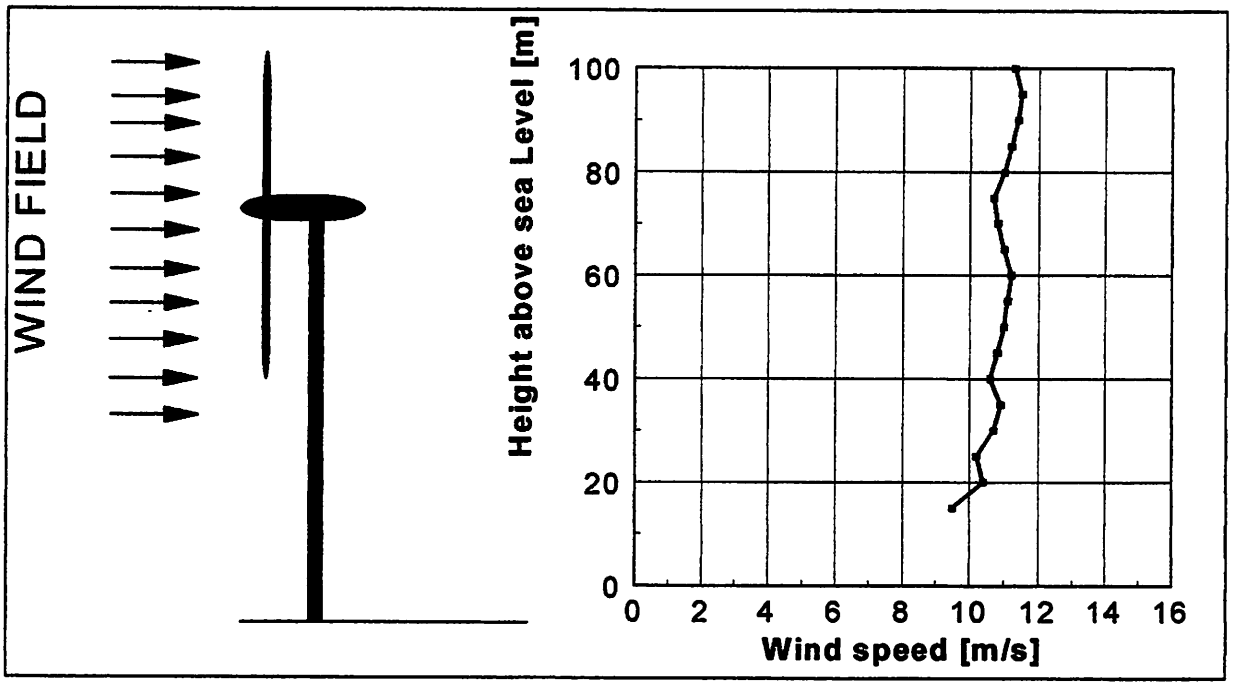


Figure 1: Sodar profile of wind speed

4 Comparative Measurement

The field tests were carried out on the test station of WINDTEST (see Figure 2). The sodar was placed near the 60m met mast. For some days data were recorded. It turned out that the mast emitted a specific noise spectrum at wind speeds of more than 8 m/s which influenced the sodar measurements. So the sodar had to be moved to a distance of about 70m from the mast.

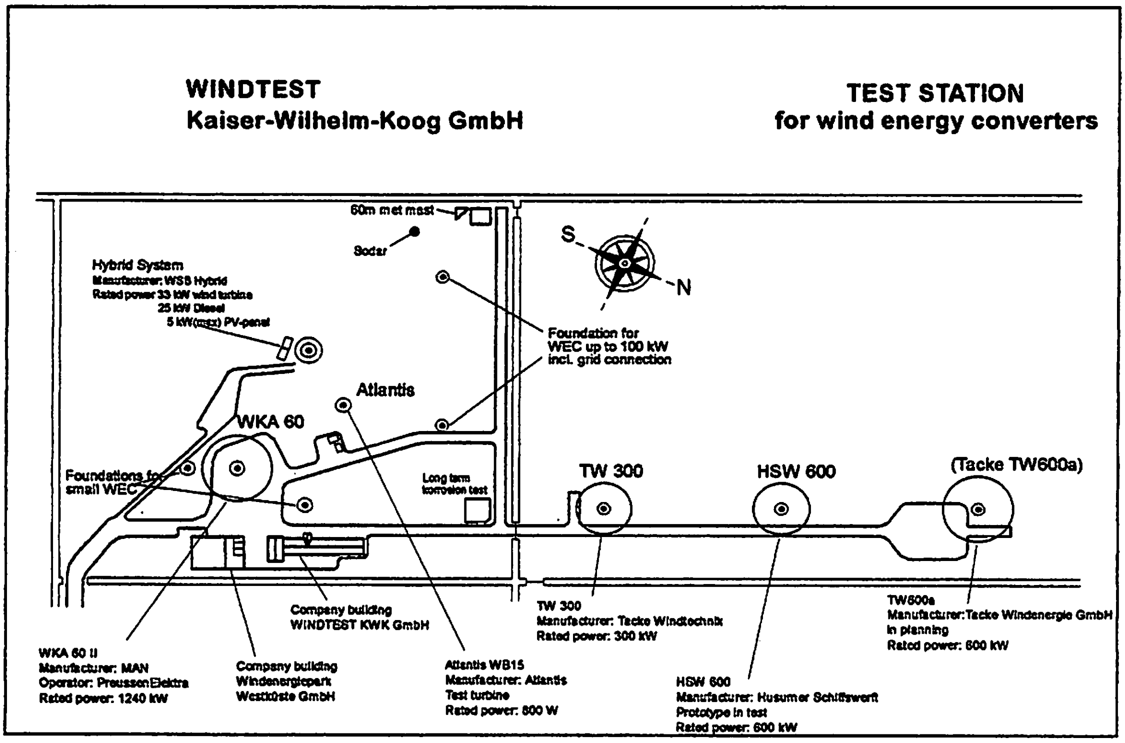


Figure 2: Sketch of WINDTEST test station

5 Results

Because of the met mast influence on the measurements the data was not easy to interprete.

In figure 3 and 4 differences in wind speed and wind direction between the sodar and the cup anemometer measurements respectively wind vanes are displayed.

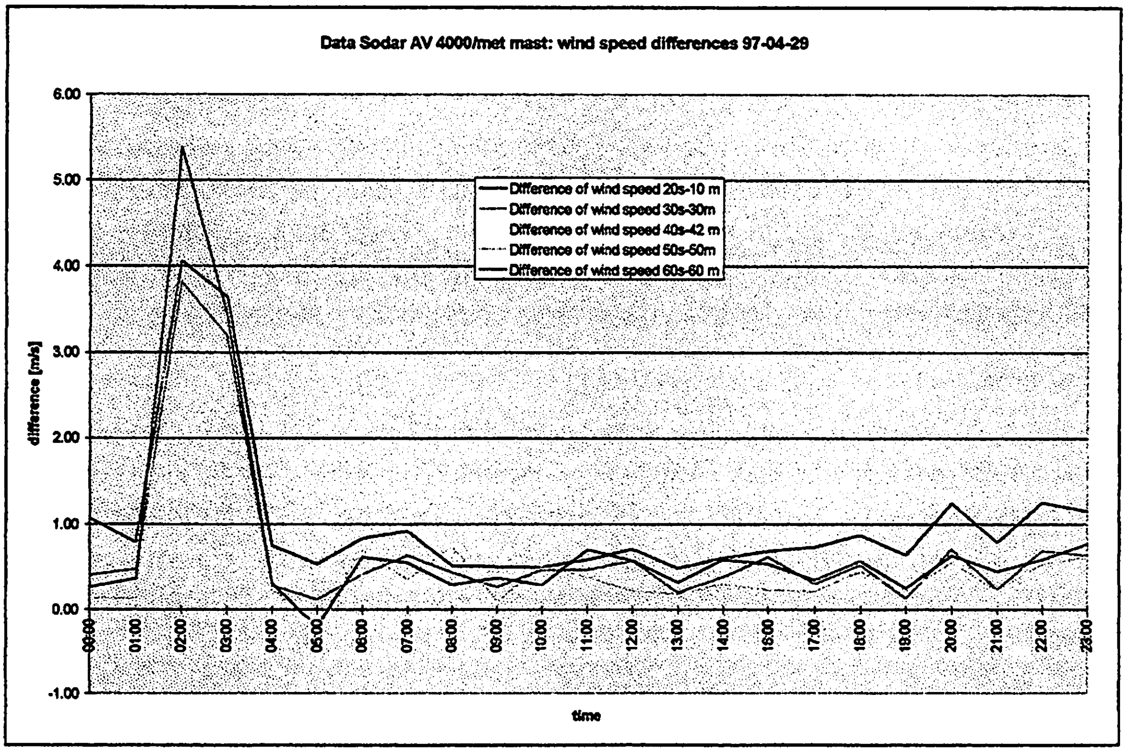


Figure 3: Differences: wind speed measurement

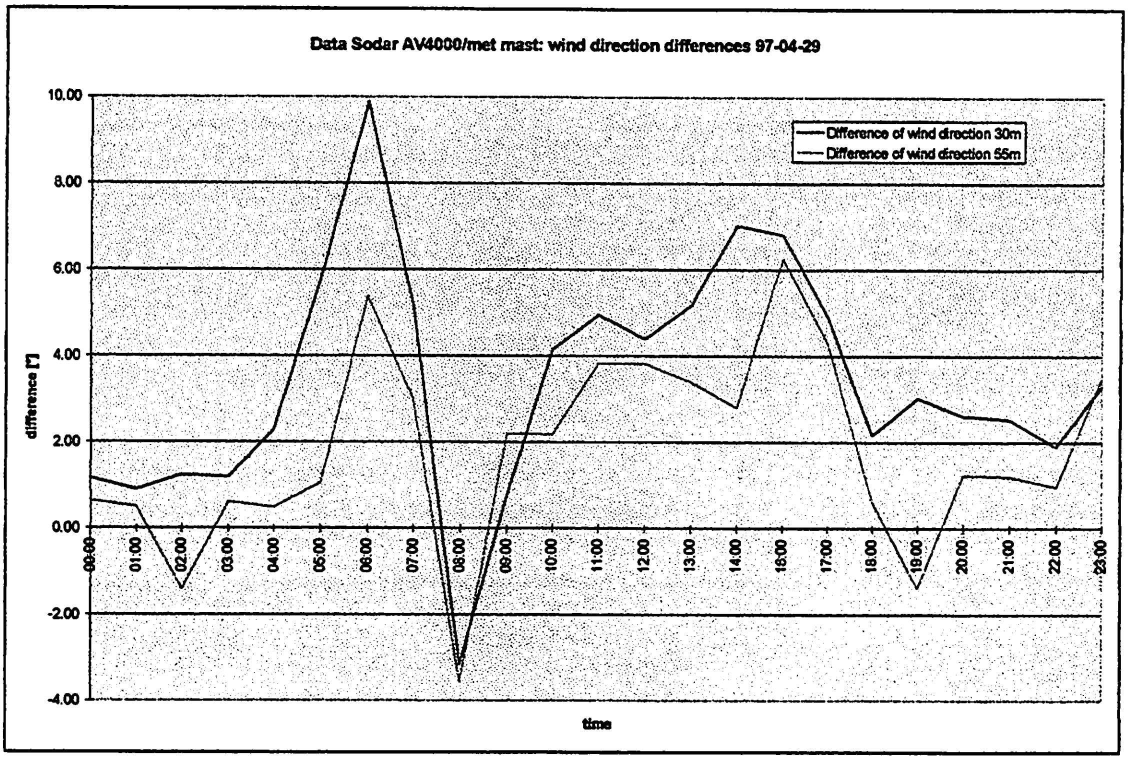


Figure 4: Differences: wind direction measurement

The occured differences seem to be systematical and could be explained by the following influences:

1. sodar works absolutely different to cup anemometers; no length constant or overspeeding,
2. influences of the mast by emitting noise,
3. way of field installation of sodar (inaccurate alignment will induce critical errors of evaluaton of wind speed and wind direction),
4. distance between met mast and sodar (but 1-hour averages should smoothen this effect).

According to GWU the main uncertainty is based on the difficulty they had to align the Sodar acurate relative to the surface. All further evaluations of the Sodar are based on an acurate alignment.

The procedure to 'calibrate' the Sodar by means of cup anemometers can not be succsesful - it is only a check. A practicable and reasionable way to verify the Sodar data has to be discovered. Without traceability to national standards the Sodar is not applicable for wind energy purposes. But after more detailed tests it could supply very helpful information for load and vibration measurements on WECs on the basis of the wind profiles.

6 Outlook

The sodar is yet not aplicable for power performance measurements. The accuracy of wind speed measurements has to be improved. Therefore WINDTEST and GWU (German distributor of sodar) will start a research project to optimize the sodar technology for wind energy application. Probably the hard and software has to be adapted to the requirements. The correct alignment of the system shall be reached by mounting the sodar on a special trailer which is equiped with exact level meters to balance the terrain structure. More comparative measurements have to be carried out. All this will be tested in an extensive field test at the test station over a period of two years.

ECN

10 February 1998

IEA expert meeting at CRES, 8 and 9 December 1997

State of the art on power performance for wind energy conversion systems

Activities at ECN with respect to site calibration

A. Curvers
ECN Renewable Energy P.O. Box 1, 1755 ZG Petten, The Netherlands
phone: +31 224 564367; fax: +31 224 563214

Recently ECN has not gained experience with performing measurements in complex terrain conditions. A few measurements were carried. In those cases the terrain conditions appeared to be fairly in agreement with the site requirements.

In October '97 a prototype wind turbine NW 46 has been installed at the ECN test station. This offers opportunities to perform special measurements with respect to site calibration.

The following activities are planned at ECN:

1. Site calibration at the ECN test station is necessary because the terrain topography and the present distance between turbine and met-mast.
2. Navier-Stokes calculations of the flow disturbances around the nacelle. The site calibration has to be carried out with an additional mast on the nacelle. Installation of a mast before the wind turbine erection was not possible in this case.
3. Wind speed measurements with the nacelle anemometer, which is part of the wind turbine, will be involved in the Power Performance determination.

The results of these activities will be used for the development of methods of site calibration techniques, measurements in complex terrain and within wind farms.

Power Performance Assessment

Contents:

- WHAT IS THAT? - Illustation, Needs, and Objectives
- WAYS OF IMPROVEMENT - A strategy
- REGRESSION ANALYSIS - What to choose?
- SOME DATA FROM VINDEBY
- INPUT PARAMETERS AND UNCERTAINTY
- CONCLUSION

Improvement of performance testing

OBJECTIVE:

- To devise a more accurate method for assessing production capability of wind farms - units and integrated plant.

WANTED OUTPUT:

- Reference power curves and mean reference power for all units + uncertainties:

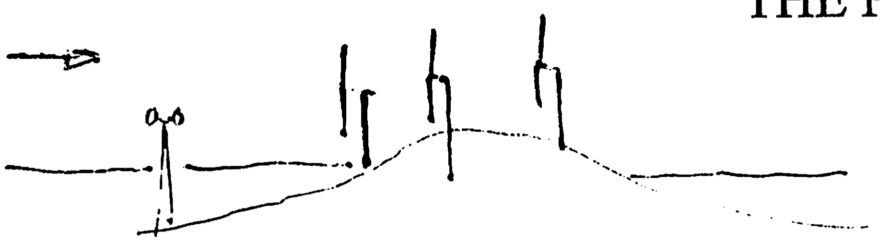
$${}_{ref}p_i = p_i({}_{ref}\mathbf{x}), \quad P_i = \iint\ldots\int_0^{?} p_i f_{ref}\, d\mathbf{x}, \quad s_i = s_i(P_i)$$

- Mean plant power + uncertainty:

$$P = \sum P_i, \quad s^2 = \sum\sum s_i s_j$$

Power Performance Assessment?

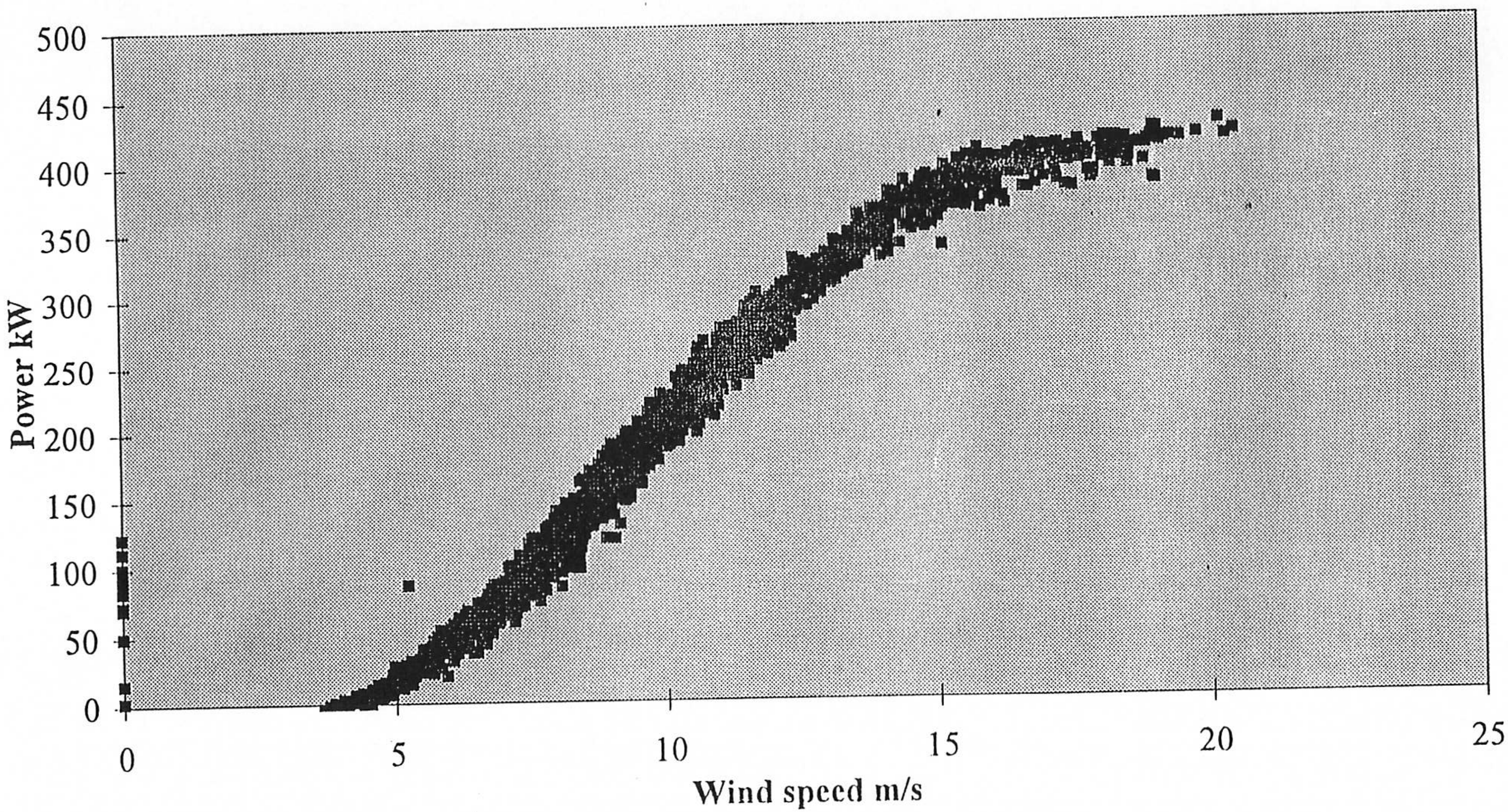
POWER PERFORMANCE ASSESSMENT
IS THE ACTION OF
RETROSPECTIVE EVALUATION OF
THE PRODUCTION CAPABILITY OF
A WIND POWER PLANT



WHY?

BUYER WANTS TO KNOW IF HE GOT WHAT HE PAID FOR

Vindeby approx 2000 ½h



Needed qualities of reference power curves

- It must come out the same way under all recording circumstances
- It shall be measurable under all circumstances (though of course with difference accuracy)
- It shall be measurable also under wake conditions
- Reference power curves measured according to procedure, at different sites, shall be comparable - poor comparability shall purely be reflected in the uncertainty measures

Reference power curve

(Disregard here site variation in variables and plant disturbance of base measurement mast)

- Test average power curve (u_r is hub height wind speed(s)):
  $p = p(u_r)$ and $x_i = x_i(u_r), \quad i = 2,3 \ldots N$
- Choose a set of reference values of input quantities:
  ${}_R x_i = {}_R x_i(u_r), \quad i = 2,\ldots,N$
- By multivariate regression analysis, the sensitivity factors are found:
  $\beta_i = \beta_i(u_r), \quad i = 2,\ldots,N$
- The derived reference power curve is

$$p_{ref}(u) = p(u) + \sum_{2}^{N} \beta_i(u)\{{}_R x_i(u) - x_i(u)\}$$

Site Calibration

(with and without wake effects)

As a function of <wind speed> and <wind direction> establish if possible

$$\mathbf{x} = \mathbf{A}\ {}_b\mathbf{x}^{-T} + {}_0\mathbf{x}\text{ , where}$$

$$\mathbf{x} = \{u_r, x_2, \ldots, x_n\} \quad \text{and} \quad {}_b\mathbf{x} = \{{}_bu_r, {}_bx_2, \ldots, {}_bx_n\}$$

are the sets of variables at wind turbine position and base measurement position and

$$\mathbf{A} = \begin{bmatrix} a_{11}\ a_{12} \cdots & a_{1n} \\ a_{21}\ a_{22} \cdots & a_{2n} \\ \cdots\cdot & \\ a_{n1}\ a_{n2} \cdots & a_{nn} \end{bmatrix}$$

is the partial regression coefficient tensor, where $a_{ij}=a_{ij}(u,d)$.

Plant disturbance of base measurements

ACCOUNTS FOR THE BASE MEASUREMENTS NOT BEING FREE STREAM MEASUREMENTS.

- The disturbed base measurement:

$$ {}_{b}\mathbf{x}' = {}_{b}\mathbf{x} - \Delta \quad \Rightarrow \quad {}_{b}\mathbf{x} = {}_{b}\mathbf{x}' + \Delta $$

- The correction term is a function og wind speed and direction:

$$ \Delta = \Delta(u, d) $$

- Probably difficult (impossible?) to evaluate in present (wind farm) case
- Is known from single unit performance measurements when distance from tower to mast is less than 1.5-2D.

Summary of procedure

1. Sensitivity analysis, regression: $\beta_i = \beta_i(u_r), \quad i = 2,\ldots,N$
2. Site calibration, regression: $\mathbf{x} = \mathbf{A}\ {}_b\mathbf{x}^{-T} +_0\mathbf{x}$
3. Disturbance from plant: $\Delta = \Delta(u,d),\ {}_b\mathbf{x} = {}_b\mathbf{x}' + \Delta$
4. Collect performance data and employ 1-3.
5. Derive reference power c's: $p_i(u) = p(u) + \sum_2^N \beta_i(u)\{{}_R x_i(u) - x_i(u)\}$
6. Derive mean reference power: $P_i = \iint \ldots \int_0^? p_i f_{ref}\, d\mathbf{x}$
7. Derive total mean ref. power and σ: $P = \sum P_i, \quad \sigma_P^2 = \frac{1}{M-1}\sum\sum(P - P_i)^2$

Regression Analysis
(Linear)

Seeking (binwise): $P = P(\mathbf{x}) \cong P_0 + \Sigma\, \beta_i(x_i - {}_0x_i)$

- LINEAR REGRESSION vs MAXIMUM LIKELIHOOD

  - ➢ORDINARY, MULTIBLE REGRESSION ANALYSIS
    (Potential problem: collinearity)
  - ➢PARTIAL LINEAR REGRESSION
  - ➢PRINCIPAL COMPONENT REGRESSION

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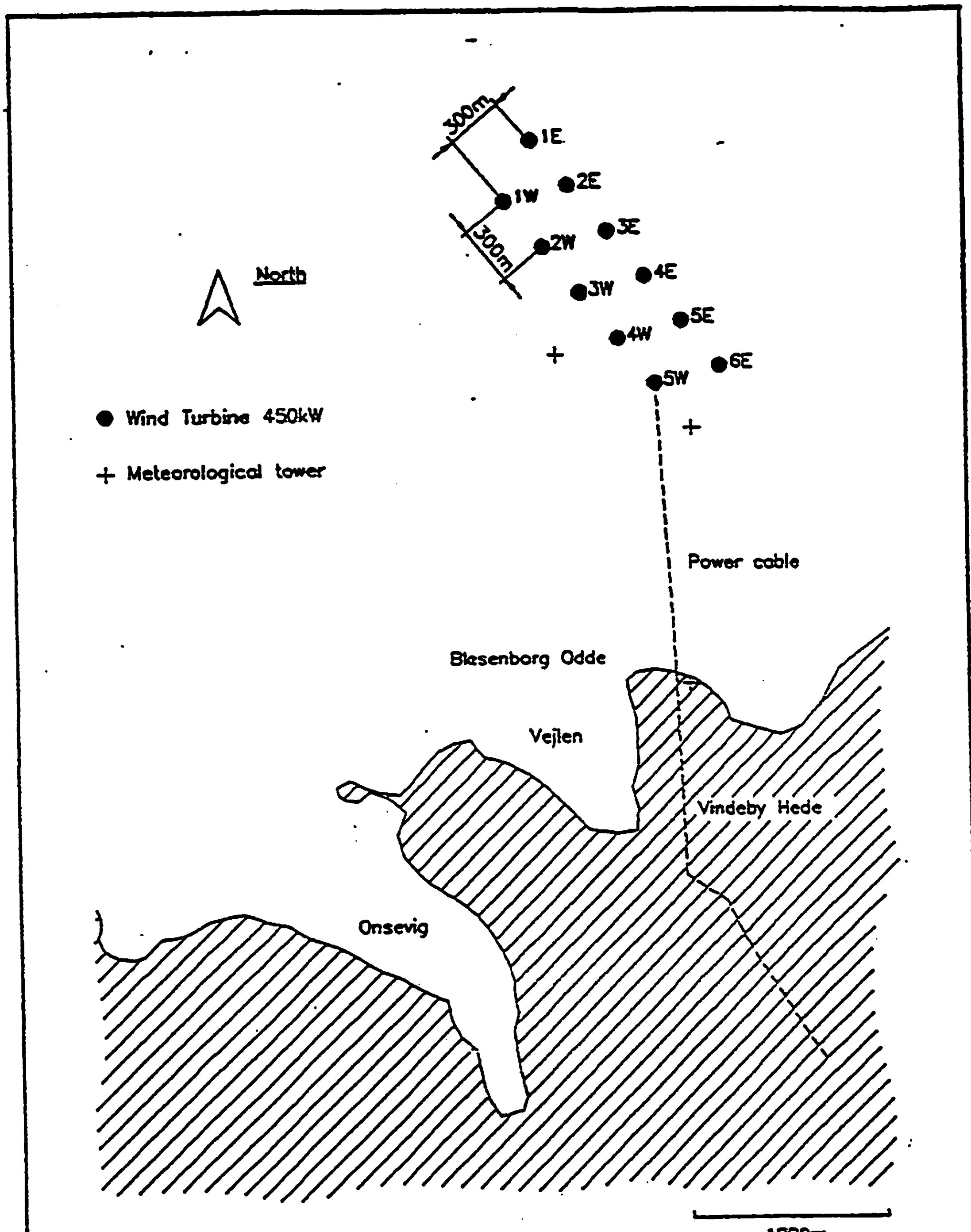


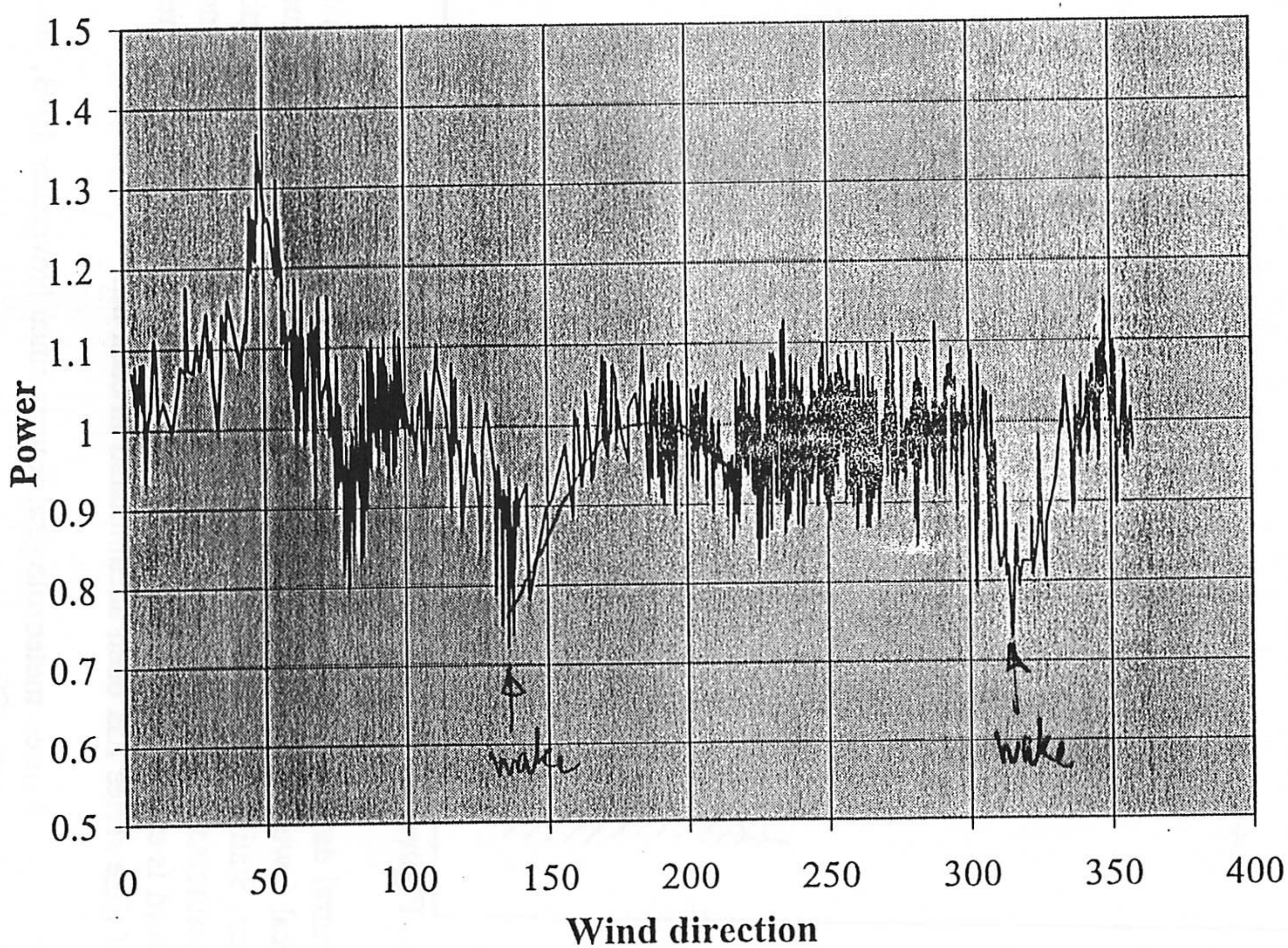
Figure 3.1 *Layout of the Vindeby Wind Farm.*

to the central data storage and processing computer, which is placed in a cabin
teorological tower. Structural and meteorological data are sampled continuously
ute records. Statistics such as mean, standard deviation, maximum and minimum
ctural measurements also damage "equivalent stress" are computed on-line and
ninute record is categorized (binned) according to wind speed and wind direction
number of time series has been accumulated in each bin.

n sampled from all three meteorological towers since November 1993, and data
ind turbines since April 1994.

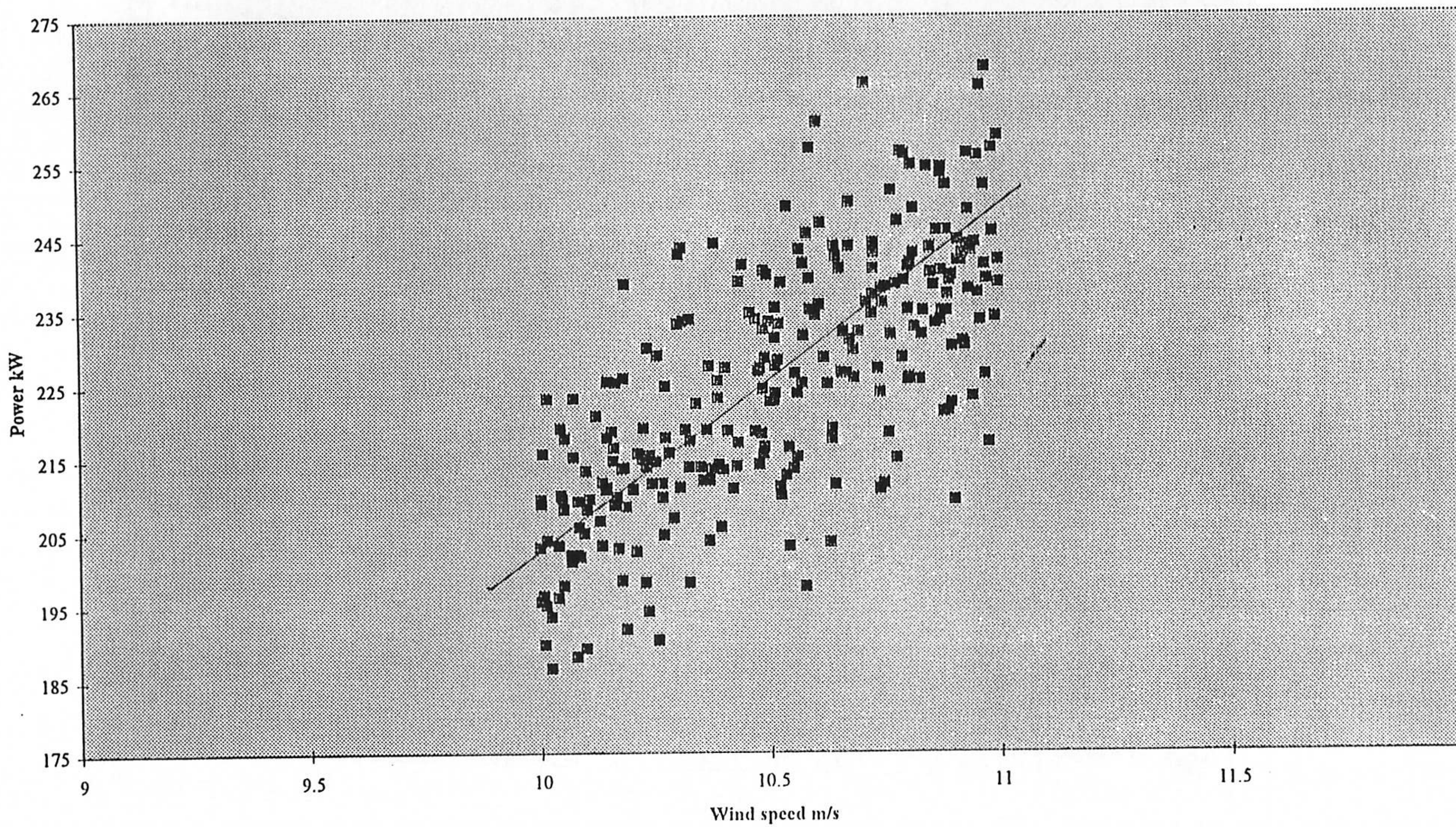
lata series have been recorded, of which all have been statistically analyzed
and a limited number has been stored in its entirety.

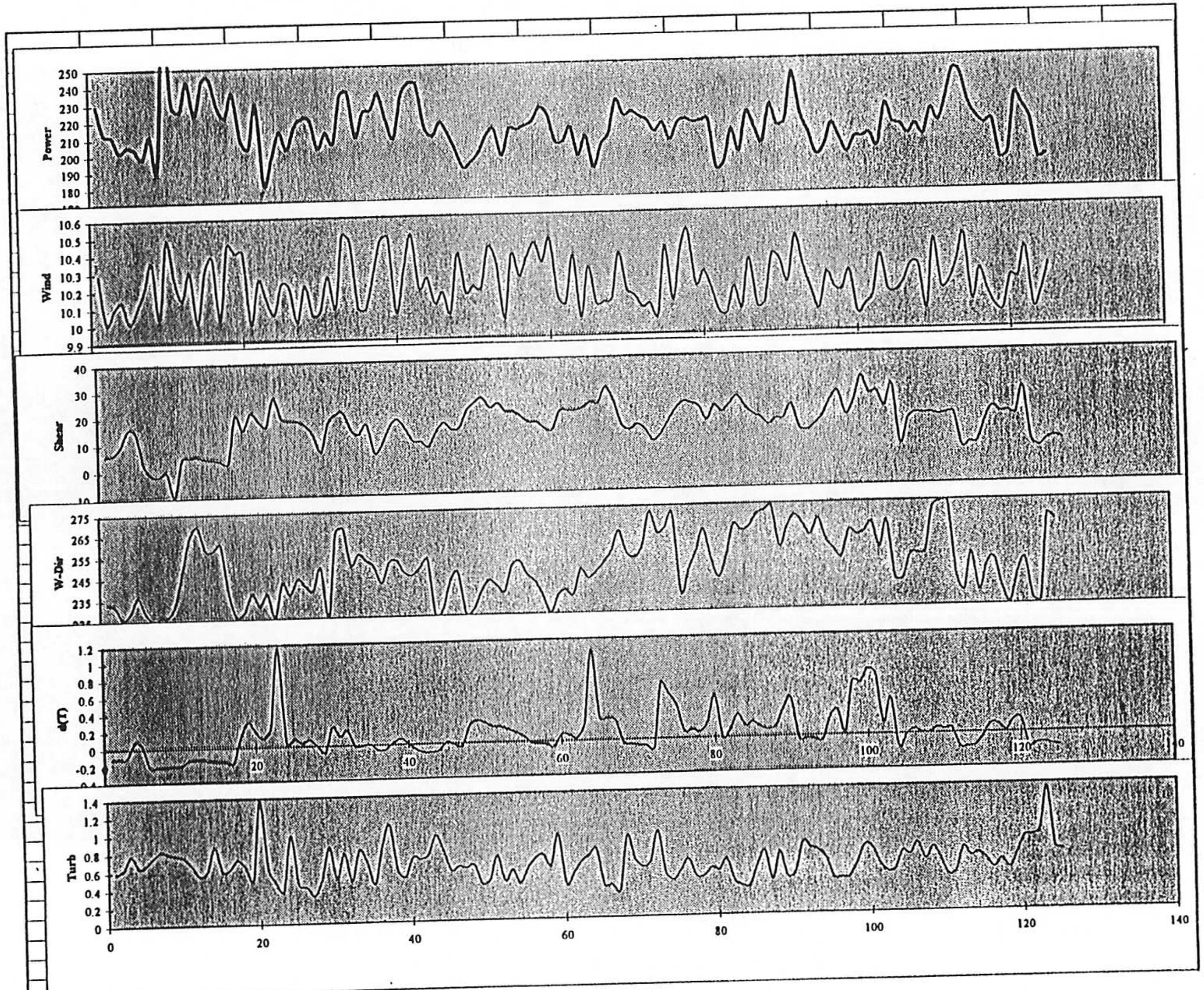
4w, 10<u<11, Vindeby



t-10-11 Diagram 1

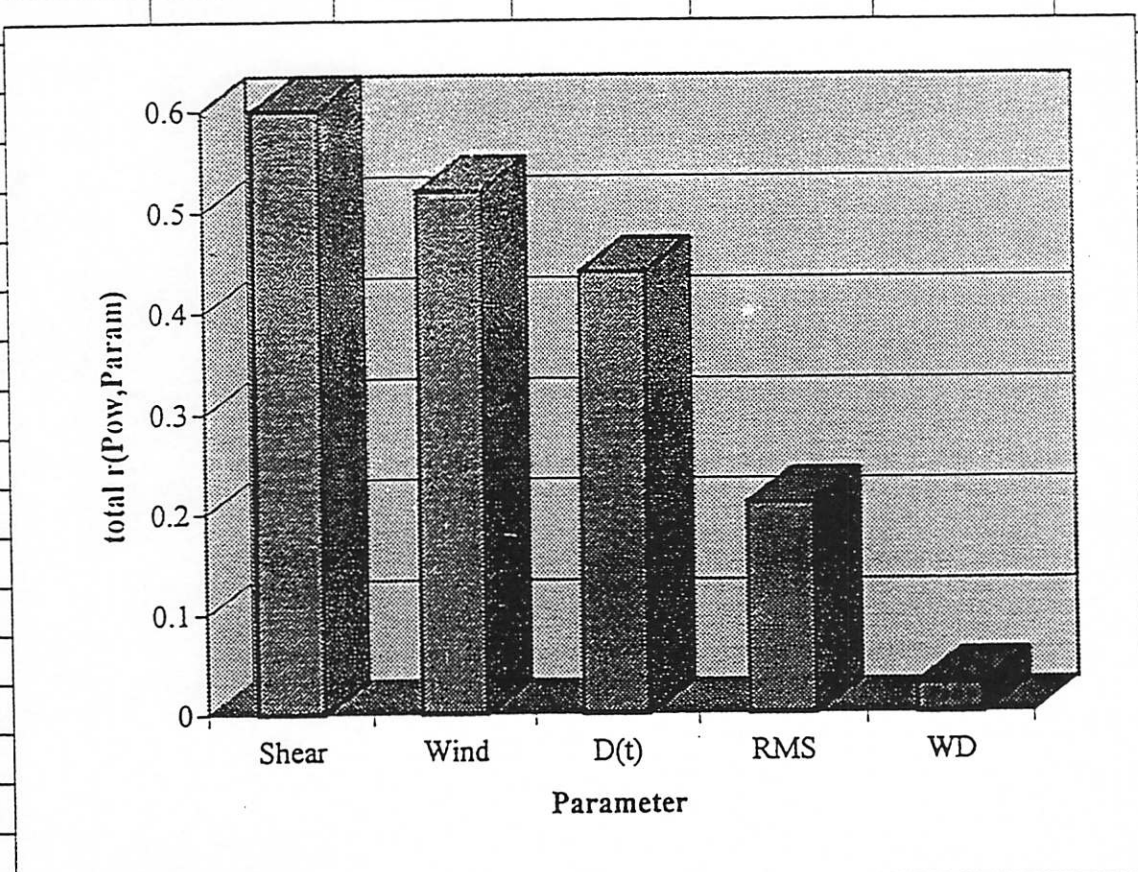
Vindeby approx 2000 ½h




Power
Wind
Shear
W-Dir
d(T)
Turb

tmp-1.xls

	POWER	WIND	SHEAR	WD	D(t)	RMS
RMS	0.214	0.047	-0.446	-0.184	-0.35287	1
D(t)	-0.443	-0.137	0.708	0.138	1	
WD	0.033	-0.031	0.112	1		
SHEAR	-0.595	-0.065	1			
WIND	0.524	1				
POWER	1					



Uncertainty components

4 main groups of uncertainty may be defined:

Group	Type	Symbol
s_1	Instruments incl. Power	$\overline{p}$+ all other
s_2	Sensitivity analysis	$\sum \beta_i ({}_R x_i - {}_C \overline{x_i})$
s_3	Extended site calibration	$\mathbf{x} = \mathbf{A}\ {}_b\mathbf{x}^{-T} + {}_0\mathbf{x}$
s_4	Plant disturbance of ref. meas.	Δ
(	No. of applied variables	N)

“Suspected” input variables

- Wind speed in some representation
- Turbulence(s)
- Air density
- Vertical shear
- Flow inclination
- Horizontal shear
- Humidity
- WAKE EFFECTS

Uncertainty components

- Instruments: Treated as in TC88
- Sensitivity: Uncertainty measure from regression analysis + instruments?
- Site calibration: Is uncertainty systematic (different wd and wt)?, is it distance-dependent?
- Plant disturbance: Is it significant or should it a priori be considered an intrinsic uncertainty?
- Number of parameters: The more parameters, the less uncertainty.

Summing up

The aim is to assess the integrated production capability (PC) by measuring the individual PCs and adding. For the individual PCs we need:

- Reliable, "short-range", extended site calibration methods are needed
- Reliable and agreed upon procedure for WT-sensitivity analysis
- Reliable anemometry
- Reliable uncertainty analysis - If we can't make it accurate, at least we must know how inaccurate

Note from discussion following presentations.

- A discussion took place on the needed quality of power curves. It was suggested (by Troels F. Pedersen) to operate with two power curve concepts, *primary power curve* and *secondary power curve*. The primary power curve is measured under ideal or near-ideal test conditions according to (IEC) standard. The secondary power curve is defined by the individual test engineer. The secondary power curve concept as such does not need consensus, it simply does not adhere to the standard. However, there seems to be agreement on the usefulness of clear terminological distinction between up-to-standard (primary) power curve and the customised (secondary) power curve.

- It was stressed (by Hal Link) that measuring power performance of wind farms should mean measuring performance of the individual wind turbines (in contrast to measuring performance of the integrated wind farm in one operation, mapping U_i and ${}_TP_i = \sum P_i$, where U_i is some reference wind speed). There seemed to be agreement on this.

- The number of machines in a wind farm on which to measure power curve when assessing power performance was discussed. Or specifically: how large a sample (of power curves) from the wind farm it needed? It was argued (by Sten Frandsen) that due to present uncertainties in determination of the individual power curve, there is a need to sample (measure) all power curves in the wind farm. There seemed to be consensus on the issue.

- It was agreed that precise measurement of wind speed is still a bottleneck.

- Concerning the cup anemometer, the presentations showed that 1) the characteristics are still not satisfactorily determined 2) the accuracy (under certain, frequently occurring circumstances) too poor, and 3) it is still not clear what we want the instrument to provide a measure of (length of U-component of wind vector, horizontal speed, length of wind vector?). The discussion displayed agreement that other anemometer types should be tested for performance assessment.

- The wind turbine's response to yaw error (which can be investigated introducing forced yaw error) could provide useful information on the turbine's response to so-called inclined flow in complex terrain.

Sten Frandsen
Risø National Laboratory
December 16, 1997

30th IEA Experts Meeting, dec. 8.-9. 1997,C.R.E.S., Greece

State of the Art on Power Performance Assessment for Wind Energy Conversion Systems

SUMMARY

prepared by
B.Maribo Pedersen

This Experts Meeting, the purpose of which is expressed in the introductory note, had gathered 14 participants from 6 different countries. 12 presentations were given and although countries with a sizeable wind program, i.e. Italy, UK and Spain were not present, it is felt that the meeting gave a fair impression of the contemporary state of the art world wide.

Although the meeting did not come to firm conclusions on how to tackle the problems described in the introductory note, it gave some valuable information on the different approaches taken by the institutions represented at the meeting. Unfortunately there were no representatives from manufacturers and buyers of turbines.

Specific problems concerning proper definition and measurement of wind speed by cup-anemometers were dealt with. Different sources of errors were analysed and valuable new experimental results were presented. Also possible other instruments for wind-speed measurements than cup-anemometers were mentioned.

It became clear, that more work is needed as well concerning formulation of the proper questions (what is in the end needed and how accurate) as to providing the answers.

The meeting hopefully has given useful input to ongoing work within the standardisation bodies as well as in several ongoing, jointly funded projects, which eventually will get us closer to reach consensus on the issues.

30th IEA Meeting of Experts
State of the Art on Power Performance Assessment for Wind Energy Conversion Systems

Athens, December 8.-9., 1997

List of Participants

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IEA R&D WIND - ANNEX XI
TOPICAL EXPERT MEETINGS

1. Seminar on Structural Dynamics, Munich, October 12, 1978
2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979
3. Data acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, September 26 - 27, 1979
4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21 -22, 1980
5. Environmental and Safety Aspects of the Present LS WECS, Munich, September 25 - 26, 1980
6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29 - 30, 1981
7. Costings for Wind Turbines, Copenhagen, November 18 - 19, 1981
8. Safety Assurance and Quality Control of LS WECS during Assembly, Erection and Acceptance Testing , Stockholm, May 26 - 27, 1982
9. Structural Design Criteria for LS WECS, Greenford, March 7 - 8, 1983
10. Utility and Operational Experiences and Issues from Major Wind Installations, Palo Alto, October 12 - 14, 1983
11. General Environmental Aspects, Munich, May 7 - 9, 1984
12. Aerodynamic Calculational Methods for WECS, Copenhagen, October 29 - 30, 1984
13. Economic Aspects of Wind Turbines, Petten, May 30 - 31, 1985
14. Modelling of Atmospheric Turbulence for Use in WECS Rotor Loading Calculations, Stockholm, December 4 - 5, 1985
15. General Planning and Environmental Issues of LS WECS Installations, Hamburg, December 2, 1987
16. Requirements for Safety Systems for LS WECS, Rome, October 17 - 18, 1988
17. Integrating Wind Turbines into Utility Power Systems, Virginia, April 11 - 12, 1989

18. Noise Generating Mechanisms for Wind Turbines, Petten, November 27 - 28, 1989

19. Wind Turbine Control Systems, Strategy and Problems, London, May 3 - 4, 1990

20. Wind Characteristics of Relevance for Wind Turbine Design, Stockholm, March 7 - 8, 1991

21. Electrical Systems for Wind Turbines with Constant or Variable Speed, Göteborg, October 7 - 8, 1991

22. Effects of Environment on Wind Turbine Safety and Performance, Wilhelmshaven, June 16, 1992

23. Fatigue of Wind Turbines, Golden Co., October 15 - 16, 1992

24. Wind Conditions for Wind Turbine Design, Risø, April 29 - 30, 1993

25. Increased Loads in Wind Power Stations, "Wind Farms", Göteborg, May 3 - 4, 1993

26. Lightning Protection of Wind Turbine Generator Systems and EMC Problems in the Associated Control Systems, Milan, March 8 - 9, 1994

27. Current R&D Needs in Wind Energy Technology, Utrecht, Sept. 11 - 12, 1995

28. State of the Art of Aeroelastic Codes for Wind Turbine Calculations, Lyngby, Denmark, April 11 - 12, 1996

29. Aero-acoustic Noise of Wind Turbines,Noise Prediction Models, Milano, Italy, March 17 - 18, 1997

30. State of the Art on Power Performance Assessments for Wind Energy Conversion Systems, Athens, Greece, Dec.8 - 9, 1997