POWER PERFORMANCE MEASUREMENT PROCEDURE

Version 5
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1. Introduction

The MEASNET Power Performance Measurement Procedure is the measurement procedure, agreed upon by the MEASNET members for mutual use and acceptance. The procedure is considered to be the most widely internationally accepted procedure on which a common interpretation and understanding has been exercised in accordance with the MEASNET Quality Evaluation Program, based on the objective of improving the quality of measurements continuously.

2. The reference measurement procedure

The measurement procedure is based on: "Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, First edition 2005-12, IEC 61400-12-1:2005(E).

3. Additional requirements

Within the reference power performance measurement procedure, several parameters and alternatives can be optionally used. MEASNET has decided to add additional requirements to the reference procedure, determining some parameters and alternatives as fixed in order to strengthen the quality and inter-comparability of the measurements. Deviations from these additional requirements shall be treated the same way as in the IEC document. With reference to the chapter numbers of IEC 61400-12-1:2005(E), these requirements are:

3.1 Normative references (IEC chapter 2)

IEC 60044-2 Ed. 1.2 b:2003, Instrument transformers - Part 2 : Inductive voltage transformers

3.2 Symbols and units (IEC chapter 4)

f_i	flow correction factors	
f_{i+1}	adjacent flow correction factors	
h	height of an obstacle	[m]
H	hub height of the wind turbine	[m]
n	velocity profile exponent (n=0.14)	
P_e	Perera formula	
TI	turbulence intensity	
$TI\text{-}std$	standard deviation of turbulence intensity	
U_h	free wind speed at height h of obstacle	[m/s]
z_0	roughness height	[m]
V_{hub}	wind speed at hub height (measurement height)	[m/s]
V_{tip}	wind speed at lower blade tip (measurement height)	[m/s]
Z_{hub}	hub height (measurement height)	[m]
Z_{tip}	height of lower blade tip (measurement height)	[m]
α	wind shear exponent	
$\alpha\text{-}std$	standard deviation of wind shear exponent	
ΔU_z	Influence of an obstacle on the wind speed difference	[m/s]

3.3 *Wind speed (IEC chapter 6.2)*

Calibration of the cup anemometer:
The cup anemometer shall be calibrated by a MEASNET accredited institution before use and it shall be re-calibrated after the measurement campaign. If an anemometer mounted to the lower blade tip is used, a re-calibration is obligatory.

The re-calibration of the anemometers should be carried out as wind tunnel calibration by a MEASNET accredited institution. If the re-calibration shows a deviation between the two calibrations that exceeds the limits set by the reference document (IEC 61400-12-1:2005), this is considered as an increased uncertainty of the measurement. In this case, the calibration uncertainty of the anemometer shall be equated with the observed deviation.
Alternatively, the data period affected by the change in the anemometer's operational characteristics could be identified (on the basis of comparisons with other anemometers and / or data analyses) and removed from the valid data sets.

The in situ comparison can be used as an inferior alternative to the re-calibration. The fact that the cup anemometer maintains its calibration over the duration of the measurement period shall be documented. The in situ comparison procedure shall be applied as described in IEC 61400-12-1:2005.
The so called in situ comparison is made by comparing the primary anemometer with a control anemometer, which was installed adjacent to it during the measurement campaign. The control anemometer shall also be calibrated.
The same criteria as for the re-calibration shall be used for evaluating the results of the in situ comparison.

Wind shear:
The wind shear should be measured during the power performance measurement. This wind shear measurement shall be done according the following specifications:

- The wind speed at different heights should be measured by means of the same measurement principle (for example: cup-anemometer, sonic anemometer, Lidar or Sodar).
- If two anemometers are used, they shall be of the same type.
- If two anemometers are used, they shall be both calibrated before and after the measurement period.
- If two anemometers are used, the booms on which the anemometers are mounted should have the same orientation.
- The heights which are used for determining the wind shear are hub height (± 2,5% of hub height) and lower blade tip height (± 10% of the rotor diameter).
- If wind shear measurements are performed on a site where a site calibration is needed, the wind shear measurements shall be carried out on the reference mast and the turbine position mast during site calibration.

3.4 *Rotational speed and pitch angle (IEC chapter 6.5)*

The rotational speed and the pitch angle shall be measured on wind turbines with active power control. In addition to the electric power, these essential values serve for characterizing the WT behaviour. Wind turbine controller output signals may be used for this purpose.

3.5 Data collection (IEC chapter 7.3)

The air pressure, air temperature and humidity measurements shall be carried out by using appropriate calibrated sensors. These measurements, together with rotational speed and blade pitch angle, shall be carried out as 10-minute-average values, at a sampling rate of 1 Hz or higher.

3.6 Data rejection (IEC chapter 7.4)

If an air temperature T < 2ºC occurs together with a relative humidity greater than 80%, the related data set shall be rejected, to avoid icing conditions.

3.7 Data normalization (IEC chapter 8.1)

If the difference between the site average density and the standard density (1.225 kg/m³) exceeds ±0,15 kg/m³, the average density results should be considered as more relevant, due to the additional uncertainty which is introduced in case of the normalization to standard density.
A note should be included in the final report indicating that the results for standard density might contain additional uncertainty.

3.8 Reporting format (IEC chapter 9 f and l)

Documentation of wind shear α and turbulence intensity *TI*:
The mean value, the variation (standard deviation) and the number of values of the α exponent for each wind speed bin will be obtained during the site calibration and during the power curve measurements, and included as tables in the final report.

Definition of the wind shear exponent α:

$$\alpha = \frac{\left(ln \frac{V_{hub}}{V_{tip}} \right)}{\left(ln \frac{Z_{hub}}{Z_{tip}} \right)}$$

Variables:
- V_{hub}: wind speed at hub height (measurement height)
- V_{tip} : wind speed at lower blade tip (measurement height)
- Z_{hub}: hub height (measurement height)
- Z_{tip} : height of lower blade tip (measurement height)

A histogram of the derived shear component α, as distribution shall be represented with a bin size of 0.05, whereas the bin centres are integer multiples of 0.05.

The calculation of turbulence intensity *TI* and wind shear α shall be made for measured wind speed values only (no appliance of air density normalisation and no appliance of site calibration ratio).

Presentation of results:
For the graphical and tabular presentation of these values, the corrected wind (including site calibration ratio, if applicable, and including air density normalisation) shall be used as x-axis in the figure and in the table, in order to have a compliance with the presentation of the power curve.
The measurement results of turbulence intensity *TI* and wind shear α shall be presented at least for database B and standard air density in a table and graphs. The bin averages of the turbulence intensity *TI*, which are also documented in the power curve table, should be presented in the graphs. Examples for the presentation of turbulence intensity and wind shear are shown in Annex A.

Reporting of the North band gap:
The North band gap of the wind direction measurement shall be reported.

3.9 Assessment of obstacles at the test site (IEC chapter Annex A)

The assessment of obstacles shall be carried out according to the following 5 supplements to the IEC.

1. The Perera formula shall be used during the significance test to determine the flow effect on the turbine and on the mast, as well as for the difference between these two values. The obstacle is considered as significant if at least one of these 3 results exceeds 1%.
   Note: This supplement is necessary to exclude non-realistic (false) results of the Perera formula. Without this supplement, default values can occur in the significance calculation of obstacles.

2. Very large and more expanded obstacles are shared into adequate small obstacles (50 m width)
   Note: Very large and expanded obstacles (woods, large halls, …) are not correctly assessed, if the obstacle is reduced to one point with one height and one width. If the large obstacle is shared into adequate small obstacles (with 50 m width) ,positioned in the complete area of the large obstacle, the calculation of the exclusion sector is more realistic.

3. The application of the Perera formula is incomplete in the IEC 61400-12-1. The result of formula A.1 is the influence of the obstacle at height *h* of the obstacle. Therefore, the determined gradient has to be extrapolated to hub height H. The change in the calculation is most significant for nearby objects.
   $$P_e = \left(\frac{\Delta U_z}{U_h}\right) \cdot \left(\frac{h}{H}\right)^n \cdot 100$$
   The result displays the influence in percent at the assessed location. In order to decide on the effect of a certain obstacle, the difference of two values has to be calculated, as well, as described above (see 1.).
   Note: The above mentioned formula is missing in the annex A.2 of the IEC 61400-12-1.

4. If the relative distance (L_e/D_e) amounts to less than 5, the significance test shall be calculated by using $x = 5 * D_e$, in order to exclude high obstacles adjacent to the wind turbine or mast.

Note: In the near vicinity of the wind turbine or the met mast, very high obstacles are permitted according to the Perera formula of annex A.2 of the IEC 61400-12-1. This restriction leads to a more realistic limitation of the permitted height.

5. The shear component α and roughness length z_0 are connected with each other. To prevent unrealistic values during the calculations, the combination of the α-value of 0.14 and the z_0 value of 3 cm should be used.
   Note: The roughness length must be defined to get comparable results in the obstacle assessment.

3.10 Site calibration procedure (IEC chapter Annex C)

C.3 Data acquisition and analysis
If low temperatures are expected during the site calibration, temperature and relative humidity measurements shall be carried out in order to identify ice formation situations, by means of the combined temperature and relative humidity filter (see chapter 3.6).

The rejection criterion 3) of the IEC guideline is supplemented as follows:
3) mean wind speed (**measured at the reference mast**) less than 4 m/s or higher than 16 m/s

Bin size for site calibration shall be higher than twice the standard uncertainty of the wind direction sensor measurement and not higher than 10º. 10º is recommended.

If the following conditions are accomplished, then a wind direction bin is valid:
The data set for each bin shall consist of at least 24 h of data. Of these, there shall be at least 6 h of data sets with wind speeds above 8 m/s and at least 6 h of data sets with wind speeds below 8 m/s.

C.5 Selection of final measurement sector
The change of flow correction factors shall be evaluated under the condition that the data base of the adjacent bin is complete.
The change of flow correction factors (f_i ; f_{i+1}) between neighbouring sectors should amount to less than 2 %:

$$\text{Abs}\,[f_i - f_{i+1}\,]\,/\,f_{i+1} < 2\,\%$$

3.11 Evaluation of uncertainty in measurement (IEC chapter Annex D)

The uncertainty calculation shall be carried out according to the procedure given in Annex E of the IEC guideline. The quantities which are used for the variables shall be determined for each measurement individually and they shall be documented.

Annex A: Exemplary table and figures for the presentation of results

Table 1: Example of presentation of the measured power curve
The wind shear exponent α has been calculated using the wind speed measurements at the heights 65 m and 31 m. The hub height is 65 m and the rotor diameter amounts to 71 m.

Reference air density: 1,225 kg/m³					Measured power curve (database B)						
Bin-no. [-]	Hub height wind speed [m/s]	Power output [kW]	C_p [-]	No. of data sets [-]	Category A Standard uncertainty s_i [kW]	Category B Standard uncertainty u_i [kW]	Combined uncertainty Standard uncertainty u_{ci} [kW]	Turbulence intensity *TI* [-]	Standard deviation of turbulence intensity *TI-std* [-]	Wind shear exponent α [-]	Standard deviation of wind shear exponent α-std [-]
4	2.13	1.9	0.08	15	0.4	8.5	8.5	0.210	0.039	0.249	0.184
5	2.52	7.5	0.19	20	1.0	8.7	8.8	0.175	0.047	0.250	0.122
6	3.01	20.4	0.31	28	1.4	9.2	9.3	0.144	0.028	0.324	0.194
7	3.52	38.8	0.37	49	1.0	10.0	10.1	0.120	0.031	0.406	0.169
8	4.01	62.8	0.40	93	1.3	11.2	11.2	0.113	0.031	0.444	0.132
9	4.46	89.9	0.42	68	1.5	12.4	12.4	0.099	0.033	0.365	0.112
10	5.03	127.8	0.41	64	2.0	14.7	14.8	0.090	0.029	0.420	0.113
11	5.49	169.0	0.42	77	2.6	18.2	18.4	0.079	0.037	0.362	0.177
12	6.02	226.5	0.43	86	3.0	23.0	23.2	0.076	0.034	0.384	0.128
13	6.52	295.8	0.44	87	3.8	28.1	28.4	0.076	0.040	0.424	0.097
14	6.99	368.7	0.45	99	4.4	33.1	33.4	0.070	0.040	0.423	0.129
15	7.50	460.2	0.45	103	4.4	39.2	39.4	0.068	0.024	0.443	0.094
16	8.00	557.7	0.45	122	5.3	44.9	45.2	0.070	0.029	0.456	0.097
17	8.49	663.3	0.45	136	6.1	58.1	58.5	0.067	0.028	0.483	0.079
18	9.01	818.3	0.46	122	6.6	69.6	69.9	0.070	0.023	0.426	0.080
19	9.53	968.5	0.46	143	7.0	78.1	78.4	0.067	0.025	0.383	0.079
20	9.98	1123.5	0.47	156	7.8	84.6	84.9	0.067	0.026	0.377	0.076
21	10.50	1287.6	0.46	135	8.1	91.7	92.1	0.068	0.021	0.367	0.066
22	11.00	1472.6	0.46	129	10.3	94.3	94.8	0.065	0.026	0.362	0.059
23	11.48	1618.5	0.44	80	13.1	91.6	92.5	0.062	0.016	0.365	0.047
24	11.98	1780.8	0.43	101	11.5	88.3	89.0	0.060	0.022	0.355	0.049
25	12.49	1912.4	0.40	106	9.5	71.3	71.9	0.059	0.027	0.345	0.045
26	12.97	2003.1	0.38	80	5.3	43.6	43.9	0.063	0.014	0.331	0.044
27	13.51	2036.8	0.34	66	7.7	25.7	26.8	0.062	0.023	0.324	0.040
28	14.00	2063.5	0.31	49	4.0	19.5	19.9	0.061	0.020	0.297	0.042
29	14.48	2063.7	0.28	64	6.9	18.0	19.3	0.062	0.030	0.290	0.040
30	14.99	2079.5	0.25	42	2.7	18.4	18.6	0.062	0.020	0.291	0.040
31	15.52	2081.9	0.23	34	1.8	17.3	17.4	0.062	0.017	0.312	0.031
32	16.04	2083.4	0.21	40	1.5	17.3	17.4	0.068	0.022	0.296	0.036
33	16.47	2085.4	0.19	26	1.3	17.3	17.3	0.069	0.021	0.297	0.025
34	17.01	2083.6	0.17	20	1.0	17.3	17.4	0.067	0.017	0.286	0.025
35	17.56	2081.6	0.16	18	2.3	17.5	17.7	0.065	0.021	0.297	0.029
36	17.97	2077.3	0.15	13	3.0	17.2	17.5	0.068	0.036	0.273	0.027
37	18.46	2083.0	0.14	12	1.9	17.3	17.4	0.065	0.021	0.270	0.035
38	18.96	2080.1	0.13	8	1.1	17.3	17.3	0.062	0.026	0.243	0.034
39	19.51	2081.7	0.12	7	1.2	17.3	17.3	0.065	0.019	0.237	0.027
40	20.05	2081.0	0.11	6	4.9	17.3	17.9	0.067	0.034	0.342	0.029

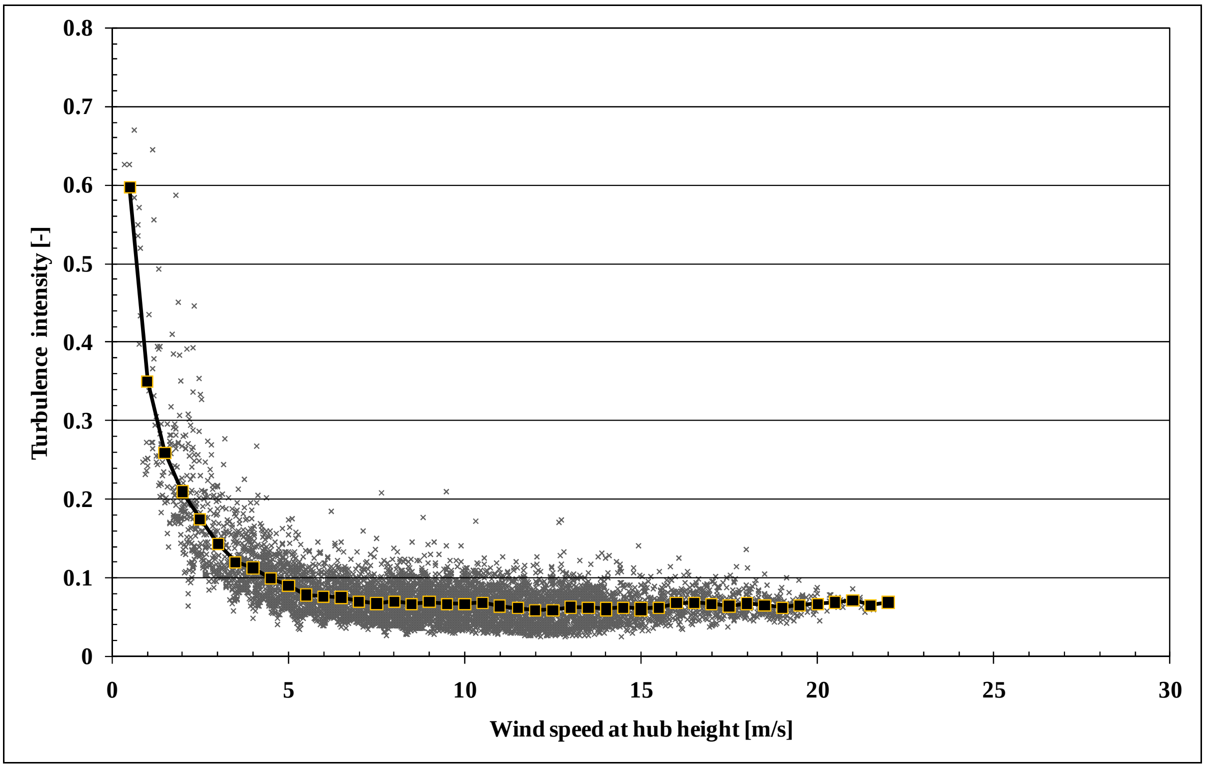

Figure 1: **presentation of turbulence intensity (example): scatter plot of 10-minute-average values and bin averaged values with a bin size of 0.5 m/s**

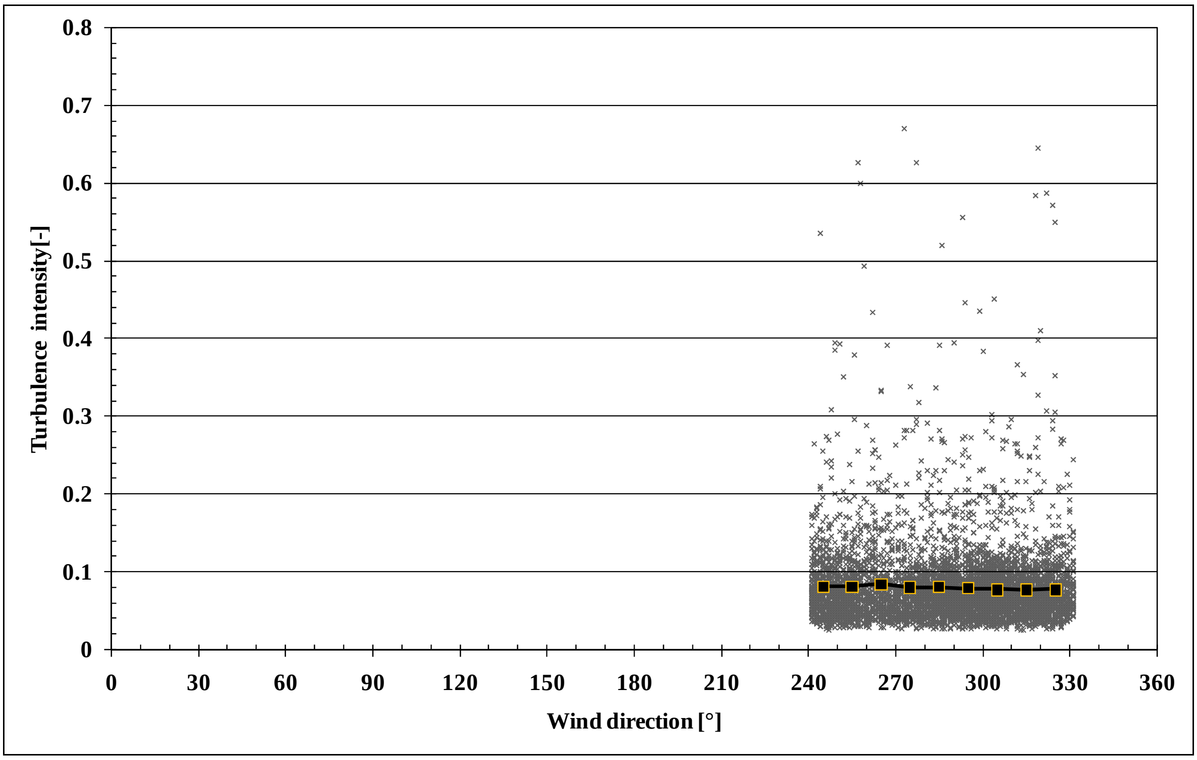

Figure 2: **presentation of turbulence intensity (example): scatter plot of 10-minute-average values and bin averaged values with a bin size of 10°**

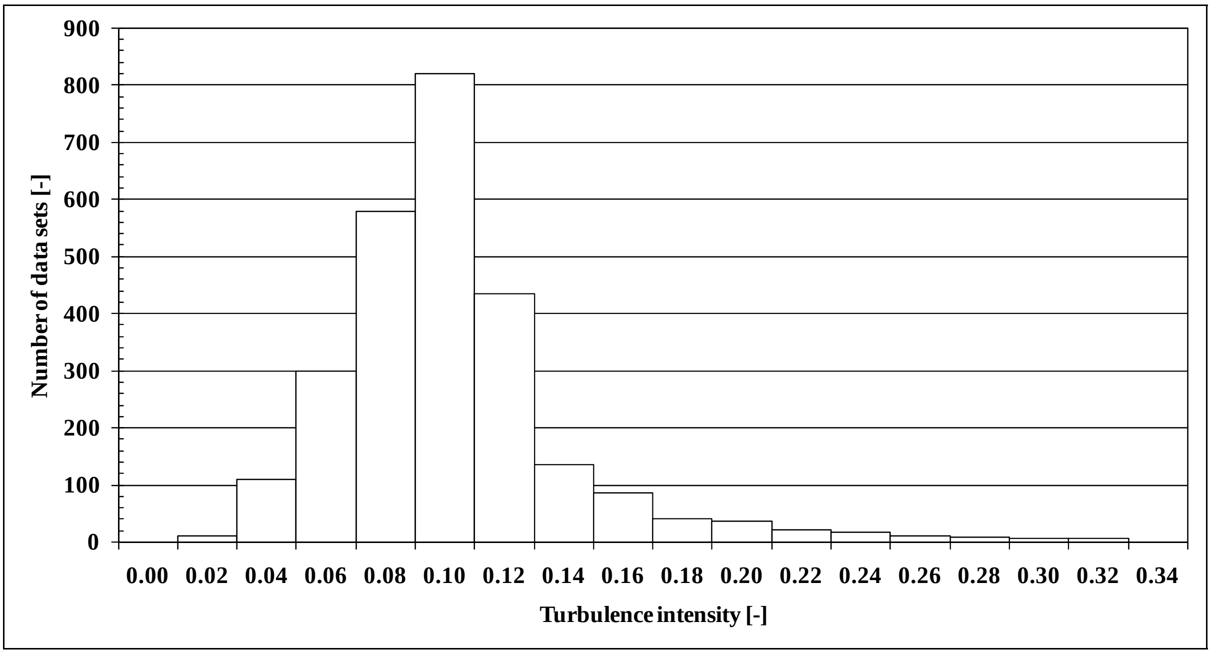

Figure 3: presentation of turbulence intensity (example): number of data sets

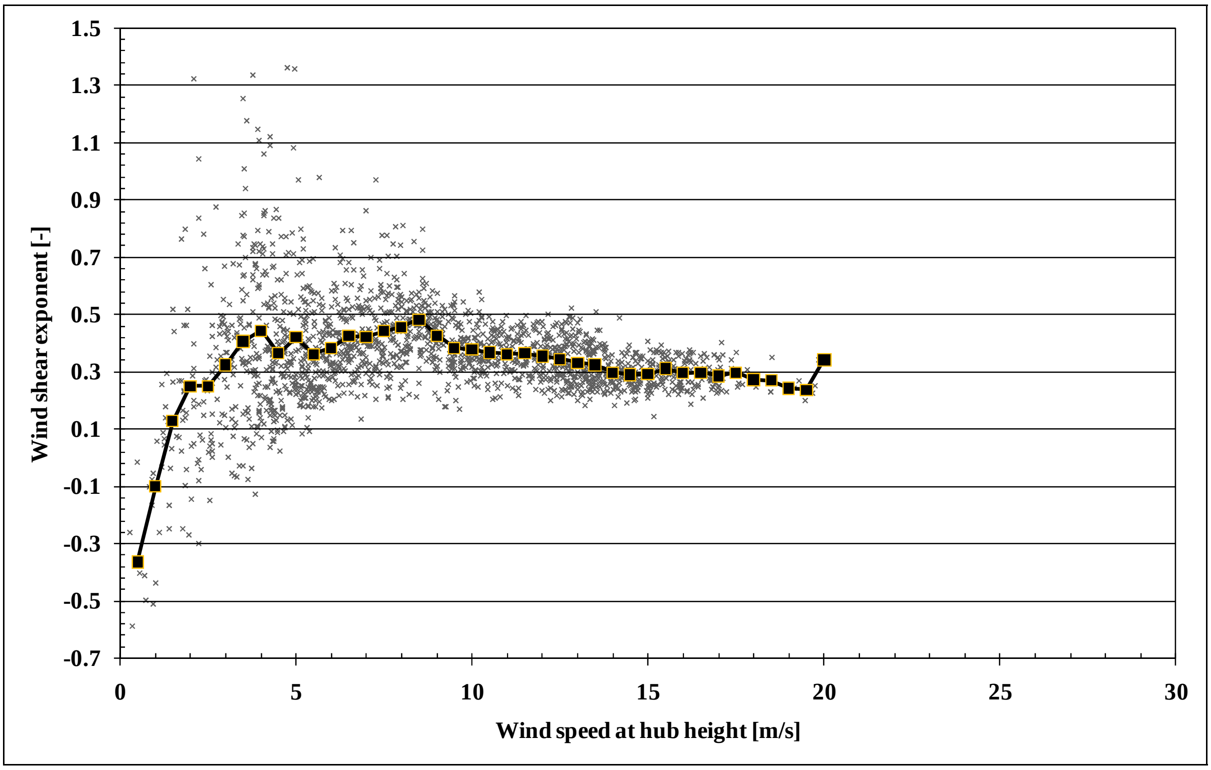

Figure 4: presentation of wind shear (example): scatter plot of 10-minute-average values and bin averaged values with a bin size of 0.5 m/s

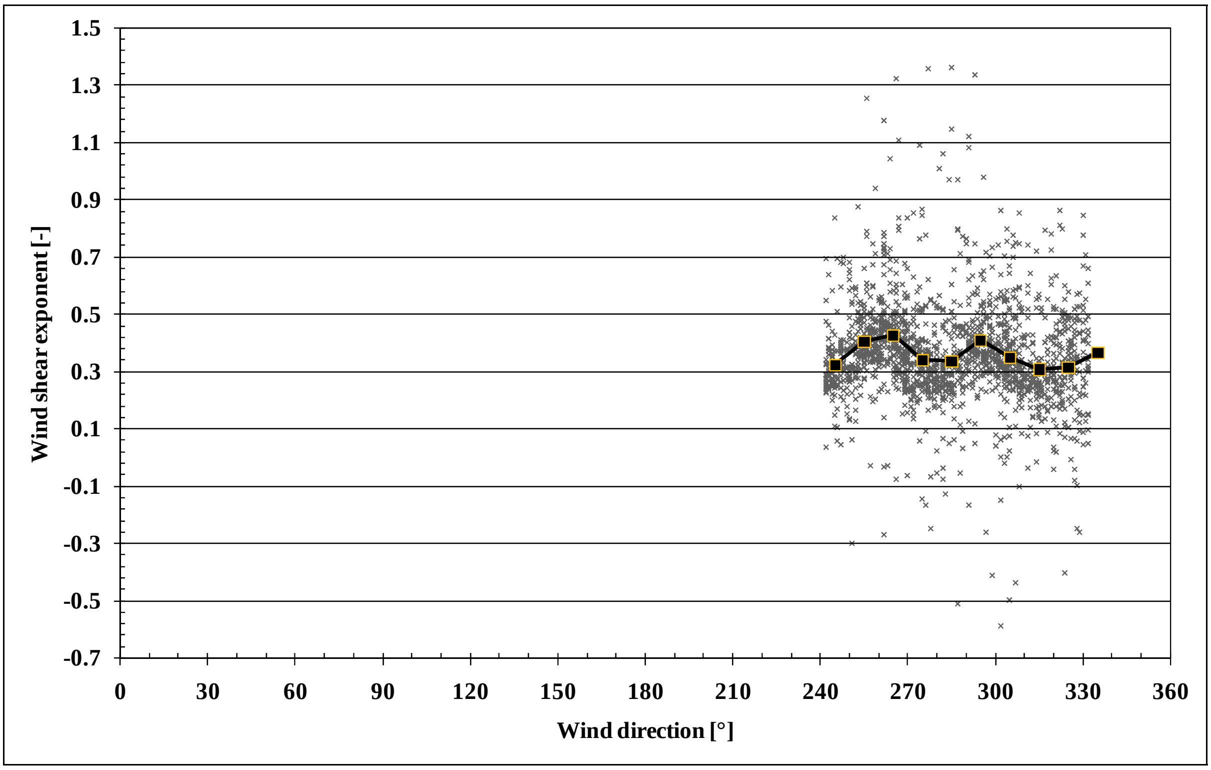

Figure 5: **presentation of wind shear (example): scatter plot of 10-minute-average values and bin averaged values with a bin size of 10°**

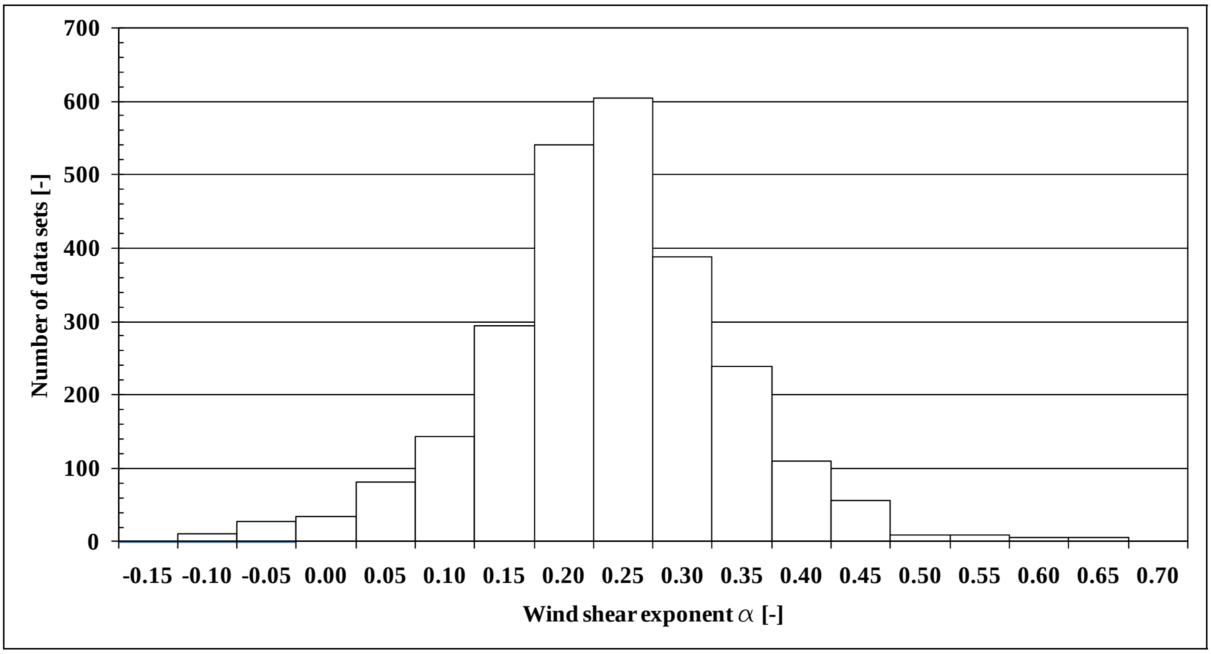

Figure 6: **presentation of wind shear (example): number of data sets**