

# INFLUENCES OF VERTICAL WIND PROFILES ON POWER PERFORMANCE MEASUREMENTS

U. Bunse, H. Mellinghoff  
DEWI GmbH, Ebertstr. 96, D – 26382 Wilhelmshaven  
e-mail: u.bunse@dewi.de

## Abstract

The IEC 61400-12-1 [1] and its former version are the base of almost any power performance warranty of the past years. This standard describes power performance measurements based on wind speeds measured on a meteorological mast at turbine hub height 2 to 4 rotor diameters away from the turbine location. This approach implicates that the wind conditions at the top of the mast are representative for the complete rotor area although it is evident that this is not necessarily the case, especially for large multi-MW turbines. In order to properly describe the inflow conditions to the wind turbine the assessment of the vertical wind profile is therefore an integral part of the discussions for revisions of standards for power performance measurements published by IEC [1], MEASNET [3] and FGW [4].

The present work focuses on the assessment of the vertical wind profile for a set of IEC power performance measurements performed by DEWI GmbH, located in complex as well as in flat terrain. The vertical wind profile has been determined by means of the power law profile and expressed as wind shear exponent  $\alpha$ .

The wind shear exponent  $\alpha$  shows strong dependencies on measuring and site conditions. Even between reference mast and turbine location there are significant differences visible so that a site calibration correction factor for the wind shear exponent  $\alpha$  is proposed.

Different kinds of wind profile filters have been compiled, i.e. defined for a limited range or based on site conditions. These filters have been applied to the measured data during the site calibration and power performance measuring campaign. Only small influences on the annual energy production (AEP) are visible. However, the kind of data filtering can influence the remaining amount of data sets significantly, especially if the filter is defined independently of the site conditions. As recent power curve guarantees often require a special range for  $\alpha$  generally independent of site conditions, this aspect should be considered in the guarantee contracts, too.

## 1 Introduction

According to the latest revisions of the MEASNET [3] and FGW [4] standards it is required to perform additional wind speed measurements in order to evaluate the wind shear exponent  $\alpha$  as additional parameter during a power performance measurement. The required measuring heights are different: MEASNET requires the lower blade tip height +/- 10 % rotor diameter (D), whereas the Technical Guideline of the FGW demands a height between lower blade tip height and 1/3 D below hub height. In order to gain comparable results DEWI GmbH performs the additional wind speed measurements at the lower blade tip height, if feasible. Investigations regarding effects of wind profiles by means of the wind shear exponent  $\alpha$  on site calibration measurements have already been published by DEWI GmbH in [2]. The present paper further develops the analysis in [2] and also focuses on effects of  $\alpha$  on power performance measurements.

## 2 Power Performance Measurements

A set of different power performance measurements according to IEC [1] performed by DEWI GmbH have been compiled. The measured turbine types are different, but all of them are of the multi-MW class. The hub height differs between about 65 m and 120 m. The turbines are located in complex and flat terrain so that different terrain conditions can be studied. Maximum terrain slopes between about 0 and 16 degrees are observed in the measurement sectors for the power performance measurements, considering a radial distance of 4 D seen from the reference mast.

In case of complex terrain the site calibrations were performed by measurements.

## 3 Assessment of Vertical Wind Profile

The vertical wind profile is determined by means of the power law profile [5]:

$$\frac{v_{HH}}{v_{H'}} = \left( \frac{HH}{H'} \right)^\alpha \quad \text{Equation 1}$$

v: wind speed [m/s]

HH: turbine hub height [m]

H': lower height, if possible at lower blade tip height [m]

$\alpha$ : wind shear exponent [-]

The wind shear exponent  $\alpha$  will be positive if the wind speed is decreasing with the height. It will be negative if the wind speed is increasing with the height, for  $v_{HH} = v_H$  it is not defined. For ideal flat terrain  $\alpha$  is 0.14 [6], assuming a roughness length of about 0.03 m.

In Table 1  $\alpha$  is exemplarily given for a fictitious turbine in combination with the effects on the wind speeds in the two different heights.

Table 1: Wind shear exponent  $\alpha$  for a fictitious turbine with hub height of 100 m and a rotor diameter of 80 m

Wind shear exponent [-]	$v_{\text{LowBlade}} / v_{\text{HubHeight}}$ [%]
0.20	90
0.14	93
0.10	95
-0.10	105

Based on measurements at sites with different terrain characteristics the frequency distribution of  $\alpha$  has been evaluated (see Figure 1). It is evident that the

distribution of  $\alpha$  clearly differs. Furthermore there is no general trend visible that in complex terrain  $\alpha$  is lower than in flat terrain, considering the average values in addition. However, the distribution of  $\alpha$  is broader for flat than for complex terrain generally.

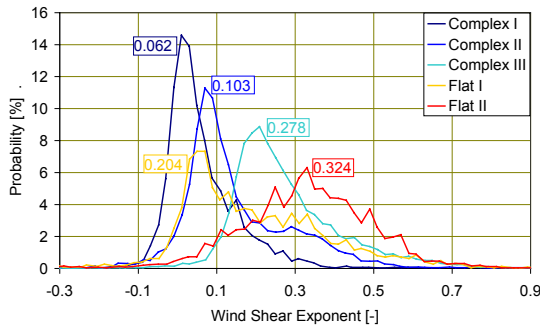


Figure 1: Frequency distribution of the wind shear exponent  $\alpha$  for different sites based on IEC compliant site calibration or power curve data sets respectively.

#### 4 Influence of Characteristic Parameters

The wind shear exponent  $\alpha$  has been investigated depending on different meteorological parameters, like wind speed (see Figure 2), wind direction (see Figure 3) and turbulence intensity (see Figure 4). Here the data sets of the final power curve, i.e. only data within the measurement sector, have been considered.

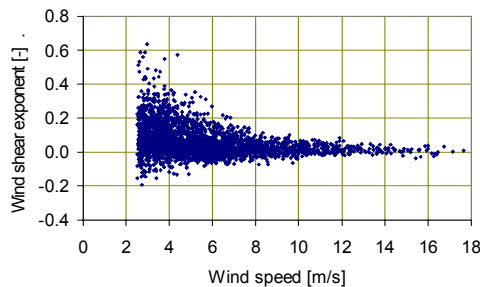


Figure 2: Wind shear exponent  $\alpha$  versus wind speed at hub height, complex site, wind speeds measured at hub height and lower blade tip height.

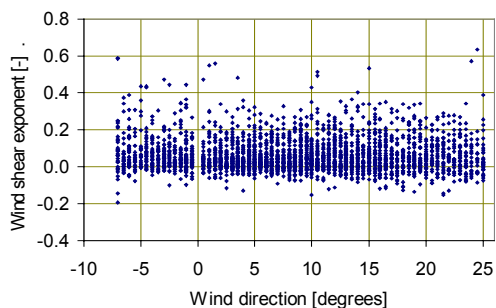


Figure 3: Wind shear exponent  $\alpha$  versus wind direction at hub height, complex site, wind speeds measured at hub height and lower blade tip height.

With respect to the wind speed the average  $\alpha$  shows generally a comparable pattern, i.e.  $\alpha$  is higher for low

wind speeds, it is decreasing with increasing wind speeds.

The correlation with the wind direction is more pronounced. Therefore bin analyses of the data using a bin width of 5 or 10 degrees have been performed additionally (see below) in order to describe this dependency more properly.

Regarding turbulence intensity there are trends visible for both flat and complex terrain that  $\alpha$  is higher or has a broader scatter in case of lower turbulence intensity. This follows the theory: Lower turbulence intensities comply with more stable stratification and a more decreasing wind speed with the height, i. e. a higher  $\alpha$ . Anyway, this behaviour is not necessarily the case for each measurement (see Figure 4).

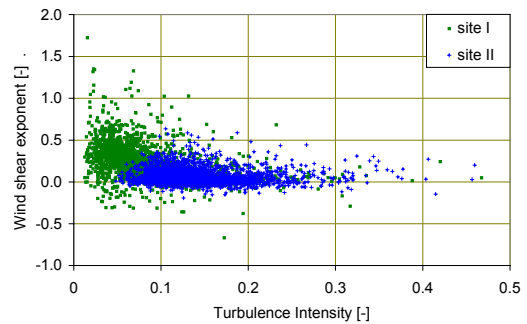


Figure 4: Wind shear exponent  $\alpha$  versus turbulence intensity, wind speeds measured at hub height and lower blade tip height.

The wind shear has been assessed at various heights at some of the considered sites. For these measurements the influence of different measuring heights of the lower anemometer on  $\alpha$  has been investigated.

For a measurement in complex terrain the results for the different wind shear exponents are presented in Figure 5. Here the focus is set on data within the power performance measurement sector. Even within this measurement sector a maximum difference of 0.035 for  $\alpha$  is observed.

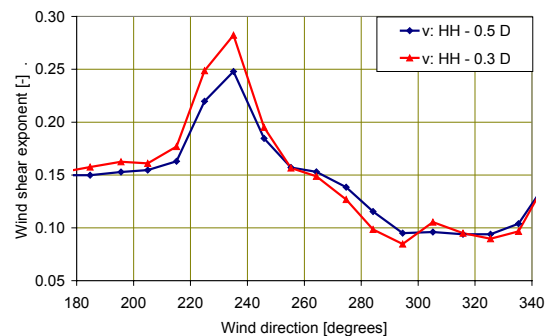


Figure 5: Wind shear exponent  $\alpha$  versus wind direction, bin width: 10 degrees, complex site, wind speeds measured at hub height (HH) and two lower heights (HH - 0.5 D and HH - 0.3 D).

At a different site in flat terrain differences between the wind shear exponents gained from different heights in

the range of  $-0.087$  to  $+0.029$  are observed within the measurement sector. The wind speed measurements were performed at HH, HH  $-0.6$  D and HH  $-0.3$  D.

Furthermore the data have been investigated with regards to stratification impacts. Theoretically the stratification during the night is more stable than during the day that is accompanied by a higher  $\alpha$  during the night. This behaviour can be confirmed for different sites, in flat as well as in complex terrain. For a measurement in flat terrain e.g. an average difference for  $\alpha$  of  $0.18$  is observed within the measurement sector (see Figure 6).

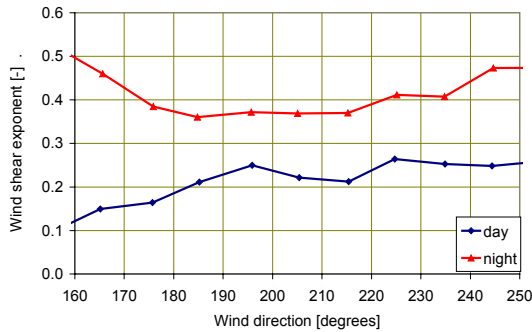


Figure 6: Wind shear exponent  $\alpha$  versus wind direction for data within power curve measurement sector, bin width: 10 degrees, flat terrain, wind speeds measured at HH and HH  $-0.3$  D.

## 5 Effects on Site Calibration Measurements

During the site calibration campaign the additional wind speed measurements were performed on the reference mast and on the mast placed at the future turbine location. For both locations  $\alpha$  has been evaluated.

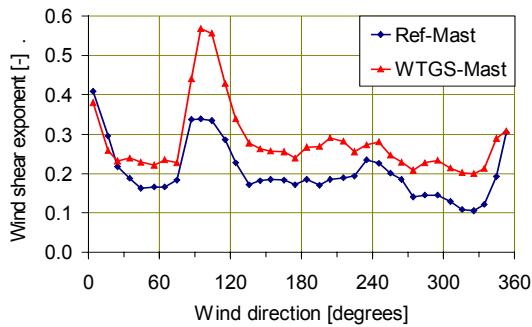


Figure 7: Wind shear exponent  $\alpha$  versus wind direction, bin width: 10 degrees, wind speed measured at HH and lower blade tip height. Power curve measurement sector within 180 and 340 degrees. Mast effects around 0 degree.

Between the different mast locations there are significant differences for  $\alpha$  visible although the mast distance was according to IEC between 2 and 4 D, mostly around 2.5 D. Depending on the site conditions  $\alpha$  at the reference mast can be lower (see Figure 7) or higher (see Figure 8) compared to the turbine location.

Consequence: The reference mast position wind shear information cannot be transferred necessarily to the turbine position.

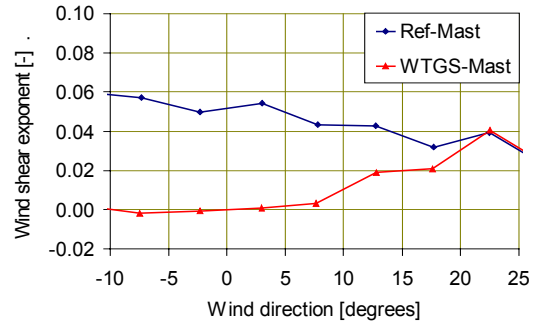


Figure 8: Wind shear exponent  $\alpha$  versus wind direction for power curve measurement sector, bin width: 5 degrees, wind speed measured at HH and lower blade tip height.

Due to these significant differences a site calibration correction factor for the wind shear exponent  $\alpha$  is proposed. For the measurement presented in Figure 7 the following correction factors were compiled (see Figure 9).

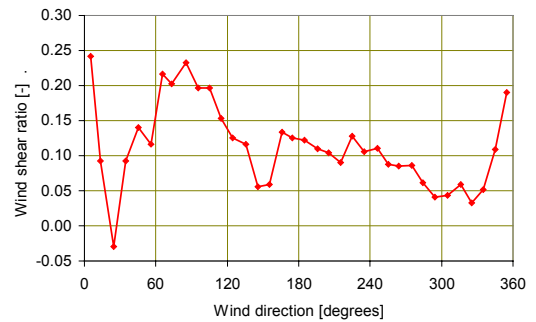


Figure 9: Site calibration correction factor for  $\alpha$ , bin width 10 degrees. Power curve measurement sector within 180 and 340 degrees.

This correction factor has been determined following the IEC methodology for the wind speed correction, depending on wind direction bins  $j$ .

$$\alpha_{SC,j} = \frac{\alpha_{WTGS,j}}{\alpha_{Ref,j}} \quad \text{Equation 2}$$

$\alpha_{WTGS}$ : wind shear exponent at turbine location [-]

$\alpha_{Ref}$ : wind shear exponent at reference mast [-]

$\alpha_{SC}$ : site calibration correction factor for  $\alpha$  [-]

For the following analyses this correction factor for  $\alpha$  has been applied to the power curve data sets to obtain the theoretical  $\alpha$  at the turbine location.

## 6 Approaches for Wind Profile Filter

Different kinds of wind profile filters have been compiled, dependent and independent on site conditions.

In recent power curve guarantees a fixed range for  $\alpha$  is often defined that has to be considered for any power curve measurement following the respective guarantee

contract. For the first wind profile filter a limited range for  $\alpha$  has therefore been established (see Equation 3). This range has been defined based on the demands on  $\alpha$  in different power curve guarantees.

$$\text{Filter I: } \alpha \in ]0.08;0.20] \quad \text{Equation 3}$$

On the other hand a second wind profile filter has been assessed to consider only typical wind profiles for the respective sites (see Equation 4). To exclude those data with extreme wind profiles only data fulfilling the following conditions have been used for the data evaluation.

$$\text{Filter II: } \alpha_j = \alpha_{\mu,j} \pm \alpha_{\sigma,j} \quad \text{Equation 4}$$

$\alpha_{\mu,j}$ : Average wind shear exponent for wind direction bin j [-]

$\alpha_{\sigma,j}$ : Standard deviation of wind shear exponent for wind direction bin j [-]

Both filters have been applied to the wind shear exponent obtained at the turbine location, i.e. for the site calibration data to the measured  $\alpha$  and for the power curve data to the evaluated one by means of the correction factor according to Equation 2.

### 6.1 Assessment of Annual Energy Production

For analysing possible effects of the wind profile filters on the annual energy production (AEP) the filters have been applied to the IEC compliant data base of four different measurements. Two of these measurements are located in flat terrain, the other two at complex sites. For the particular databases the extrapolated AEP has been calculated according to IEC 61400-12-1 [1]. For an annual average wind speed of 7 m/s the results are given in Table 2.

Table 2: Comparison of the extrapolated AEP for an annual average wind speed of 7 m/s for databases with and without wind profile filtering. Wind speed measurements at HH and at lower height as stated in column 2. Incomplete data sets are marked in italics.

Terrain Conditions	Measuring Height Low Anemometer	Data Filtering	AEP extrapol. u = 7 m/s	Remarks
Flat, site 1	HH – 0.3 D	IEC	100.0 %	
		Filter I	(96.4 %)	33 % data
	HH – 0.6 D	IEC	100.0 %	
		Filter I	(98.1 %)	39 % data
Flat, site 2	HH – 0.5 D	IEC	100.0 %	
		Filter I	(100.6 %)	52 % data
Complex, site 3	HH – 0.5 D	IEC	100.0 %	
		Filter I	(100.7 %)	91 % data
Complex, site 4	HH – 0.5 D	IEC	100.0 %	
		Filter I	(sc incomplete)	
		Filter II	(sc incomplete)	

The AEP evaluated for the IEC compliant database has been set to 100 % and compared with the AEP obtained for the filtered databases.

It should be noted that all data sets with application of Filter I are incomplete according to IEC 61400-12-1

because the accumulated measuring time is less than 180 hours of sampled 10 minutes data. Between 33 % and 91 % of the required amount of data sets remain in the final power curve data set. Nevertheless the AEP is given for these calculations, too, although these results have to be considered with reservations.

However, there are only small differences visible for the AEP of the filtered, complete databases. These AEP differ by less than 1 % from the IEC compliant AEP. This aspect suggests that the method of the IEC 61400-12-1 for evaluating a power curve is also representative for sites with different wind shears without specifically filtering for the wind shear exponent  $\alpha$ .

At site 1  $\alpha$  has been evaluated for two different heights. Although it has been concluded that the measuring height of the additional anemometer influences  $\alpha$  (see Figure 5), the impacts on the AEP are low.

Furthermore it is evident that there are no significant differences visible between sites in flat and complex terrain considering the complete databases so that terrain characteristics seem to have less influence on this kind of data filtering either.

For site 4 which is located in complex terrain the site calibration data set has been incomplete after application of both wind profile filters so that no further analysis is possible.

Thus, the kind of data filtering can influence the amount of remaining data sets significantly. Especially if only a fixed range for  $\alpha$  is allowed (Filter I), the remaining data sets are often incomplete according to IEC 61400-12-1, like it is the case for all presented measurements. That means that it is either required to perform these measurements for a longer period or that it is impossible at all to get a complete database because the requested  $\alpha$  is untypical for the respective site.

For power curve guarantees a special range for  $\alpha$  should therefore be defined based on site specific conditions if it is used at all.

### 7 Conclusions and Outlook

1. The present study demonstrates that the wind shear exponent  $\alpha$  differs significantly between different sites. Furthermore different measuring heights are influencing the results for  $\alpha$ .
2. The wind shear exponent  $\alpha$  calculated during the site calibration campaign for the reference mast and turbine location can differ significantly so that a site calibration correction factor for  $\alpha$  is proposed.
3. Approaches for data filtering have been proposed to exclude data with special vertical wind shear from the database. The suggested wind profile filters have only small influences on the extrapolated AEP.
4. Power curve guarantees should define requirements on  $\alpha$  based on site specific conditions because otherwise it may happen that the power performance measurements have to be performed for really long periods or that it is not possible at all to complete the measurements.
5. Further investigations on possible influences on the vertical wind shear for different conditions like

possible seasonal effects should be performed in a research frame for at least one year measuring time.

6. To estimate the vertical wind shear versus the complete rotor area, wind speed measurements at the higher blade tip height should also be performed. Remote sensing methods offer a convenient approach for this data base.

## 8 References

- [1] IEC 61400-12-1 Ed.1: Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, Dezember 2005
- [2] Bunse, U., Mellinghoff, H.: Assessment of wind profile effects for a set of site calibration measurements following IEC 61400-12-1, DEWI Magazin No. 32, February 2008
- [3] MEASNET: Power Performance Measurement Procedure, Version 4 Draft 5, 2008
- [4] FGW Fördergesellschaft Windenergie e.V.: Technische Richtlinien für Windenergieanlagen, Teil 2: Bestimmung von Leistungskurve und standardisierten Energieerträgen, Revision 15, 01.05.2008
- [5] IEC 61400-1 Ed. 3: Wind turbines – Part 1: Design requirements, 2005
- [6] Gasch, R., Tewle, J.: Windkraftanlagen, 4<sup>th</sup> edition, B.G. Teubner Verlag, 2005