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Rotor equivalent wind speed for power curve measurement – comparative exercise for IEA Wind Annex 32

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Abstract. A comparative exercise has been organised within the International Energy Agency (IEA) Wind Annex 32 in order to test the Rotor Equivalent Wind Speed (REWS) method under various conditions of wind shear and measurement techniques. Eight organisations from five countries participated in the exercise. Each member of the group has derived both the power curve based on the wind speed at hub height and the power curve based on the REWS. This yielded results for different wind turbines, located in diverse types of terrain and where the wind speed profile was measured with different instruments (mast or various lidars). The participants carried out two preliminary steps in order to reach consensus on how to implement the REWS method. First, they all derived the REWS for one 10 minute wind speed profile. Secondly, they all derived the power curves for one dataset. The main point requiring consensus was the definition of the segment area used as weighting for the wind speeds measured at the various heights in the calculation of the REWS. This comparative exercise showed that the REWS method results in a significant difference compared to the standard method using the wind speed at hub height in conditions with large shear and low turbulence intensity.

1. Introduction

The performance of large wind turbines is known to be influenced by the vertical wind shear across the rotor [1][2][3][4][5]. The Rotor Equivalent Wind Speed (REWS) method consists of averaging the weighted wind speed over the swept rotor area [6]. It provides a more accurate estimate of the kinetic energy flux passing through the rotor than considering only the wind speed measured at hub height. Presenting the wind turbine power output as a function of the REWS instead of the wind speed at hub height can provide a power curve significantly less dependent on the shear.

The REWS method is one of the main modifications proposed to the IEC 61400-12-1 standard for wind turbine power performance measurement currently under revision [7]. It requires measurements of the wind speed at several heights distributed between the lower and higher tip heights. These measurements can be performed with a tall mast or a ground based remote sensing wind profiler such as a lidar. In both cases the uncertainty if the wind speed measurements must be thoroughly determined and quantified through a calibration and a classification procedure as suggested in Annex L in the new IEC 61400-12-1 standard draft [5].

The IEA Annex 32 aims at producing best practices for the use of lidars in wind energy. One subgroup under this task (work package 3.1) has been working on the implementation of the REWS method. The aim of this exercise was to compare the difference between the power curve obtained using the wind speed at hub height as reference (hub height power curve from now on) and the REWS power curve, for various conditions such as: various turbine types and sizes, various wind speed profile sensors (met mast, pulsed or continuous wave (cw) lidars), various locations that imply various shear and turbulence conditions. Furthermore, the variation in the interpretation of the method from one institute to another is also a major factor, as we learned during the exercise.

Such a comparative exercise can only be beneficial if the REWS method is applied in a systematic way to all the different datasets. For this reason, the participants took two preliminary steps to define the main pitfalls in the methodology as currently described in the IEC draft and to agree on the implementation to be adopted for the final step of this work.

The following section briefly explains the REWS method. Sections 3 and 4 present the results from the two preliminary steps. The results from the various datasets are presented in Section 5.

2. Rotor equivalent wind speed as defined in the new standard draft

The Committee Draft (CD) of the second edition of the IEC 61400-12-1 [5; pp. 30-31] is not publicly available; the text which relates to the REWS relevant to the comparative exercise discussed in this paper is therefore provided below.

The rotor-equivalent wind speed is the wind speed corresponding to the kinetic energy flux through the swept rotor area, when accounting for the vertical shear. For the case that at least three measurement heights are available the rotor equivalent wind speed is defined as

$$v_{eq} = \left(\sum_{i=1}^{n_h} v_i^3 \frac{A_i}{A} \right)^{1/3} \quad (1)$$

where

n_h is the number of available measurement heights ($n_h \geq 3$);

v_i is the 10 min average wind speed measured at height i;

A is the complete area swept by the rotor (i.e. πR^2 with Radius R);

A_i is the area of the i th segment, i.e. the segment the wind speed v_i is representative for.

The segments (with areas Ai) shall be chosen in the way that the horizontal separation line between two segments lies exactly in the middle of two measurement points.

The segment areas are then derived according to

$$A_i = \int_{z_i}^{z_{i+1}} c(z)dz \quad (2)$$

where

z_i is the height of the i^{th} segment separation line, numbered in the same order as v_i (either top down or bottom up);

$c(z) = 2\sqrt{R^2 - (z-H)^2}$ with R the rotor radius and H the hub height.

3. Step 1: one wind speed profile

3.1. Exercise description

As a first preliminary step the participants were provided with one 10 minute wind speed profile, which as measured by the met mast at the Høvsøre DTU test site [8]. This profile is given in Table 1. The participants were asked to calculate the REWS, according to the indications given in the IEC 61400-12-1 CD (presented in Section 2), assuming a hub height at 80m and a rotor diameter of 100m.

3.2. Results

Eight organizations from five countries participated in this exercise and one of them provided two different answers, which already indicates some ambiguities in the interpretation of the method described in section 2. The nine results for the REWS are shown in Figure 1. Three different values were obtained: six participants returned 9.38m/s (R1), two returned 9.40m/s (R2) and one returned 9.35m/s (R3). The results all agree in that for this profile, the REWS is higher than the wind speed at hub height. The relative difference is between 1.2% to 1.8%. The discrepancies between the answers might not appear to be very large. From a purely analytical point of view, however, given the simplicity of the exercise, the only possible reasons for discrepancies are differences in the interpretation of the method.

Table 1. Ten minute wind speed profile used in the first preliminary step

Measurement Heights [m]	Wind speed [m/s]
116	11.46
100	10.43
80*	9.24
60	7.81
40	6.05

*assumed hub height

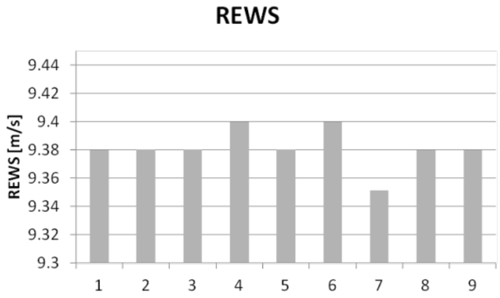

Figure 1. Results for first preliminary step: REWS from one given wind speed profile

The discrepancies result from the combination of (1) the treatment of the wind speed profile and (2) the weighting function applied to the different wind speeds constituting the profile. A discussion of the three results (R1, R2 and R3) follows.

Result R1 was obtained by using the wind speed profile directly as provided and adapting the weighting to the profile, defining the limit between two consecutive segments as the middle height between two consecutive wind speed measurement heights (see details in Table 2).

Table 2. Details of profile and weighting function resulting in REWS=9.38m/s (R1)

Measurement Heights [m]	Wind speed [m/s]	Segment weighting* [%]	Segment inferior limit height [m]	Segment superior limit height [m]	Segment height [m]
116**	11.46	16.31	108	130	22
100	10.43	21.04	90	108	18
80	9.24	25.3	70	90	20
60	7.81	23.16	50	70	20
40	6.05	14.24	30	50	20

*ratio between the segment area (A_i in section 2) and the rotor swept area (A in section 2)
** Values in red indicates differences between Tables 2, 3 and 4.

Result R2 was obtained by linearly interpolating the wind speed profile to estimate the wind speed at 120m (see Table 3). As a result, the heights in the profile have are spatially distributed evenly. The weighting function was defined following the same principle as in R1 (defining the limit between two consecutive segments as the middle height between two consecutive wind speed measurement heights), but adapting to the profile with a wind speed available at 120m instead of 116m (all the segments have the same height).

Table 3. Details of profile and weighting function resulting in REWS=9.40m/s (R2)

Measurement Heights [m]	Wind speed [m/s]	Segment weighting [%]	Segment inferior limit height [m]	Segment superior limit height [m]	Segment height [m]
120	11.71	14.24	110	130	20
100	10.43	23.115	90	110	20
80	9.24	25.29	70	90	20
60	7.81	23.115	50	70	20
40	6.05	14.24	30	50	20

Result R3 was obtained by using directly the wind speed profile as provided but defining the weighting function so that all the segments had the same height (see Table 4).

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Table 4. Details of profile and weighting function resulting in REWS=9.35m/s (R3)

Measurement Heights [m]	Wind speed [m/s]	Segment weighting [%]	Segment inferior limit height [m]	Segment superior limit height [m]	Segment height [m]
116	11.46	14.24	110	130	20
100	10.43	23.115	90	110	20
80	9.24	25.29	70	90	20
60	7.81	23.115	50	70	20
40	6.05	14.24	30	50	20

The participants agreed to use the measured wind speed profile and avoid interpolation or extrapolation because they increase the uncertainty in the wind speed and subsequently in the power curve measurement. Regarding the weighting, because the wind speed is assumed to be representative for the whole segment, the measurement height should be more or less in the middle of the segment; we have chosen to follow the definition given in the IEC standard draft: the segment limit should lie in the middle of two consecutive measurement heights. These two indications result in solution R1, which is the REWS value obtained by the largest number of participants.

4. Step 2: one power curve dataset

In the second preliminary step, the participants received a full power curve data set including 10 min power data from a wind turbine and simultaneous wind speed measurements at 5 heights from a met mast located at 2 rotor diameters upstream of the turbine in the prevailing wind direction. The participants were asked to produce the hub height power curve and the REWS power curve and derived quantities such as (measured) Annual Energy Production (*AEP*) and scatter around the bin-averaged power curve.

4.1. Description of the dataset

The power data came from the Nordtank wind turbine located at DTU Risø Campus test site. It is a passive stall regulated 500kW wind turbine with a hub height of 36m and a rotor diameter of 41.1m. The met mast is located on the west side of the turbine (283°) at 91m (2.2D). The mast was instrumented with cup anemometers at 5 heights: 18m, 27m, 36m, 45m, 54m, and with 3 sonic anemometers at 16.5m, 34.5m, and 52.5m boom mounted on the north side of the mast [9].

The dataset provided to the participants was pre-filtered as follow:

- quality check of the data;
- absolute temperature at 54m above 2°C;
- selected wind sector: 250°-300° (based on 10 min averages wind direction)
- wind turbine under "normal operating" status.

To minimize the differences in the results that would not be related to the REWS method, the following assumptions were made:

- no need for correction for the effects induced by the mast;
- no need to correct the data for air density.

These assumptions allowed, so that the participants could to use the data set to calculate the REWS without applying to apply any pre-processing to the data:

4.2. Results

The first results from the eight participants are illustrated by the discrepancies in measured *AEP* (see Figure 2). This exercise was an iterative process. The participants discussed the results to identify the source of the discrepancies. After three iterations, all participants reached an agreement. The real outcomes of this preliminary step are the identified sources of disagreement in the interpretation of the IEC standard.

Figure 2 shows that there were discrepancies in the hub height power curve; these needed to be solved before going any further in the comparison with the REWS power curve. However, the relative difference of the REWS *AEP* to the hub height *AEP* already shows that there were also discrepancies related to the REWS method application. The various points that needed to be adjusted to reach agreement are discussed below.

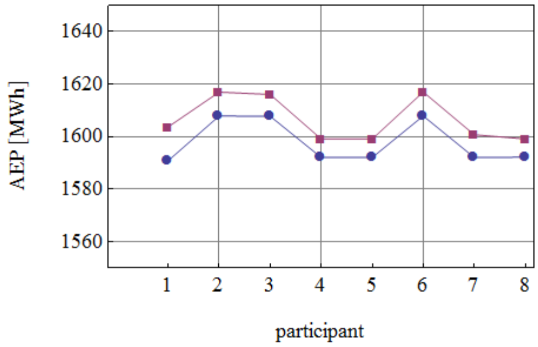


Figure 2. *AEP* with Rayleigh distribution and an annual mean wind speed of 8m/s for hub height power curve in blue and REWS power curve in red.

4.3. Discrepancies in the hub height power curve

4.3.1. Method of bin. According to the IEC 61400-12-1 standard [10], the power curve results from binning the 10 minute data in wind speed bins with a width of 0.5m/s and the bin are centred on multiples of 0.5 (e.g. 2.0m/s, 2.5m/s, 3.0m/s, ...). There is an ambiguity, however, on the bin boundaries selection, because it is not clear which end should be closed (≤) and which end should be open (<). This can be an issue when wind speed measurements are rounded to two decimals, as is often done in algorithms used to calculate the power curve from the data. An ambiguity in the bin definition can lead to different bin-averaged power curves. For this exercise, the participants chose to have the lower boundary closed and the upper boundary open. Bin *i* is defined as: $u_{k-1} \leq v < u_k$.

4.3.2. Measured AEP. Another ambiguity was experienced on the method to calculate the measured *AEP*. According to the IEC 61400-12-1 standard [10, p.32], the *AEP* should be calculated according to the equation:

$$AEP = N_h \sum_{k=1}^{N} [F(V_k) - F(V_{k-1})] \left(\frac{P_{k-1} + P_k}{2} \right) \tag{3}$$

where

AEP	is the annual energy production;
N_h	is the number of hours in one year ≈ 8760;
N	is the number of bins;
V_k	is the normalized and averaged wind speed in bin *k*;
P_k	is the normalized and averaged power output in bin *k*.

Furthermore, the "*AEP*-measured shall be obtained from the measured power curve by assuming zero power for all wind speeds above and below the range of the measured power curve"[10, p.33]. There is then an ambiguity on the number of bins, *N*, to be used in formula (3). For the example of this exercise, the bin-averaged measured power curve is given in Table 5. Formula (3) can either be applied with *N*=50, which results in Measured *AEP*=1607.75MW; or with *N*=32, which results in Measured *AEP*=1592.12MW. This issue has recently been discussed in the MEASNET power performance expert group and is hoped to be resolved and exposed soon [11]. The second method appears to be preferred, because it does not require any kind of extrapolation beyond the measured power curve.

4.3.3. Scatter quantification. Using the REWS method to account for the shear in the measured power curve is primarily expected to reduce the scatter in the power curve. The scatter influences the statistical uncertainty (type A) in power. However, the standard uncertainty, defined as the power standard deviation normalised by the square root of the number of data in the bin, is also strongly influenced by the mean slope of the power curve in the bin. The REWS power curve can have both a different slope and a different scatter compared to the hub height power curve. To isolate the scatter, we chose to quantify the scatter defined relatively to the linearly interpolated bin averaged power curve as described in Wagner et al. [4]. The main ambiguity is that the scatter is quantified for a segment of the power curve (i.e. the bins used to calculate the scatter are different from those that were used originally in the power curve; see [4] for details).

Table 5. Measured hub height power curve

Bin no. (k)	u_k	u_{k+1}	Hub height wind speed (v_k)	Power output (P_k)	Power standard deviation	No. of data sets
			[m/s]	[kW]	[kW]	(10 min. avg.)
7	3.25	3.75	3.655	0	0	0
8	3.75	4.25	4.155	3.575	2.667552	4
9	4.25	4.75	4.603276	14.53103	4.504742	58
10	4.75	5.25	5.00969	28.98527	6.85569	129
11	5.25	5.75	5.489747	48.81582	8.167104	158
12	5.75	6.25	6.016235	73.87412	9.549394	170
13	6.25	6.75	6.493007	98.73007	11.71569	143
14	6.75	7.25	6.984	128.3262	12.42405	145
15	7.25	7.75	7.519036	162.7747	14.15206	166
16	7.75	8.25	7.992827	193.4764	14.29509	191
17	8.25	8.75	8.501456	229.2987	15.37504	158
18	8.75	9.25	8.992438	263.7263	13.40885	160
19	9.25	9.75	9.48181	300.1069	14.47183	116
20	9.75	10.25	10.00235	335.3924	15.79203	119
21	10.25	10.75	10.51489	366.9859	17.46467	92
22	10.75	11.25	10.98959	393.8384	14.34714	73
23	11.25	11.75	11.49453	419.2547	15.02506	53
24	11.75	12.25	11.97321	440.4357	12.14835	28
25	12.25	12.75	12.53955	462.4364	6.338585	22
26	12.75	13.25	12.97533	472.16	9.979035	15
27	13.25	13.75	13.45778	484.7	8.059622	9
28	13.75	14.25	13.998	488.73	16.66227	10
29	14.25	14.75	14.52938	494.3375	17.85149	16
30	14.75	15.25	14.97875	483.7875	4.176614	8
31	15.25	15.75	15.48	497.9143	17.13305	7
32	15.75	16.25	16.03429	493.1857	19.63283	7
33	16.25	16.75	16.5	0	0	0
34	16.75	17.25	17	0	0	0
35	17.25	17.75	17.5	0	0	0
36	17.75	18.25	18	0	0	0
37	18.25	18.75	18.5	0	0	0
38	18.75	19.25	19	0	0	0
39	19.25	19.75	19.5	0	0	0
40	19.75	20.25	20	0	0	0
41	20.25	20.75	20.5	0	0	0
42	20.75	21.25	21	0	0	0
43	21.25	21.75	21.5	0	0	0
44	21.75	22.25	22	0	0	0
45	22.25	22.75	22.5	0	0	0
46	22.75	23.25	23	0	0	0
47	23.25	23.75	23.5	0	0	0
48	23.75	24.25	24	0	0	0
49	24.25	24.75	24.5	0	0	0
50	24.75	25.25	25	0	0	0

4.4. Discrepancies in the REWS power curve

Once the participants had accounted for all the sources for of discrepancies in the hub- height power curve, were accounted for, the discrepancies related to the application of the REWS were isolated. This time all the participants used directly the measured wind speed profile directly (again, no extra- or interpolation was applied). The main difference in the REWS results came once again from the weighting of the different wind speeds resulting from the chosen segment definition. Two models were applied by the eight participants, as shown in Table 6 and Table 7.

Table 6. Segments model 1 (used by six participants)

Measurement Heights [m]	Segment weighting* [%]	Segment inferior limit height [m]	Segment superior limit height [m]	Segment height [m]
54	11.42	49.5	56.55	7.05
45	24.75	40.5	49.5	9
36	27.66	31.5	40.5	9
27	24.75	22.5	31.5	9
18	11.42	15.45	22.5	7.05

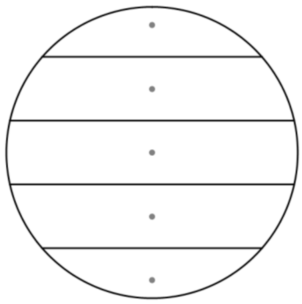
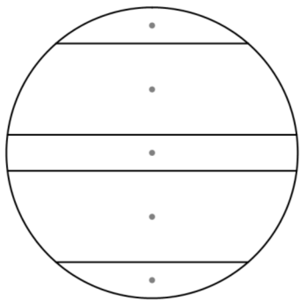


Table 7. Segment model 2 (used by two participants)

Measurement Heights [m]	Segment weighting* [%]	Segment inferior limit height [m]	Segment superior limit height [m]	Segment height [m]
54	7.14	51.45	56.55	5.1
45	34.98	38.55	51.45	12.9
36	15.76	33.45	38.55	5.1
27	34.98	20.55	33.45	12.9
18	7.14	15.45	20.55	5.1



As shown in Figure 3, the difference in the bin averaged power between the hub height power curve and the REWS power curve is clearly larger than the difference between the two REWS models. The scatter is slightly smaller for the REWS (both models) than for the hub height power curve, as shown in Figure 4. The *AEPs* obtained with the REWS power curve for the two weighting definitions differ only by 1MWh whereas they differ by 9MWh and 10MWh respectively from the hub height *AEP*, as shown in Table 8. The difference obtained with the different weighting functions is very small.

The REWS makes a relatively small difference in the scatter compared to hub height because the shear was limited for this dataset. This did, however, affect the purpose of this exercise which was to work on a common dataset.

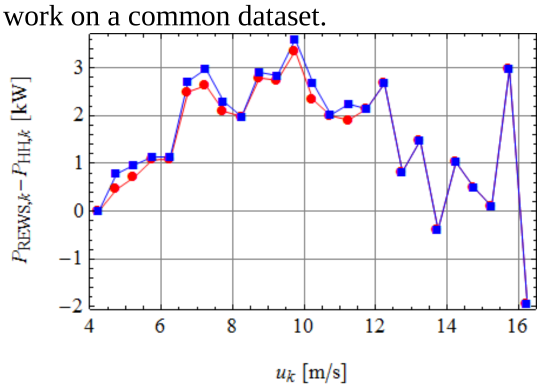


Figure 3. Difference in the binned average power between the hub height power curve and the REWS power curve; red represents REWS model 1and blue represents REWS model 2

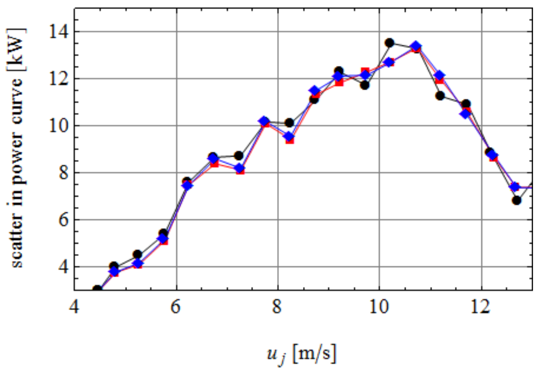


Figure 4. Scatter around the bin averaged power curve, as defined in 4.3.3 (black shows the hub height power curve, red represents REWS model 1and blue represents REWS model 2)

Table 8. *AEP* obtained with the hub height power curve and the two REWS models

Power curve	*AEP* [MWh]
Hub height	1608
REWS model 1	1617
REWS model 2	1618

5. Step 3: different or separate REWS power curve datasets

Finally, each of the participants derived the hub height power curve and the REWS power curve from their own dataset. The characteristics of the different datasets are summarized in Table 9.

Table 9. Characteristics of the eight datasets used in the intercomparison

Dataset number	**Turbine rotor [m]**	**Hub height [m]**	**Profile measurements**	**site**	**Number of measurement heights in REWS**	**Number of data**
1	116	91	Windcube v1 + mast	Offshore	7	2183
2	83	70	simulations	Flat terrain	?	1524
3	80	80	Windcube v2	Flat terrain, farmhouse, trees	5	1004
4	93	68	Mast	Offshore	9	3580
5	90	75	ZephIR 300	Rolling hills small trees	5	1387
6	77	80	Windcube v1	Flat slight slope	5	888
7	77	80	mast	Flat slight slope	3	2498
8	Undisclosed	Undisclosed	Windcube v2	Undisclosed	5	1611

5.1. Air density correction

This exercise brought up the issue of applying the air density correction required in the IEC standard. For hub height wind speed measurements taken with a met mast, the necessary air and pressure sensors are usually mounted on the same mast as close as possible to hub height. When applying the REWS method, in theory the wind speed measured at each height should be corrected for air density at the same height; however this is usually not applicable in practice because the temperature profile is not measured. In the eight cases presented here, the air density was assumed to be constant with height. The air density at hub height was used when it was available (e.g. when a hub height mast or taller met mast was available); in some cases, where a lidar was used, the temperature and pressure measured by the lidar pressure/temperature/humidity (PTH) probe at ground level were used.

5.2. AEP Difference

To show the difference between the power curves obtained with the two wind speed definitions, Figure 5 shows the relative difference in *AEP* obtained with the REWS power curve and the hub height power curve. Both assume a Rayleigh wind speed distribution with an annual mean wind speed of 8m/s. There is no general trend; the difference in *AEP* varies from -0.68% to +0.85%. For five of the datasets, the REWS *AEP* is larger than the hub height *AEP* (shown in black); for two of them, the REWS *AEP* is smaller than the hub height *AEP* (shown in red). For dataset 2 there was no difference between the two *AEP* estimates.

The difference in the power curve obtained with the two methods and subsequently on the *AEP* is due to the relative difference between the REWS and the hub height wind speed. Figure 6 shows the frequency distribution of this difference for each dataset. Note that, for this exercise, the REWS and the hub height wind speed were measured with the same instrument for every dataset and no normalization needed to be applied. For the five datasets for which the *AEP* difference was positive, it was observed that the REWS is smaller than the wind speed at hub height (i.e. the hub height wind speed overestimates the kinetic energy flux) on average (shown in black Figure 5). The REWS power curve was therefore shifted to the left compared to the hub height power curve, which results in a higher *AEP*. For the two datasets for which the difference in *AEP* was negative, the REWS was larger than the hub height wind speed on average (shown in red) and the REWS power curve was shifted to the right to the hub height power curve. Dataset 2 resulted from simulations where the vertical shear was represented with a power law and the shear exponent was evenly distributed between 0 and 0.5 (and the turbulence intensity was evenly distributed between 0% and 40%).

It can be noticed however, that datasets 1 and 4, both resulting from offshore measurements, present similar results.

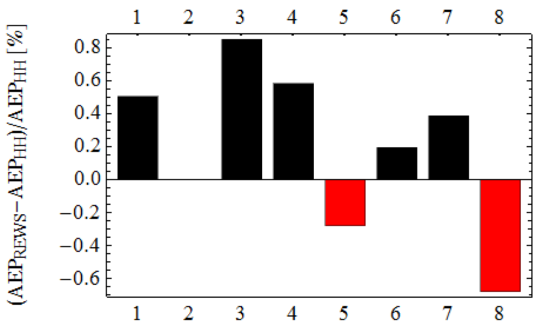


Figure 5. Relative difference between REWS *AEP* and hub height *AEP* for the eight different datasets

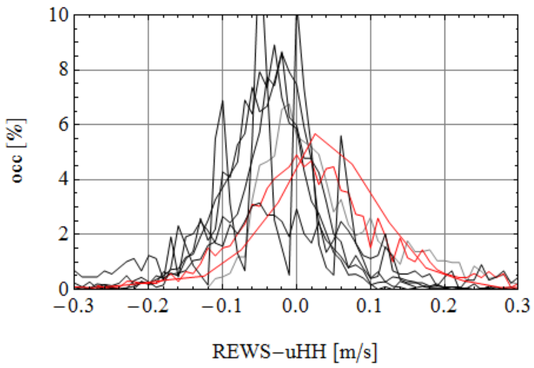


Figure 6. Distribution of the difference between hub height wind speed and REWS for the eight different datasets

5.3. Difference in scatter

The REWS is expected to reduce the scatter caused by the wind shear variation in the power curve. However, such a reduction has only been observed for datasets 4 and 8 (see Figure 7). This is quite interesting because the two datasets have different characteristics, as listed here:

- the difference in REWS and hub height wind speed are very different (see Figure 8); a positive *AEP* difference was obtained for dataset 4 whereas it was negative for dataset 8 (see Figure 5);
- the scatter in the hub height power curve is significantly larger for dataset 8 than for dataset 4 (see Figure 9). Note that the turbulence intensity for dataset 4 is low: at 8% on average (this information was not available for dataset 8).

For dataset 5, the scatter is slightly higher with the REWS compared to the hub height power curve (see Figure 7). It can be observed in Figure 9 that the scatter in the hub height power curve for dataset 5 is already relatively large; this may be because the complex terrain affects the homogeneity of the flow and therefore the lidar measurements.

For the other datasets, no significant difference was observed between the scatter in the REWS power curve and that seen in the hub height power curve.

6. Conclusions

Eight organisations (including wind farm operators, measurement institutes and universities) from five different countries have participated in a comparative exercise to explore the application of the REWS method for power curve measurement proposed in the Committee Draft of the IEC 61400-12-1. The exercise revealed that the main challenge in using the REWS method was to determine the number of measurement heights to be used, the distribution of these measurement heights in space and the definition of the segment areas which represent the weighting of each measurement height in the REWS.

In addition, the REWS power curve was compared to the hub height power curve for eight different datasets. This showed that the difference between the REWS and the wind speed at hub height depends on the site. The REWS resulted in a higher *AEP* than the hub height power curve in five cases and in a lower *AEP* in two cases. Finally, the reduction of scatter in the power curve expected with the REWS did not appear clearly as it was only observed in two cases out of eight. The effect of the turbulence intensity on the power curve and the scatter of the lidar measurements in some cases could have counter balanced the reduction of the scatter resulting from shear.

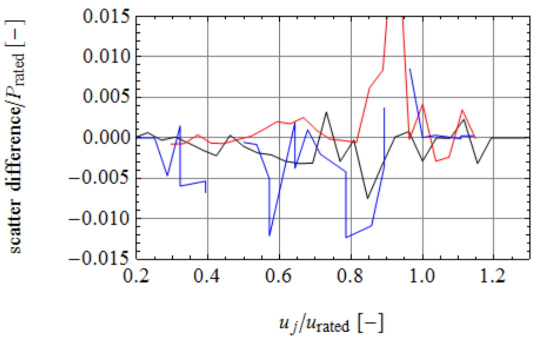


Figure 7. Difference per wind speed bin between the scatter in the REWS power curve and the hub height power curve (black:4; red:5; blue:8)

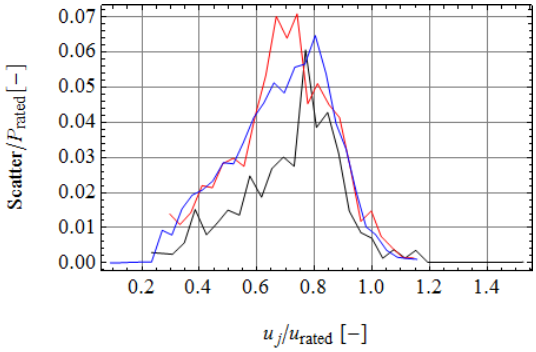


Figure 8. Scatter in hub height power curve (black:4; red:5; blue:8)

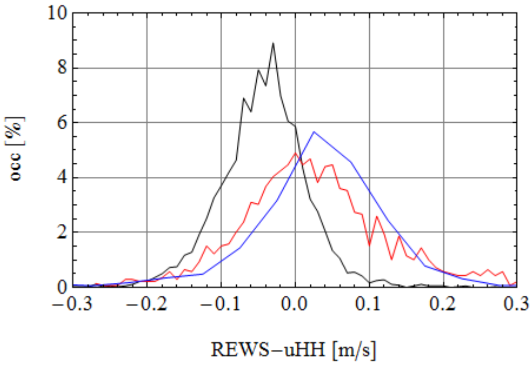


Figure 9. Distribution of the difference between hub height wind speed and REWS (black:4; red:5; blue:8)

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