Improving the Accuracy of Wind Turbine Power Curve Validation by the Rotor Equivalent Wind Speed Concept

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Abstract.
The measurement of the wind speed at hub height is part of the current IEC standard procedure for the power curve validation of wind turbines. The inherent assumption is thereby made that this measured hub height wind speed sufficiently represents the wind speed across the entire rotor area. It is very questionable, however, whether the hub height wind speed (HHWS) method is appropriate for rotor sizes of commercial state-of-the-art wind turbines. The rotor equivalent wind speed (REWS) concept, in which the wind velocities are measured at several different heights across the rotor area, is deemed to be better suited to represent the wind speed in power curve measurements and thus results in more accurate predictions of the annual energy production (AEP) of the turbine. The present paper compares the estimated AEP, based on HHWS power curves, of two different commercial wind turbines to the AEP that is based on REWS power curves. The REWS was determined by LiDAR measurements of the wind velocities at ten different heights across the rotor area. It is shown that a REWS power curve can, depending on the wind shear profile, result in higher, equal or lower AEP estimations compared to the AEP predicted by a HHWS power curve.

1. Introduction
The power performance of a wind turbine is represented by its power curve, which states the electrical power production as a function of wind speed

\[ P = \frac{1}{2} \rho A V^3 C_P \]  

where \( P \) is the electrical power, \( \rho \) is the air density, \( A \) is the rotor area, \( V \) is the wind speed, and \( C_P \) is the power coefficient. The electric power thus depends on the wind speed cubed which makes the power production very sensitive to small variations in the wind speed. It is therefore absolutely essential to use a representative wind speed in power curve validations.

The international standard IEC 61400-12-1 [1] defines how a power curve should be measured. According to this standard, the wind speed measurement takes place at some distance in front of the wind turbine using a cup anemometer located on a meteorological mast (MetMast) at turbine hub height, here defined as the hub height wind speed (HHWS). The underlying assumption
is that the hub height measurement is representative of the wind across the entire swept area of the turbine rotor. While this assumption was adequate for the size of wind turbines designed and manufactured at the time that the concept was conceived, rotors of modern multi-megawatt wind turbines span across a large area which may include significant differences in wind flow. It is thus very questionable whether a single-point measurement is an adequate representation of the wind field. As a consequence, deviations between the measured and the expected Annual Energy Production (AEP) may occur when the AEP prediction is based on the HHWS power curve.

Figure 1 illustrates the problem by showing two arbitrary wind speed profiles which have the same hub height wind speed but will result in different power output, and thus different AEP, because the deficit and surplus of the wind speeds across the rotor area compared to the hub height wind speed are different. A better representation of the incoming flow across the entire rotor can be determined when wind speeds and directions at several heights are measured simultaneously using remote sensing (e.g. LiDAR - Light Detection And Ranging) or anemometers at several heights on a MetMast.

![Figure 1. Schematic representation of different arbitrary inflow velocity profiles on a wind turbine. Although the wind profiles have - arguably - different energy contents, the hub height wind speed is the same, whereas this difference is accounted for in the rotor equivalent wind speed concept.](image)

2. The Rotor Equivalent Wind Speed (REWS) Concept
The rotor equivalent wind speed (REWS) concept aims to represent the kinetic energy flux through the entire rotor via an equivalent wind speed. This method portrays more accurately the flow through the rotor plane, in particular in wind conditions with non-standard shear profiles, than the HHWS method where the wind speed only at one single height is used.

Although the REWS concept has first been suggested by Frandsen et al. [2] in the year 2000, the acceptance of this method developed slowly. The REWS methodology is thus still a relatively new concept, and also remote sensing devices represent a relatively new technology. These devices, and particularly LiDARs, have nevertheless attracted a lot of attention in the past years due to their potential benefit to the wind industry. Several studies have confirmed the feasibility of LiDARs and the REWS concept, as documented by Wagner et al. [3] and Antoniou et al. [4], amongst others. In addition, procedures have been established, for example by Gottschall et al. [5], for the traceable calibration of LiDARs. The next edition of the standard IEC 61400-12-1 (edition 2) [6] will include the REWS methodology as an option for wind turbine power curve measurements.
The combination of a ground-based LiDAR and the wind speed measured at hub height by a cup anemometer on a MetMast is used in order to achieve the highest accuracy. The LiDAR is employed, in other words, to determine the shape of the wind shear profile, and this profile is then scaled with the hub height wind speed measured by the cup anemometer. The numerical implementation of the REWS can then be written as

\[
REWS = \frac{HHWS}{U(HH)} \sqrt[3]{\sum_{i=1}^{N} A_i [U(z_i) \cos(\theta(z_i) - \theta(HH))]^3}
\]  

(2)

where \(HHWS\) is the hub height wind speed measured by the cup anemometer, \(U(z_i)\) is the wind speed measured with the LiDAR at the height \(z_i\), \(HH\) is the hub height, \(A\) is the rotor area, \(\theta(z_i)\) is the wind direction, \(N\) is the number of segments in which the rotor plane has been divided into, \(A_i\) is the area of segment \(i\), and \(z_i\) is the height above ground at the centre of the segment, as illustrated in Figure 2.

**Figure 2.** Rotor area and arrangement of LiDAR measurement heights, \(z_i\), at which the representative velocity \(U(z_i)\) and wind direction \(\theta(z_i)\) for the respective segment \(A_i\) is determined. A higher number of LiDAR heights has been used below hub height - where the changes in the gradient of the wind velocity profiles are expected to be highest - in order to resolve wind shear with highest accuracy.

**3. Description of the Wind Turbines, Test Sites and Measurement Equipment**

The performance of two different Siemens Wind Power turbines, denoted here as turbine 1 and turbine 2, has been analyzed. The turbines vary in rated power between 3MW and 7MW, in rotor diameter between 100m and 160m and in hub height between 90m and 120m. The turbines have been tested at two different sites - turbine 1 at site 1 and turbine 2 at site 2. Both sites are located in Northern Europe and can be categorized as flat and non-forested. A commercial LiDAR is used to measure the wind speed at ten different heights that cover the entire rotor area. All measurements and data filtering were made in compliance with the IEC standard [6].
4. AEP estimation using REWS and HHWS power curves

The AEP estimations were made using a Rayleigh cumulative probability distribution function for wind speed, as suggested by the IEC standard [6]. The same wind distribution was used for both the HHWS and the REWS power curves when the corresponding AEP was estimated. This was done in order to make a rigorous comparison between the two methods. All AEP comparisons documented in this paper were made for 7.5 m/s mean annual wind speed.

Figures 3(a), (c) and (e) show the ratio between LiDAR measured wind speeds at different heights across the rotor area with respect to the LiDAR measurement at hub height for a one-week period representative for the summer and the winter season at site 1 and the autumn period at site 2, respectively.

The AEP difference between REWS and HHWS power curves

\[ \Delta_{AEP} = \frac{REW_S{AEP} - HHWS{AEP}}{HHWS{AEP}} \]  

(3)

for the different seasons is given in the captions of the subfigures 3(b), (d) and (f) for 7.5 m/s mean annual wind speed.

The subfigures 3(b), (d) and (f) show the velocity profiles at a hub height wind speed of 7.5 m/s along with theoretical wind shear profiles for three different shear exponents for the sake of reference. It is usually assumed that a single point hub height wind speed measurement is sufficient to represent the kinetic energy flux through the entire rotor area in that range of shear exponents - depending on the turbulence intensity and other site-specific effects. The assumption is thus usually made that when the wind profile can be described by shear exponents in the range between 0.2 and 0.3, then the energy content in the wind for these moderate shear profiles can be approximated by a constant wind speed over the entire rotor area; and this is done by the HHWS power curve approach.

In the summer period at site 1, the measured velocity profile agrees fairly well with the velocity profiles that have a shear exponent of 0.25 below hub height and 0.30 above hub height. It is thus not surprising that the AEP estimation based on the HHWS and REWS power curves are almost identical. Indeed the REWS power curve results only in slightly lower AEP, −0.2%, than the HHWS power curve does.

The winter period at site 1, however, shows a significant discrepancy between the measured velocity profile determined by the LiDAR and the three theoretical shear profiles. The measured wind velocities at the heights below hub height are lower compared to all three theoretical shear profiles, whereas the velocities above hub height are significantly larger than the theoretical profiles would suggest. The discrepancy between the measured and the theoretical wind profiles at the upper portion of the rotor, i.e. the surplus above hub height, has a larger weight for the calculation of the energy flux than the deficit below hub height, due to the dependency of power on wind speed cubed. This explains why the REWS power curve results in lower AEP than the HHWS power curve does because this surplus above hub height is simply not taken into account in the HHWS method where only one velocity measurement at hub height is taken. In other words, the HHWS method simply under-estimates the energy flux and thus over-estimates the resulting AEP. On a standard power-vs-wind-speed plot, the HHWS power curve is - in this case - shifted towards the negative x-direction, where the x-axis represents wind speed, compared to the REWS power curve, due to the fact that the hub height wind speed is lower than the rotor equivalent wind speed. As a consequence, the AEP estimation based on the HHWS power curve is simply too high. The REWS concept, in contrast, accounts for that higher energy content in the wind and thus arguably represents a better description of the inflow conditions.
Figure 3. Subfigures (a), (c) and (e) show the ratio between the wind velocities at different heights across the rotor area and the measured LiDAR velocity at hub height (mean values of 10-min-bins) for representative one-week periods in three different seasons. Subfigures (b), (d) and (f) show the corresponding wind velocity profile at a HH wind speed of 7.5 m/s along with theoretical wind shear profiles for three different shear exponents. The AEP difference $\Delta_{AEP}$ between REWS and HHWS power curves has been calculated according to Equation (3).
The opposite can be observed for the autumn period at site 2, where the REWS power curve results in higher AEP than the HHWS power curve does because the wind profile bends ‘backwards’ above hub height. Indeed the velocities measured below hub height are higher, whereas the wind velocities above hub height are lower than the ones expected from the theoretical profiles. The HHWS concept can, again, not accurately capture the correlated energy content in the flow through the rotor and the AEP estimation using HHWS is inaccurate and, in this case, too low.

It should also be noted that the AEP that is based on the REWS curve is less susceptible to seasonal variation of the inflow conditions and thus more consistent than the HHWS method. Indeed the AEP that is based on the HHWS power curve varies around 1.2% more than the AEP that is based on the REWS power curve between the winter and summer period at site 1.

The difference between HHWS and REWS is analyzed further in Figure 4 that shows the difference between the two wind speeds for the three different seasons. It is clear that when the difference in AEP between HHWS and REWS power curves is small, then the difference between HHWS and REWS is, overall, small too, as indicated in Figure 4(a) that shows wind speed deltas for the summer period at site 1.

![Graph showing difference in wind speeds](image)

(a) summer: mean $= -0.017 \text{m/s}$

(b) winter: mean $= -0.054 \text{m/s}$

(c) autumn: mean $= +0.12 \text{m/s}$

**Figure 4.** Difference between mean values of HHWS and REWS for 10-min-periods in the three different seasons along with the binned mean for all wind speeds. The presented data shows the measurements for the respective entire campaigns after standard filters according to the IEC standard were applied.

Larger differences in AEP between HHWS and REWS power curves are caused by larger differences in the underlying wind speeds, as for example shown in Figure 4(c), where the mean of the velocity difference between HHWS and REWS for all wind speeds is more than $+0.1 \text{m/s}$. The REWS power curve is, in other words, shifted in the negative x-direction compared to the
HHWS power curve since the rotor equivalent wind speed is smaller than the hub height wind speed, as indicated in Figure 5 that shows both REWS and HHWS power curves for turbine 2 at site 2 in the autumn period. As a consequence, the AEP for the REWS power curve is higher than the AEP for the HHWS power curve.

![Image](image_url)

**Figure 5.** HHWS and REWS power curves for turbine 2 at site 2 resulting in $\Delta AEP = +1.3\%$.

5. Conclusion

Three wind shear profiles in different seasons at two wind turbine test sites are investigated using a LiDAR. Although the test sites are categorized as flat and non-forested terrain, the HHWS concept in wind turbine power curve validations can be too simplistic to capture accurately the kinetic energy flux through the rotor area. It is shown that the HHWS method can thus result in inconsistent and potentially incorrect predictions of the annual energy production (AEP) in the order of magnitude that is relevant for business cases of turbine manufacturers and wind farm developers. It is also demonstrated that a REWS power curve can, depending on the wind shear profile, result in higher, equal or lower AEP estimations compared to the AEP predicted by a HHWS power curve.

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7. References

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