

Impact of the distance between mast and wind turbine on the results of power curve measurements

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Introduction

For standard power curve measurements, it is assumed that the wind speed measured at the met mast represents the true wind speed that is to be allocated to the power produced by the wind turbine for each time interval of 10 minutes. The present contribution tries to show that this assumption is not fully correct and that this causes systematic distortions of measured power curves.

Approach

In order to assess the situation where the wind speed is measured on a met mast (or other instrument) in flat terrain close to a wind turbine, the situation of two wind measurements placed in flat terrain at a few 100 m distance from each other is considered in the major part of the present document. This arose from studies on the data collected and observations made during verifications of Sodar instruments. However, the verification of Sodars is only addressed in the present text as far as it helps understanding the effects to be discussed. Measured data are used to illustrate those effects, but the relevant results are derived from simple simulations.

Background

For standard power curve measurements, it is assumed that the wind speed measured at the met mast represents the true wind speed that is to be allocated to the power produced by the wind turbine at each time interval of 10 minutes. The same applies to the situation where a Sodar instrument is placed at some 100 m to 300 m distance from a met mast in order to be verified or calibrated. It would apply similarly to a situation with two met masts located at a distance of a few 100 m from each other, but such a situation only exists in the context of site calibrations where it is not assumed that the wind speeds at both locations are on average the same. Since Lidar instruments are commonly placed very close to masts for verification or calibration, the effects discussed here have a negligible magnitude during verifications / calibrations of Lidars.

Since it is assumed in both situations, power curve measurement and Sodar verification, that the true wind speed is shown by the mast, the power curves of the wind turbines (respectively the deviations of the Sodar wind measurement) are established by binning the average power of the wind turbine (respectively the average wind speed data of the Sodar) following the wind speed measured on the mast during the corresponding 10 minute intervals.

If the test site and its surroundings are sufficiently homogenous, the wind speed measurement on the met mast provides a correct representation of the situation at the wind turbine (respectively Sodar) location on average and regarding the frequency distribution over a long period (say several days). However, due to the turbulent nature of the ambient wind, this is not fully true for each individual period of 10 minutes. This simply means that the wind measured at the mast is not a fully true representation of wind at the location of the wind turbine (respectively Sodar instrument). It is commonly assumed that this difference is sufficiently small due to the averaging period of 10 minutes. However, at some sites which are compatible with the requirements of IEC 61400-12-1, the wind seems to vary more between two locations which are just a few 100 m apart than what is commonly assumed. Since the rotor diameters of wind turbines have increased significantly during recent years, the distances between mast and wind turbine for the power curve tests increased correspondingly, making the issue discussed here more important than before.

How homogenous is the wind field?

The following graphs compare the wind shear calculated for two neighbouring height intervals from concurrent 10 minute average wind speeds on a 140 m tall met mast. Disturbed wind directions and wind speeds below 3.75 m/s have been excluded from the data base.

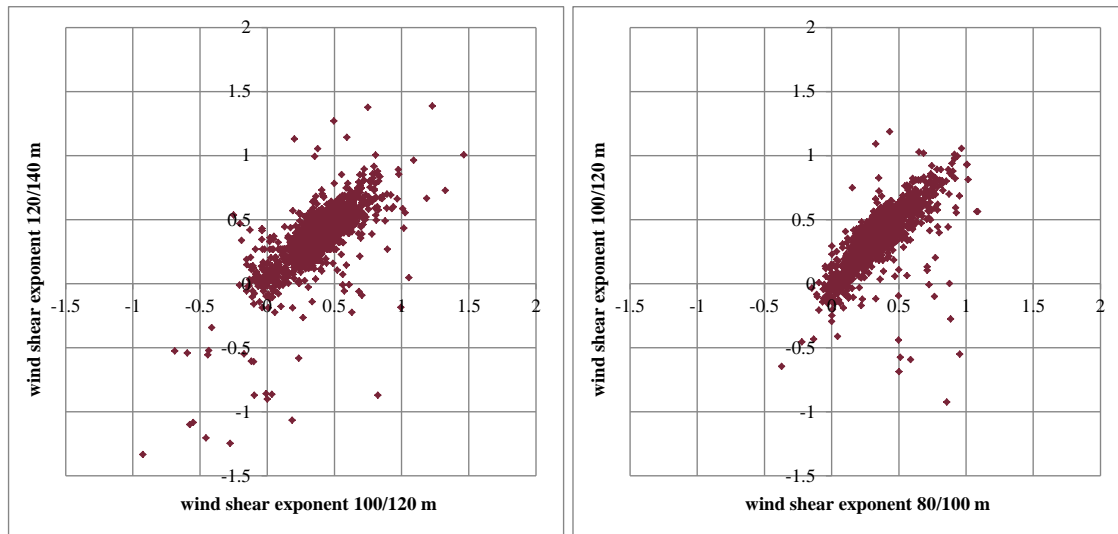


Figure 1: Comparison of calculated wind shear from concurrent 10 minute intervals between different height intervals on a met mast

Significant scatter can be found on figure 1. This is often connected with strong changes of mean wind speed or wind direction, but not limited to such situations. We conclude from figure 1, that even when looking at a mast location only, the wind field cannot always be considered consistent. Even more, it cannot be assumed that the wind observed on a mast always represents the wind at several 100 m distance from it correctly.

Theoretical experiment for two wind speed time series

A hypothetical time series of wind speed was constructed with a number of rising and falling parts. This was assumed to be the “true” wind speed for a site. Two arbitrary wind speed time traces were derived from this, representing two observation points at some distance from the point of the “true” wind speed. Both were assumed to be identical with the “true” wind speed for half of the data points. For half of the remaining time intervals, wind speed observation 1 was assumed to see 0.4 m/s higher wind speeds and wind speed observation 2 0.4 m/s lower ones, and for the rest, the opposite was assumed. Figure 2 shows part of the time traces of wind speeds 1 and 2.

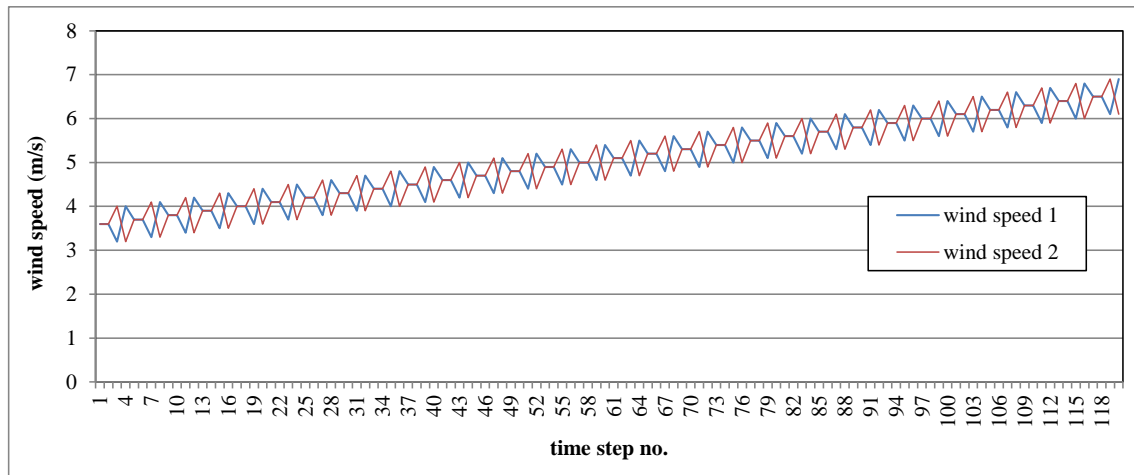


Figure 2: Extract of the hypothetical time traces

The frequency distributions and, consequently, the averages of both time traces are identical:

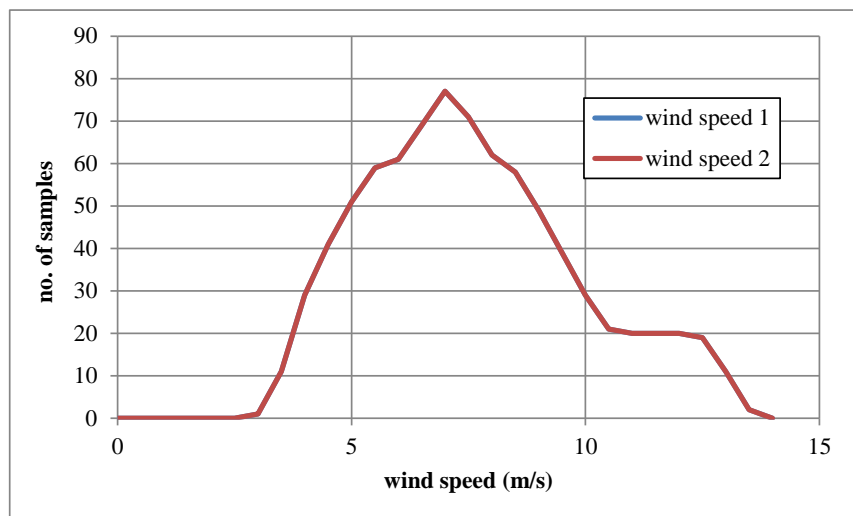


Figure 3: Frequency distributions of the hypothetical time traces

This situation corresponds to that of a power curve measurement, where the wind field is on average the same at the location of the met mast and the wind turbine, but due to the natural variation of the wind, this is not true for each moment in time. The magnitude of the variation shown in figure 2 may or may not be representative of a typical test site. The purpose of the present experiment is therefore only to show the principle of the effect on the result of the data analysis. Its magnitude needs to be considered separately.

If wind speed 2 is traced in a scatter plot against wind speed 1 and vice versa, the resulting plots are obviously the same.

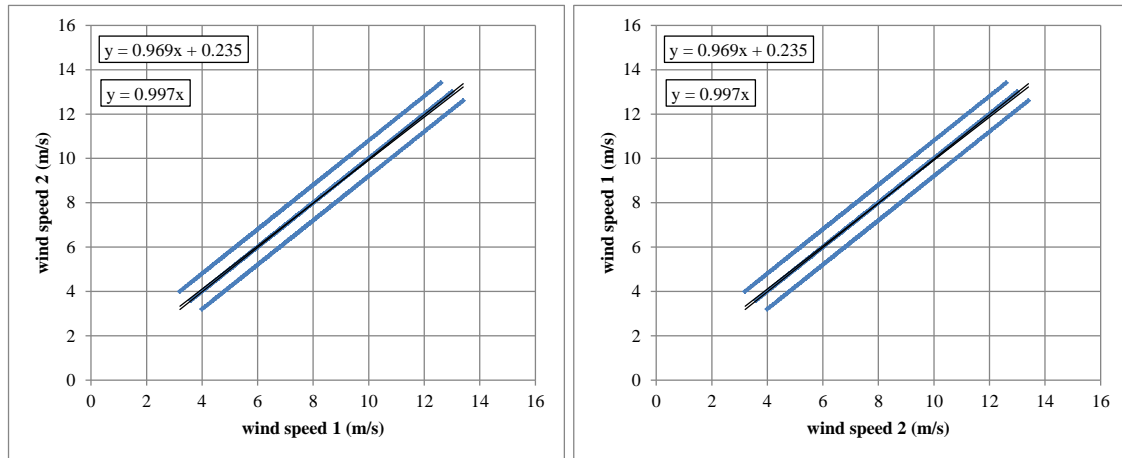


Figure 4: Scatter plots of both time traces against each other and linear regressions

Linear regressions are then applied to the scatter data, once forced through the origin and once with two parameters. On the left hand graph, wind speed 1 is considered as “the true wind speed” and on the right hand graph, it is wind speed 2. Although it has been shown above that both wind speed time traces show in total the same wind resource, the linear regressions return the answer that wind speed 1 and wind speed 2 are not equivalent. The difference is 0.3 % if the linear regression is forced through the origin. For the two-parametric linear regression, a positive offset value is calculated. For a mean wind speed of 6 m/s for instance, this linear equation indicates an error of +0.8 % and an error of -0.8 % for 10 m/s. Of course, the correct result would be *wind speed 1 = wind speed 2* at all wind speed levels.

If the data sets are now inter-compared with the method of bins, even higher deviations are found.

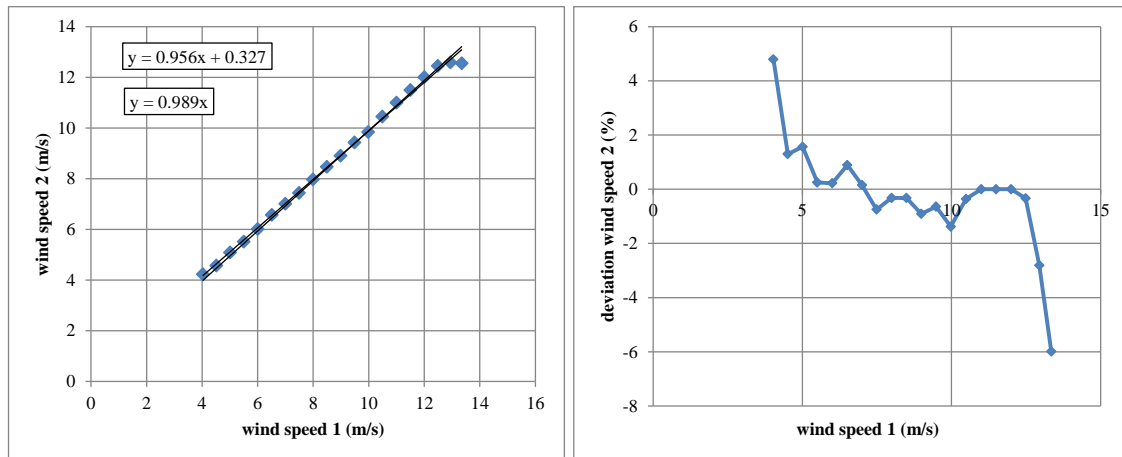


Figure 5: Bin analysis of the left hand side graph of figure 4; left: comparison of mean values of each bin, right: error of wind speed 2

The linear regression via the binned values claims that the wind speed measurement 2 is on average 1.1 % too low compared to wind speed measurement 1 if the linear regression is forced through the origin. The two-parametric linear regression again returns a positive offset value and the error calculated from it at e.g. 6 m/s is +1.1 %, i.e. the wind speed measurement 2 appears to be too high for low wind speeds.

The error calculated for each wind speed bin on the right hand side of figure 5 shows roughly an s-shape. Such s-shapes can indeed often be found in the verification / calibration tests of Sodar instruments, and the positive offset values calculated with the two-parametric regressions are also very common in such verifications / calibrations.

It can be concluded that the result of the comparison of two wind speed time series strongly depends on the statistical method used, and that all methods used above show deviations that are artefacts which obscure the fact that the wind speed time series are effectively equivalent.

Extreme examples from field tests

As an extreme example, the data of three Sodar instruments which were operating with some 500 m and more distance in flat terrain, but under highly varying wind conditions, are inter-compared using the method of bins.

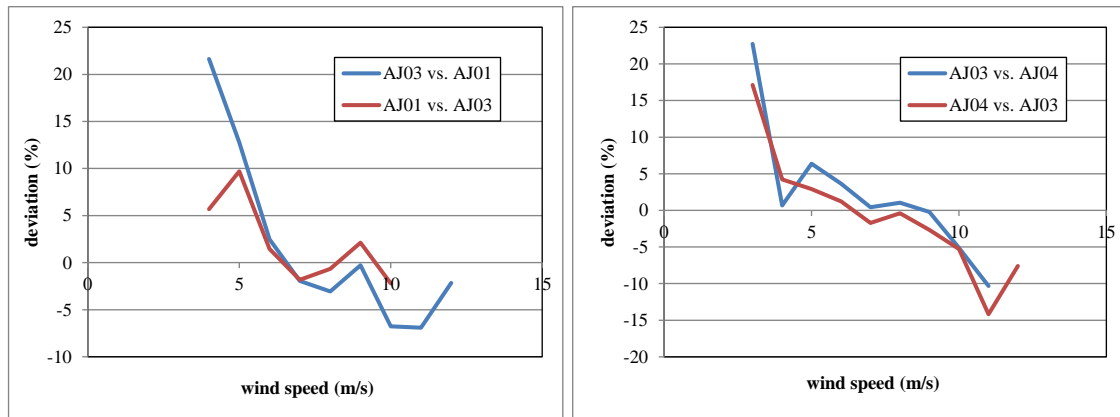


Figure 6: Bin analysis of the inter-comparison of three concurrent Sodar measurements

Whether the data of Sodar AJ01 are traced against those of Sodar AJ03 or vice versa (respectively AJ03 / AJ04), the resulting patterns of the bin analysis are roughly similar. According to the left hand graph, blue line, AJ03 measures strongly higher values than AJ01 at low wind speeds. The red line, to the contrary, indicates that AJ01 measures strongly higher values than AJ03 at low wind speeds. Clearly, the results of the binning cannot be considered as correct representations of the properties of the instruments. If the curves showed the difference between the instruments correctly, both lines in the left hand graph respectively the right hand graph would be mirrored on the x axis. The real difference between the instruments is hardly visible, it is obscured by the systematic errors caused by the method used to derive the apparent differences.

This example proves with a real world example that the bin analysis is not the right means for inter-comparing the wind speeds observed at two different points, as it has already been shown in the theoretical experiment in figure 5.

In order to demonstrate that this effect is not limited to Sodar instruments, the following example is added. A Lidar instrument has been operating over several months at some 500 m distance from a met mast. In this case, the terrain was not flat, but softly shaped and the average wind speeds and wind resources of both measurement points were found to be the same. This example was added a posteriori for the present written version as a consequence of the discussion held at the PCWG meeting.

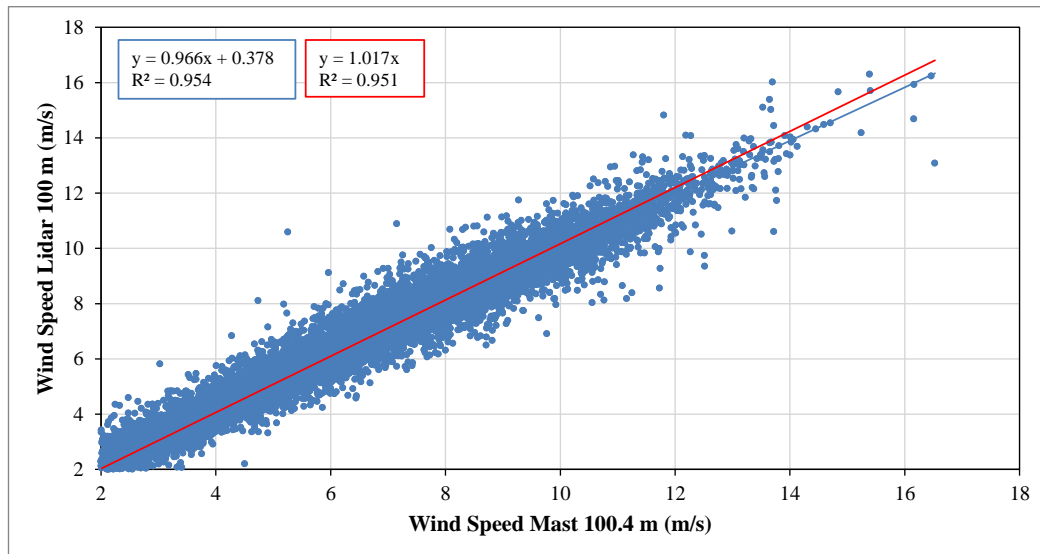


Figure 7: Scatter comparison of concurrent wind measurements on a met mast and a Lidar instrument

Again, a positive offset value appears on the two-parametric linear regression above and an s-shape on the bin analysis of the wind speed “error” of the Lidar shown below.

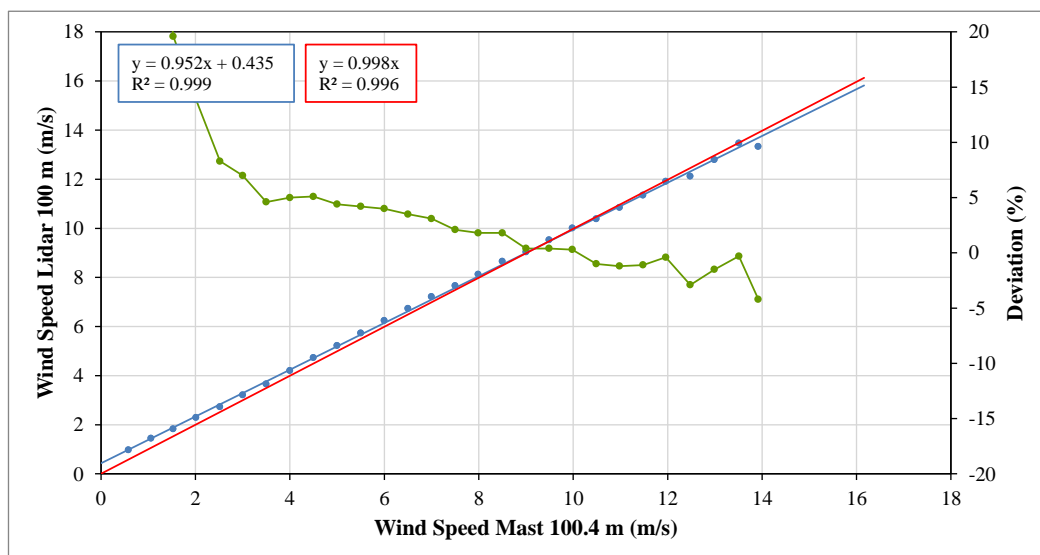


Figure 8: Binned comparison of concurrent wind measurements on a met mast and a Lidar instrument

Theoretical experiment for a wind speed and power time series

Now a theoretical experiment was performed similar to that above where two wind speed time series had been inter-compared. In this case, a rising wind speed time series was applied twice to the power curve of a wind turbine. A power curve with steps of 0.5 m/s was used and the wind speed was assumed to increase by 0.5 m/s with each time step. The third part of the time series was similar, but with the wind speed shifted by one time step forward and the fourth part of the time series with the wind speed shifted backwards. This was to emulate the time dependent varying wind field on a test site.

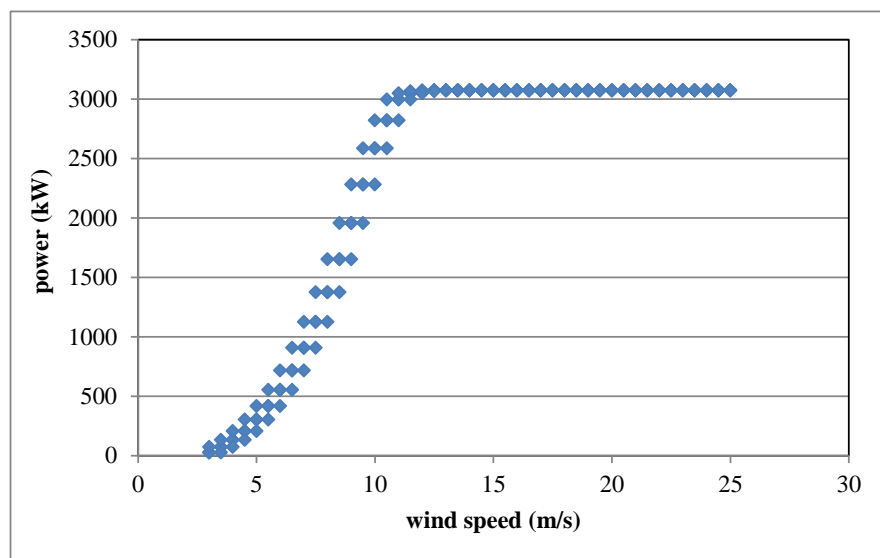


Figure 9: Scatter plot of the hypothetical power curve measurement

The binned power curve below hardly shows any obvious changes compared to the original power curve.

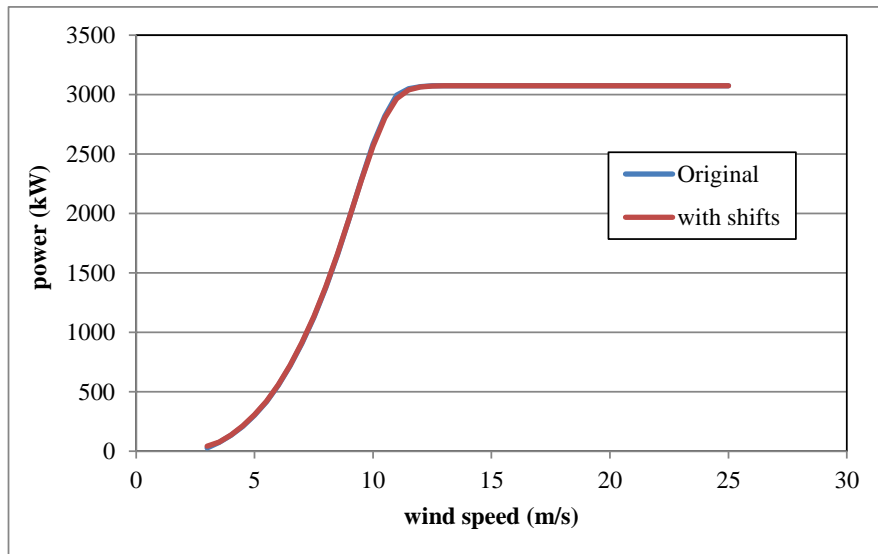


Figure 10: Binned result of a hypothetical power curve measurement, power values

Nevertheless, the deviations from the original power curve are significant in the transitions from stand-by to operation and from partial to rated power.

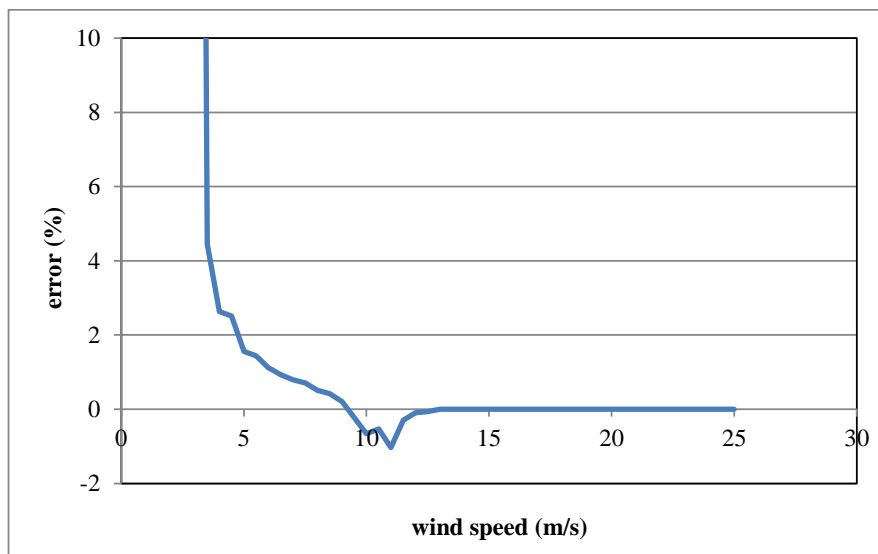


Figure 11: Binned result of a hypothetical power curve measurement, deviations from the original power curve

Conclusions and outlook

Due to the natural variation of the wind, increasing distance between mast and wind turbine will result in increasing systematic errors of the measured power curves if the current standard method of bins is used to derive the power curves. The error consists in an over-prediction of the power near cut-in and an under-prediction near rated power. It is effectively similar to the impact from increased turbulence and will therefore usually be interpreted as a consequence of ambient turbulence. Based on aj's experience from the verification of Sodar instruments, it must be assumed that the magnitude of this effect is site dependent (and also weather dependent). Since it increases with increasing distance between the observation points, it becomes more relevant as the rotor diameters of wind turbines increase. For the verification / calibration of Sodar instruments, the corresponding issue can mainly be resolved by using different strategies for the data analysis. However, since different physical parameters are inter-compared during power curve measurements which are linked non-linearly, it is less obvious how this systematic error can be corrected for. Inter-comparisons between mast and nacelle anemometer signals and combination with the methods for correcting for the influence of turbulence may be a route.

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