An Analysis of Wind Resource Uncertainty in Energy Production Estimates

Mark Taylor, Meteorologist (mtaylor@awstruewind.com)
Pawel Mackiewicz, Project Engineer (pmackiewicz@awstruewind.com)
Michael C. Brower, Principal (mbrower@awstruewind.com)
Michael Markus, Senior Meteorologist (mmarkus@awstruewind.com)

AWS Truewind, LLC
463 New Karner Road
Albany, NY 12205 USA
Tel: (518) 437-8653
Fax: (518) 437-8659

Key Words: Uncertainty, Measure-Correlate-Predict, Extrapolation to Hub Height, Wind Speed, Long-Term Projection, Wind Shear

Summary:

Uncertainty in the long-term wind resource at turbine hub height is one of the most important sources of uncertainty in the total energy production of wind projects. This study considers two important uncertainty sources in energy production estimates: the measure-correlate-predict (MCP) method and wind shear extrapolation to hub height.

Bulk regressions between monitoring sites and reference sites provide more accurate and precise long-term wind speed projections than directional regressions or ratios. However, for micrositing purposes, the directional methods become useful. In applying MCP, careful attention must be paid to the temporal period employed and how well it represents the primary meteorological scales responsible for the climatological relationship. It is also necessary to monitor for 12-month increments to minimize seasonal effects.

In looking at extrapolated hub height wind speeds, instrument uncertainty is important, as it appears to translate directly into the final estimate. Vertical anemometer spacing is also important because an accurate wind shear estimate needs to be obtained. If too small of a vertical distance is used, the uncertainty grows considerably; while if the distance is too large, surface roughness features could bias the shear figure, leading to an inaccurate estimate.

This research has addressed the uncertainty associated with the measure-correlate-predict method and wind speed extrapolation to hub height. Additionally, there is uncertainty associated with the consistency of long-term reference data, project-wide estimates derived from wind flow models, and the consistency of future project conditions, among other sources. These sources are the subject of continuing research at AWS Truewind.

Introduction

Uncertainty in the long-term wind resource at turbine hub height is one of the most important sources of uncertainty in the total energy production of wind projects. With few exceptions, however, there are no standard rules or methods for estimating the uncertainty. This can lead to a considerable range of variation in uncertainty estimates by different experts reviewing the same project.

This study considers two important sources of uncertainty in energy production estimates: the measure-correlate-predict method and wind shear extrapolation to hub height. Respective uncertainties associated with measurement accuracy; the impacts of different monitoring periods; the relationships between site data and long-term reference data; methods of assessing the consistency of long-term reference data; and uncertainty in wind shear exponents or logarithmic formulas used to estimate hub height wind speeds are analyzed.

Uncertainty Analysis Methods

Application of the Measure-Correlate-Predict Method

The measure-correlate-predict method of estimating long-term wind speeds correlates short-term data from a site with concurrent data from a long-term reference station. A regression or other relationship between the two stations is derived, and the long-term mean speed at the reference stations is applied to estimate the long-term speed at the site. In this analysis, three such methods are investigated in order to compare the precision and accuracy of each.

Three monitoring sites – each with a four-year continuous data record and without major data gaps – were chosen to assess the estimate uncertainty derived from varying sub-periods of data. Analyzing shorter data periods attempts to mimic the constraints encountered in typical wind resource studies where there is a limited period of record and limited choice of reference data. In this study, it was necessary to correlate the different periods of monitoring site data with several reference stations in order to measure the variability in the long-term estimates. Sub-periods of 1-month (typical of monitoring periods for sodar studies), 3-months, 6-months, 12-months, 18-months, and 24-months were analyzed to assess the variability on long-term estimates. The wind speed estimate ranges are the bases of the uncertainty estimates set forth in this study. Table 1 provides information about the three monitoring sites analyzed. It should be noted that the specific site names and locations for two of the sites cannot be disclosed for proprietary reasons.

Table 1. Monitoring Site Information

Monitoring Site	Elevation (m)	Monitoring Height (m)	Period of Record	Reference Station Count
Western New York	625	40 m	May 1998 – Apr 2002	7
Mount Sunapee, New Hampshire	813	40 m	Oct 1998 – Sep 2002	6
Southwestern Minnesota	560	50 m	Sep 2000 – Aug 2004	8

Since each wind-monitoring site had a 4-year period of record, it was assumed that the entire data set represented the site's long-term data population and was therefore defined as the "long-term" site wind speed. This convention applies to reference station mean speeds as well. Projecting the 4-year mean wind speeds (as opposed to projecting true long-term mean wind speeds) was done to isolate the uncertainty associated with the MCP method. Since an accepted value for the site long-term mean wind speed is defined, the only estimate uncertainty is associated with the quality and consistency of the relationship between the measurements at the site and reference masts.

There are overlapping data in the tested periods of 6 months or greater. Applying the assumption that each selected data period corresponds to an independent monitoring duration, data overlap is not considered to be a factor in this analysis. Period of record cutoffs were chosen based on the following criteria:

- Monthly periods correspond to calendar months

- The first 3-month period was selected starting with the first month of data with subsequent periods starting exactly 3 months after the previous period.
- The first 6-month period was selected starting with the first month of data with subsequent periods lagging the previous period by 3 months
- Data periods of 12-months or greater were selected starting with the first month of data with subsequent periods lagging the previous by 6 months

Three types of analyses comparing monitoring site wind speeds with reference station observations were performed to estimate the monitoring site long-term annual mean wind speeds. Two methods employed regression analysis and one used a ratios of means approach. Reference data were acquired from the following quality-controlled sources: National Weather Service (NWS) Automated Surface Observing System (ASOS) sites, National Data Buoy Center (NDBC) Coastal-Marine Automated Network (C-MAN) sites, and NWS rawinsonde sites. Table 2 lists the reference stations selected correlated with each monitoring site.

Table 2. Meteorological Reference Stations Used to Estimate Monitoring Long-term Wind Speeds

Western New York	Mount Sunapee	Southwestern Minnesota
Dunkirk, NY C-MAN (C-MAN)	Jaffery, NH ASOS (KAFN)	Watertown, SD ASOS (KATY)
Bradford, PA ASOS (KBFD)	Albany, NY Upper Air (KALB)	Sioux Falls, SD ASOS (KFSD)
Buffalo, NY ASOS (KBUF)	Concord, NH ASOS (KCON)	Huron, SD ASOS (KHON)
Dunkirk, NY ASOS (KDKK)	Gray, ME Upper Air (KGYX)	Mitchell, SD ASOS (KMHE)
Erie, PA ASOS (KERI)	Lebanon, NH ASOS (KLEB)	Redwood Falls, MN ASOS (KRWF)
Rochester, NY ASOS (KROC)	Manchester, NH ASOS (KMHT)	Rochester, MN ASOS (KRST)
Syracuse, NY ASOS (KSYR)		Spencer, IA ASOS (KRST)
		Sioux City, IA ASOS (KSUX)

The first technique – called bulk regression – involved computing one regression equation between the concurrent daily mean wind speeds at both the monitoring site and each reference station for each data sub-period. Wind speed projections were then calculated by substituting the appropriate reference station long-term mean wind speed into each equation.

In the second method, individual regression equations were calculated using concurrent hourly wind speeds for each of 16 direction sectors for each period of record. A reference station long-term wind speed was computed for each of these direction sectors and then substituted into the corresponding regression equation to project the monitoring site directional long-term mean wind speeds. These directional estimates were then weighted by the reference site long-term annual wind rose to estimate the monitoring site long-term wind speed.

The third procedure was similar to the second but employed directional ratios rather than directional regressions. For each direction sector, the monitoring site and reference site sub-period average wind speeds were calculated in order to compute their ratios. These ratios were then multiplied by the reference station directional long-term wind speed and then the results weighted by the reference station long-term wind rose.

For all three methods, the long-term wind speed estimates were averaged and the corresponding standard deviations were calculated, with ratios between the two values computed for each temporal period analyzed. Several plots detailing the relationships between the wind speed estimate variation and both the period of record and the r-squared value, respectively, are presented to illustrate the change in long-term estimate uncertainty based on those two variables.

Uncertainty in Extrapolated Hub Height Wind Speed Estimates

As wind turbine hub heights constantly grow in size, it is a common practice to conduct wind speed measurements on towers of lower height and extrapolate hub height wind speeds using the power law approximation. Although many wind projects are based on measurements carried out on towers as tall as the prospected wind turbines – often 80 m to 100 m high – it is still a common practice to collect data using 40 m to 60 m tall towers.

Extrapolation of hub height measurements obtained from such towers inherently contains a measure of uncertainty that is dependent upon several factors and is a subsequent factor when calculating the uncertainty in the expected energy yield of a project. The uncertainty sources can be divided into the following two groups:

- Measurement Uncertainty
- Wind Shear Model Uncertainty.

The measurement uncertainty can be further divided into systematic measurement errors – which can be estimated and minimized – and random errors.

The most common sources of systematic errors are mistakes in the application of anemometer calibration constants when converting raw data, mistakes in data processing, unequal tower effects (due to tapered diameter of the tower, different boom lengths and different boom azimuth) on different level anemometers, overspeeding of cup anemometers, etc. These errors can be limited by scrutiny in data analysis, consistent setup of the sensors on monitoring towers (constant tube diameter face width, identical boom lengths and orientations, application of only side-mounted anemometers for shear estimate etc.), and correcting for overspeeding using experimental characteristics of the sensors.

Another source of uncertainty is random measurement errors related to anemometer calibration error – or standard transfer function in the case of uncalibrated units. In order to investigate this issue more closely, consider a site where the wind shear profile is described ideally by the power law (1), where a monitoring tower was installed with anemometers at heights of h_1 and h_2, and prospective wind turbines have hub height of h_3 (where $h_1 < h_2 < h_3$).

$$\frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad (1)$$

Measured wind speeds V_1 and V_2 at the corresponding heights of h_1 and h_2 can therefore be used to calculate the shear exponent α using the following expression:

$$\alpha = \frac{\ln\left(\frac{V_2}{V_1}\right)}{\ln\left(\frac{h_2}{h_1}\right)} \qquad (2)$$

Combining expressions (1) and (2) results in the following expression for V_3 as a function of known parameters:

$$V_3 = V_2\left(\frac{h_3}{h_2}\right)^{\left[\frac{\ln\left(\frac{V_2}{V_1}\right)}{\ln\left(\frac{h_2}{h_1}\right)}\right]} \qquad (3)$$

Random error of wind speed V_3 at hub height for uncorrelated and normally distributed uncertainties of input parameters can be expressed as:

$$\Delta V_3 = \sqrt{\sum_{i=1}^{J} \left(G_i \cdot \Delta x_i \right)^2} \quad (4)$$

where the coefficients G_i are known as sensitivity coefficients and expressed as follows:

$$G_i = \left. \frac{\partial f}{\partial X_i} \right|_{X_i = V_1, V2, h_1, h_1} \quad (5)$$

and Δx_i are the measurement errors of input parameters. Major sources of uncertainty for wind speeds extrapolated to hub height are the respective uncertainties in the measured wind speeds V_1 and V_2. Uncertainties in h_1 and h_2 have substantially smaller impact and therefore are neglected here. The total uncertainty of wind speed V_3 at hub height is calculated from the partial derivatives of (3) with respect to V_1 and V_2 and the corresponding measurement errors.

Results and Discussion

Measure-Correlate-Predict Uncertainties

In defining the uncertainty of each analytical method, emphasis is placed on the mean relative long-term wind speed estimate produced by each analysis and the mean relative standard deviation of those estimates. These define the precision and accuracy of each method. Tables 3 and 4 provide these values for each sub-period and monitoring site.

Table 3a-c. Mean Relative Wind Speed Projections for Each Climatological Adjustment Method

a. Western New York

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.619	0.8%	-5.9%	12.2%
3-months	0.631	0.3%	-2.1%	9.1%
6-months	0.646	0.5%	-0.8%	8.3%
12-months	0.660	0.1%	0.0%	7.6%
24-months	0.663	-0.2%	-0.3%	7.6%

b. Mount Sunapee

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.408	1.5%	-6.5%	61.7%
3-months	0.407	0.9%	3.0%	59.6%
6-months	0.396	0.6%	3.5%	53.1%
12-months	0.395	-0.3%	3.3%	51.0%
24-months	0.396	-0.6%	3.8%	49.0%

c. Southwestern Minnesota

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.573	1.3%	-2.8%	6.8%
3-month	0.574	0.4%	-0.1%	6.2%
6-month	0.579	0.3%	1.3%	5.4%
12-month	0.577	0.4%	1.8%	5.1%
24-month	0.583	0.1%	1.9%	4.8%

Table 4a-c. Mean Relative Standard Deviations for Each Climatological Adjustment Method

a. Western New York

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.619	6.4%	9.6%	8.7%
3-months	0.631	4.9%	7.8%	5.6%
6-months	0.646	3.5%	5.3%	3.8%
12-months	0.660	1.2%	1.2%	2.1%
24-months	0.663	0.6%	0.7%	0.7%

b. Mount Sunapee

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.408	11.8%	15.1%	23.2%
3-months	0.407	10.3%	13.0%	16.0%
6-months	0.396	7.8%	9.6%	9.5%
12-months	0.395	2.8%	4.2%	4.0%
24-months	0.396	1.4%	2.1%	1.8%

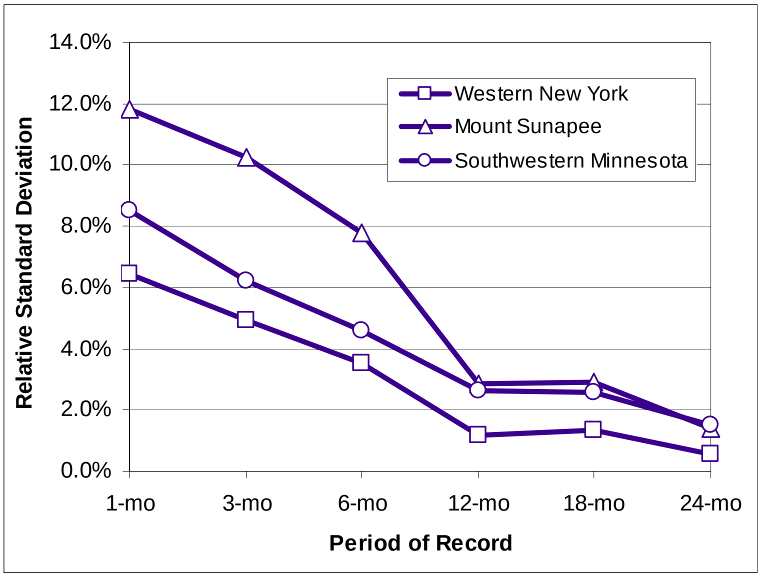
c. Southwestern Minnesota

Period of Record	Mean r-squared	Bulk Regression	Directional Regression	Directional Ratio
1-month	0.573	8.4%	9.6%	10.3%
3-month	0.574	6.2%	7.3%	6.0%
6-month	0.579	4.6%	4.6%	3.9%
12-month	0.577	2.6%	2.6%	1.9%
24-month	0.583	1.5%	1.4%	0.6%

The results show that the bulk regression measure-correlate-predict method provides the highest precision and accuracy of the three methods tested. Upon analyzing the relationships between meteorological temporal and spatial scales and the distances between the monitoring and reference sites, these results should not be surprising. Since in most cases, the long-term reference stations are at least 50 km away, the similarities between monitoring site and reference site climate are generally on the meso- and synoptic meteorological scales. For these phenomena, the spatial scales start roughly on the order of 100 km and have temporal scales of 6 h or greater. For features that are any smaller, there often becomes a certain amount of lag time in the passage of microscale (convective) meteorological features at both the reference and monitoring sites, if the same feature even affects both sites. In any case, these features likely will not simultaneously affect both locations resulting in scatter that can incorrectly influence monitoring/reference site relationships. However, in micrositing situations where sodar or other towers are installed within a proposed project area and the spatial scale is less than 10 km, hourly periods would then be appropriate. Since the goal of long-term analyses is to mathematically determine the climatological relationship between two sites, it is most appropriate to select the temporal scale that corresponds with the meteorological scales that are responsible for the relationships.

Having discussed the relationship between the meteorology and the appropriate temporal period to select when computing long-term estimates, it is important to determine the appropriate monitoring period that will sufficiently minimize the corresponding uncertainty in those projections. Figure 1 contains a plot of the mean relative standard deviation of the bulk regressions for each monitoring site as a function of monitoring period.

Figure 1. Mean Relative Standard Deviations for Each Monitoring Period (Bulk Regressions)



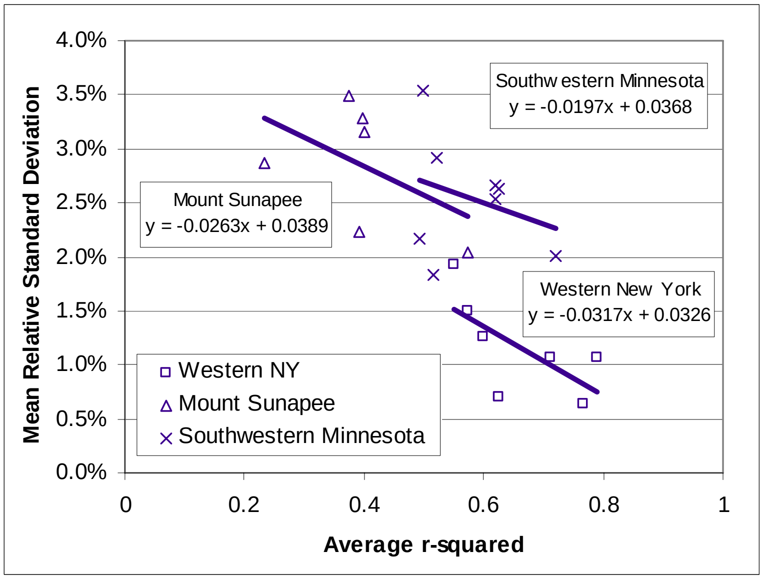
A one-month monitoring period – typical for most sodar deployments – provides an uncertainty range between 6.5 % and almost 12 % for the long-term wind speed estimates. For the other subannual periods evaluated, despite an inverse relationship between uncertainty and period of record, the ranges are still rather large (~ 4 % for the 6-month sub-period). However, once the period of record reaches 12 months, there are large drops in the uncertainties and the range becomes significantly smaller (~ 2 %). Interestingly, there is little change in the uncertainties when analyzing 18-month sub-periods. The 24-month period of record shows a resumption of the downward uncertainty trend. This signature provides evidence that there is a significant seasonal influence on the quality of long-term estimates.

In the results, there is also an apparent relationship between the r-squared of the monitoring/reference station correlation and the uncertainty. Figure 2 shows the mean relative standard deviation for each monitoring/reference site pair using bulk regressions for a 12-month period of record.

In looking at the linear trend lines for each monitoring site, the equations are fairly similar. Taking their average provides a new equation ($y = -0.0259x + 0.0361$, where x is the r-squared value of the regression) that provides reasonable uncertainty estimates for varying r-squared values. For example, in a monitoring/reference site regression relationship where the r-squared value is 0.7, the uncertainty would be about 1.8 %. This value would rise to roughly 2.3 % for an r-squared value of 0.5.

In studying the uncertainty associated with the measure-correlate-predict method, bulk regressions provided the most precise and accurate results compared to the directional relationships. However, the directional methods are useful tools despite limitations resulting from meteorological scale analyses. Finally, strong evidence of seasonal influences on long-term projection quality exhibits the importance of monitoring for at least 12 months and at multiples thereof.

Figure 2. Relationship Between Estimate Uncertainty and r-squared for 12-month Bulk Regressions



Extrapolated Hub Height Wind Speed Uncertainties

All of the extrapolated wind speed uncertainties presented herein assume an 80 m hub height. Both the measurement accuracy (anemometer uncertainty) and the site monitoring levels strongly influence uncertainty of these wind speeds.

In looking at the measurement accuracy, anemometers with uncertainties of 1 %, 1.5 % and 2 % – corresponding to the typical measurement uncertainty range for high-end anemometers calibrated in reputable wind tunnels and low-cost, uncalibrated sensors. Figure 3 shows the varying extrapolated wind speed estimate uncertainties associated with different quality anemometers. In each example, it is assumed that the upper anemometer is installed at 50 m and the lower anemometer height is the independent variable.

The data in Figure 3 suggest that there is a directly proportional relationship between anemometer measurement uncertainty and the associated uncertainty in the extrapolated hub height wind speed projections. For example, hub height wind speed projections from the typical 50 m and 30 m vertical spacing exhibit between 2.3 % and nearly 5 % for measurement uncertainties of 1 % and 2 %, respectively. If the lower instrument is raised to the 40 m level, the uncertainties rise to 4 % and 8 % respectively. It appears that instrument uncertainty projects directly into the extrapolated hub height uncertainty regardless of the monitoring heights.

Figure 4 shows the relationships between extrapolated hub height wind estimate uncertainty and the vertical orientations of anemometers with respective 1 % and 1.5 % measurement uncertainties.

The data in Figure 4a show that the hub height measurement standard error is approximately 2.3 % (1) when extrapolated from 50 m using a 50 m / 30 m wind shear profile and anemometers with a 1 % measurement uncertainty. If the lower anemometer was positioned at 40 m, the standard error would be above 4 %. This substantial rise is due to the smaller vertical layer that would be sampled under this monitoring scenario. If a 60 m tower was employed and the lower anemometer positioned at 30 m, the hub height wind speed standard error would be reduced to 1.6 % (2). Raising the lower anemometer by 10 m to provide the same 20 m separation (60 m and 40 m) between sensors as in the first set-up provides a smaller standard error (about 1.9 %) than the initial case. There are two factors – both of which are somewhat related – likely dictating this drop in the uncertainty. The first is that the extrapolation to hub height is being computed over a smaller distance than in the initial setup. The second is that the wind shear profile being sampled is likely closer to the actual profile near hub height due to less surface roughness influence. The final important setup to consider is when sensors are positioned at 60 m and 50 m for use in the wind shear calculation. Despite the closest proximity of both sensors to hub height, the standard error is almost 1 % larger (3.1 %) than the initial scenario (2.3 %) with anemometers at

50 m and 30 m levels. This final vertical spacing example demonstrates that care needs to be taken to select anemometer heights that will provide the most accurate wind shear estimate while minimizing the uncertainty of that value.

Figure 3. Uncertainties in Extrapolated Hub Height Wind Speed Estimates Using Different Quality Anemometers

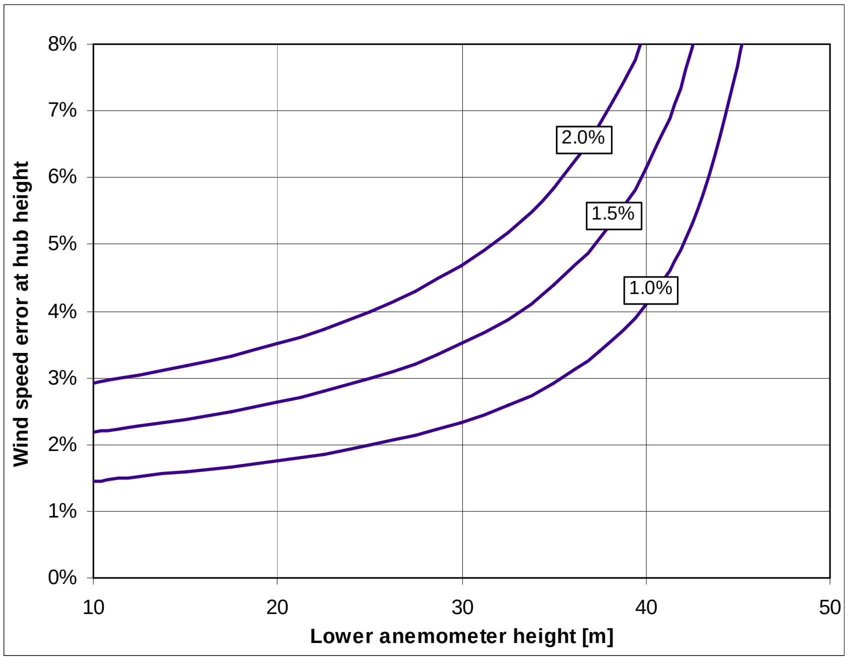
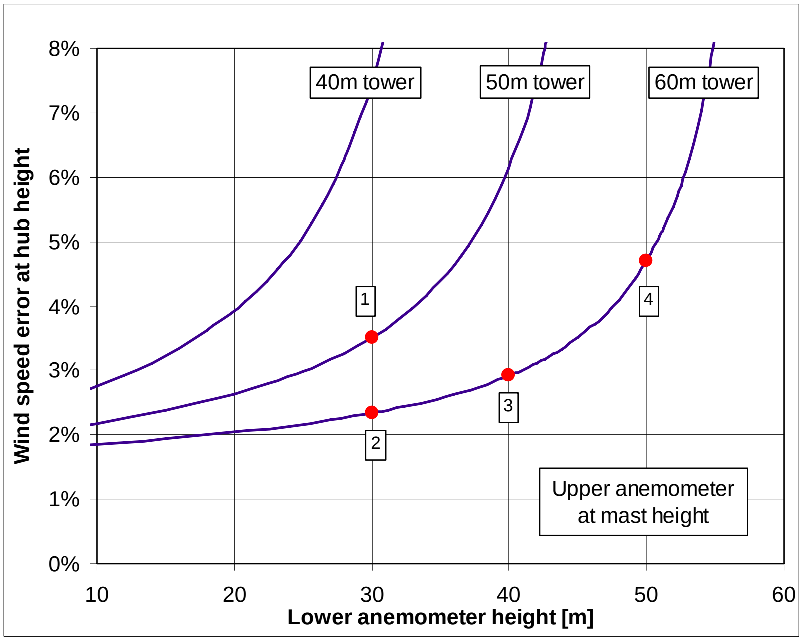


Figure 4. Extrapolated Wind Speed Uncertainty as a Function of Vertical Spacing

a. Anemometers with 1.5% Measurement Uncertainty



b. Anemometers with 1% Measurement Uncertainty

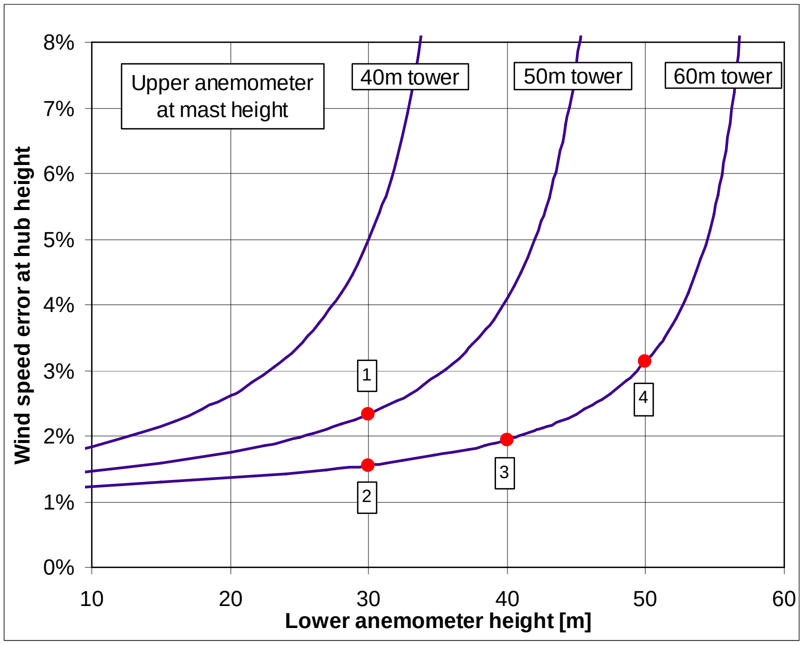


Figure 4b depicts the same patterns for anemometers with 1.5 % measurement uncertainty. However, not surprisingly, it also indicates that the uncertainty of extrapolated hub height wind speeds increases accordingly. If a hub height mast is employed for wind speed monitoring, then the measurement uncertainty is reduced to the anemometer measurement uncertainty and any uncertainties associated with tower effects on the measurements.

All of the data presented suggest that the uncertainty in power law extrapolated wind speeds increases dramatically if the vertical separation between the measurements is too small, regardless of monitoring height. There is also strong evidence that the separation between the sensors should be as large as possible to minimize the hub height wind speed estimate error. However, there is an obvious trade off to mounting the lower anemometer too close to the ground. Atmospheric boundary layer theory and field practice have shown that if the lower anemometer is mounted too closely to the ground, the wind shear profile will not conform to the actual profile because surface roughness changes and obstructions close to the tower strongly affect low-level wind speed data. As a result, the calculated wind shear profile would not be accurate due to substantially greater turbulent air mixing between the two monitoring levels.

Considering vertical anemometer spacing effects on wind shear uncertainty and the systematic errors caused by, among others, flow acceleration around the tower, the suggested practice is to mount the upper level anemometer on a side oriented boom 1 m to 2 m below the tower top and place the lower anemometer at a level that minimizes surface influences while maximizing the vertical layer being sampled. Furthermore, both sensors should be oriented in the same directional orientation. These guidelines attempt to equilibrate the simultaneous tower-induced flow acceleration experienced by both anemometers, thereby canceling the tower effects on the measured shear. Collecting data at 3 levels is another advantageous practice that provides more information about the wind shear profile because it determines whether or not there is variability with respect to height. Mounting redundant anemometers at each level enables further validation of observed wind speeds and therefore easier identification of sensor damage or icing.

In looking at the uncertainties associated with extrapolated hub height wind speeds using the power law approximation, the data show that both the anemometer measurement uncertainty and the vertical spacing are important factors that need to be considered when collecting wind speed data. There is a balance that needs to be satisfied between vertical spacing and anemometer accuracy to achieve extrapolated hub height wind speed estimates within acceptable uncertainty margins.

Conclusions

In evaluating the wind speed estimate uncertainty, the results show that the following factors have to be considered: the anemometer measurement uncertainty; the vertical spacing on the tower; the monitoring period; the temporal period used in the measure-correlate-predict analysis; and the r-squared of the monitoring/reference station relationship. With that being said, there is uncertainty at every stage of a wind resource assessment that must be properly accounted for in the final results. Assuming each source of uncertainty is statistically independent from the others, the total uncertainty, σ_{total} is defined as follows:

$$\sigma_{total} = \sqrt{\sum_{i=1}^{J} \sigma_i^2}$$

where each σ_i represents the uncertainty associated with each source (measurement, climatological adjustment, extrapolation to hub height, etc.).

This research has addressed the uncertainty associated with the measure-correlate-predict method and extrapolation to hub height. Additionally, there is uncertainty associated with the consistency of long-term reference data, project-wide estimates derived from wind flow models, and the consistency of future project conditions, among other sources. These sources are the subject of continuing research at AWS Truewind.