# EFFECTS OF TUBULAR ANEMOMETER TOWERS ON WIND SPEED MEASUREMENTS

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**Abstract**

Tubular tilt-up towers have been a popular platform for collecting wind resource data. The use of towers of 40 m and 50 m heights is widespread, and now 60 m towers of this type are being erected. Some of these towers have been equipped with anemometers mounted on stub masts at the top of the tower (top-mount booms - TMB). Data from such towers with redundant sensors on side-mount booms (SMB) at the top level suggest that there is a speed-up effect with the TMB.

In order to investigate this effect and determine its magnitude, five 50 m tilt-up towers were instrumented with three anemometers at the top, two on SMB and one on a TMB. On four of the towers, the SMB were positioned on opposite sides of the tower, but on one tower the SMB were oriented in orthogonal directions.

Analysis of the wind speed data shows that the tower produced a shadowing effect on the downwind SMB, which was evident over a range of some 50 degrees of wind direction. The maximum wind speed deficit was on the order of twenty percent. Additionally, data from the tower with the orthogonal SMB suggests an upwind deficit in the wind speed, possibly coupled with an acceleration around the side of the tower. After screening the data to eliminate these effects, the average wind speed recorded at the TMB was approximately three percent higher than the wind speed measured at the SMB. This error in wind speed resulted in an error of approximately five percent in turbine theoretical energy.

When the erroneous 50 m wind speed data from the TMB is used to estimate wind speed and energy at higher levels, the errors are increased. The continued use of these short top-mounted stub masts for wind speed measurements on tilt-up towers is discouraged in favor of using side-mount booms or much longer TMB while employing proper data screening techniques and avoiding effects from the lightening rod.

## Introduction

The use of tilt-up tubular towers for making wind resource measurements has been quite common in the wind energy industry for many years. Over the years tower heights have increased from approximately 26 m to 60 m. As the height of these towers has increased so has the diameter of the tubes that are pieced together in their construction. A number of these towers have been erected using a short 30 cm (12 in.) or 41 cm (16 in.) stub mast to mount an anemometer at the top of the tower – a top-mount boom (TMB). Most of these towers are installed with a lightening rod at the top, which is fixed to the side of the tower and extends upward well above the instrumentation. Typically, additional anemometers are mounted on SMB at lower elevations in order to measure the vertical wind shear.

In some instances a second, redundant anemometer has been installed as close to the top of the tower as possible, employing a side-mount boom (SMB). Anecdotal evidence from individuals who have collected data from towers with the redundant anemometers at the tower top has indicated that the wind speeds measured at the TMB were higher than those at the SMB. This situation would then require a decision as to which wind speed to use to define the wind resource at the measurement site.

The criticality of having accurate wind resource data cannot be overstated. Contract awards and financing of projects can be won or lost because of differences in energy projections on the order of one percent.

Errors of this magnitude can be obtained as a result of errors in wind speed measurements of less than one percent. Using the higher wind speed would improve the apparent wind resource, however, over estimation of energy output from a project has serious implications for debt payment and other financial obligations of a project.

**Measurement Program**

In order to determine the existence of TMB errors and their magnitude a measurement program was instituted. A total of five 50 m tubular towers, with a diameter of 15 cm (6 in.), were installed. These sites will be referred to here as sites 1 through 5. Each had a configuration of anemometers that included a total of three Maximum Cup anemometers at the ~50 m level. Two were mounted on 107 cm (42 in.) SMB, approximately 30 cm (12 in.) below the top of the tower. With this boom length the anemometers were seven tower diameters from the tower, which is consistent with industry standards. One was on a TMB at approximately 30 cm (two tower diameters) above the top of the tower, not to industry standards, but common for such installations. At four of these tower sites (sites 1 through 4) the SMB were oriented on opposites sides (east and west) of the tower. At the other, site 5, the SMB were oriented in orthogonal directions (west and south). A wind vane and a lightening rod were also installed at the top of the towers.

Collection of hourly average data began in December 2001 at the first four sites and in March 2002 at the site with the orthogonal booms. The data received careful quality assurance checks to remove values with icing effects.

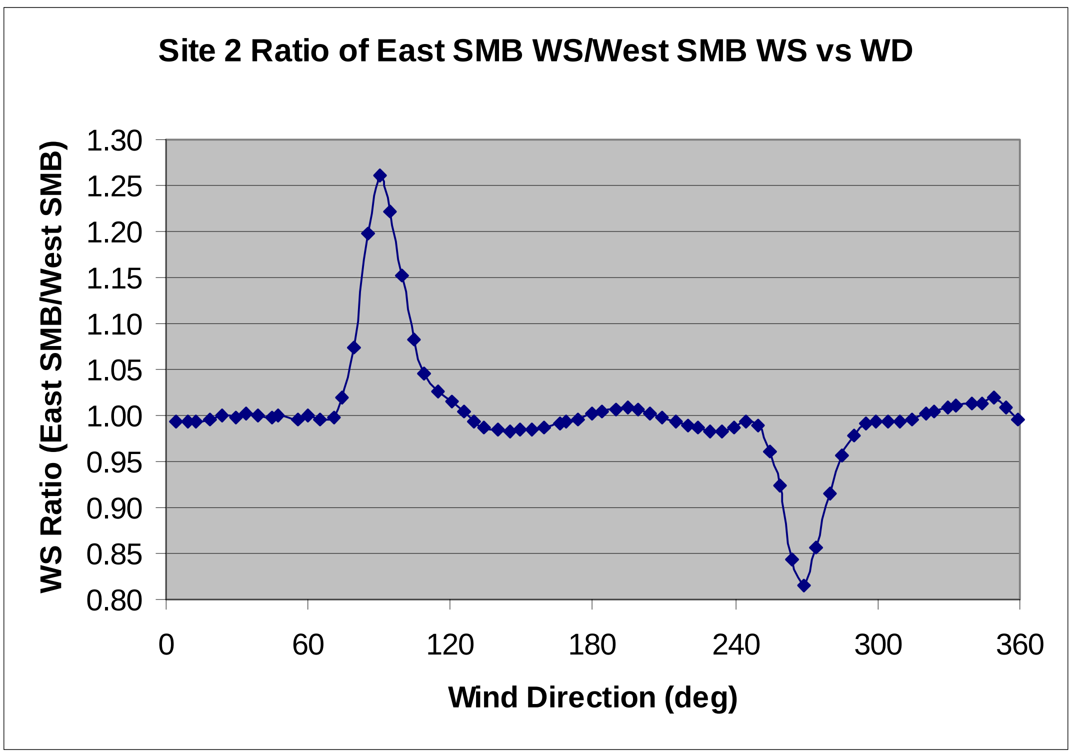


FIGURE 1. SMOOTHED RATIO (EAST SMB/WEST SMB) OF AVERAGE WIND SPEED AT SITE 2 EAST SMB/WEST SMB VERSUS WIND DIRECTION.

**Downwind Effects on SMB**

The first analysis of the data was performed to check for tower shadow effects on the SMB anemometers. The ratios of the average wind speeds from the SMB were calculated as a function of wind direction and then plotted. Figure 1 above illustrates the kind of effect that was prevalent. This shows the ratio of the average wind speed from the east SMB divided by the average wind speed from the west SMB at site 2. Observe that when the wind direction is westerly, the east anemometer is in the tower shadow and the ratio dips to a minimum of ~0.80 at a wind direction of 270°. Conversely, when the wind direction is easterly the anemometer on the west SMB is shadowed and the ratio is ~1.25. Of course the effect is almost exactly the same on both sides of the tower – the inverse ratio of 0.80 = 1.25. The tower shadow affects the downwind SMB over a range of some 50°.

The reason for having the SMB oriented in orthogonal directions at Site 5 is shown below in Figure 2. The analysis of the data is basically the same as in Figure 1, except here there are ratios of west SMB/south SMB. Similar to Site 2 the wind speeds on the SMB show the effects of tower shadow. In east winds the west SMB is shadowed and reads lower wind speed than the south SMB, and in north winds the south SMB is shadowed and reads lower speeds than the west SMB. However, an interesting new feature is revealed.

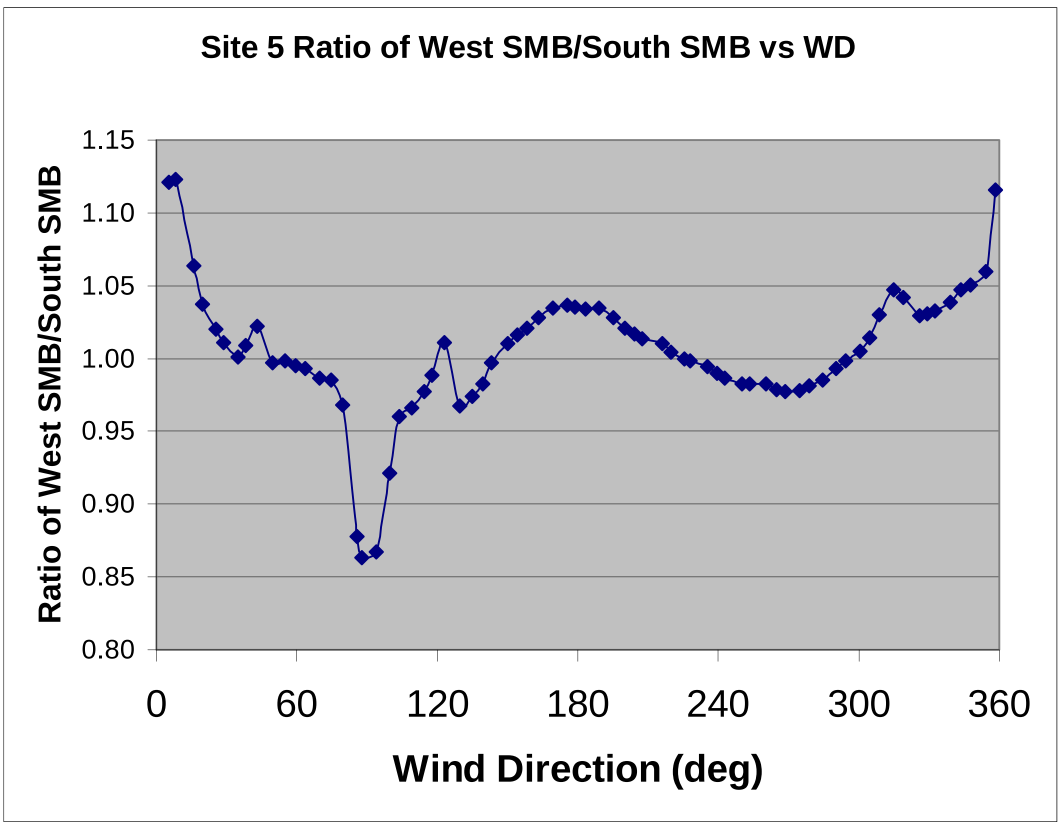


FIGURE 2. SMOOTHED RATIOS (WEST SMB/SOUTH SMB) OF AVERAGE WIND SPEED AT SITE 5 VERSUS WIND DIRECTION.

Note the pattern in the ratios beginning at a wind direction of about 150° and ending at about 300°. Starting from 150° the west SMB begins to read higher than the south, with the ratio peaking at 180° with a value of 1.037. Then as the direction moves toward the west, the ratio decreases to less than 1.0 with a minimum value of 0.977 at 274°. This pattern is consistent with two effects, either or both of which could be present. One is an upwind speed deficit and the other is a crosswind acceleration around the side of the tower. Both of these are predicted by potential flow theory, although the magnitudes of the theoretical effects are much smaller than what is observed here. Because of the orientation of the booms it is impossible to determine if both possible effects are indeed present or what their individual magnitudes may be, but theoretical calculations suggest that the upwind deficit would be approximately twice the magnitude of the crosswind acceleration. Certainly, the effect is quite distinct and not insignificant.

There is another interesting effect that seems to be evident in Figure 2. Note the upward perturbation in the ratios peaking at a direction of approximately 315° and a similar one downward at approximately 135°. The feature at ~315° would suggest a wake effect (shadow) from the west SMB anemometer on the south SMB anemometer, and the converse wake effect (south SMB shadowing the west) would be responsible for the reduced ratio at ~135°.

**Top-mount Boom Effects**

To analyze the effects on the wind speed seen at the TMB, the data used for comparison, the SMB data, had to be screened to eliminate tower effects. Certainly, the downwind effects must be avoided and the other effects (upwind and/or crosswind), as well. Since crosswind acceleration is expected to be lower in magnitude than the upwind deficit, and both of these are much less than the downwind effect the filtering process that was used was to simply use the higher of the two wind speeds from the SMB as the reference speed. This is an imperfect method. However, at the time of the TMB analysis the upwind and crosswind effects had not yet been analyzed and the timing of events did not allow reanalysis of the TMB data for this paper. The result of this work are not intended to represent the final and absolute answer to the problems presented, but do show what is possible under circumstances that may be encountered in field measurement programs.

First, the average wind speeds at the TMB and SMB were calculated. These and the ratios of the TMB wind speed/SMB wind speed are presented in Table 1 below.

TABLE 1. AVERAGE WIND SPEEDS (M/S) AT TMB AND SMB AND RATIOS OF TMB/SMB WIND SPEED AT THE FIVE MEASUREMENT SITES.

| | SMB | TMB | TMB/SMB |
|---|---|---|---|
| Site 1 | 8.3 | 8.6 | 103.4% |
| Site 2 | 8.6 | 8.8 | 102.5% |
| Site 3 | 8.3 | 8.5 | 102.5% |
| Site 4 | 8.4 | 8.7 | 103.4% |
| Site 5 | 7.0 | 7.1 | 101.7% |

At all sites the average wind speed at the TMB was higher than the filtered SMB wind speed by as much as 3.4 percent, which is a rather significant difference.

An analysis of the ratios of TMB/SMB wind speed versus wind direction at all sites was prepared and the one from Site 5 is presented in Figure 3 below. The results from Site 5 were selected because an effect that was present at all sites to varying degrees of magnitude and clarity is well represented at this site.

The most striking feature in Figure 3 is the high-amplitude curve that occurs between wind directions of 80° and 170°. Of course the Figure clearly shows that there are significant variations in wind speed as measured at the TMB and SMB locations in other wind directions, but the feature in that direction range is most prominent. It turns out that at this site, the TMB anemometer is mounted on the tower at a position on the northwest side of the tower and the lightening rod is mounted on the southeast side of the tower, and this prominent feature is a result of the anemometer being shadowed by the lightening rod.

The anemometer spins in a counter-clockwise sense due to differential forces exerted by the wind on the front side and back side of the cups. At a wind direction of 104° the shadow of the lightening rod falls with full effect on the side of the anemometer that presents the backside of the cups to the wind (reducing the retarding force) and this results in the cups over speeding. Then as the wind direction shifts to the south at a direction of 140° the shadow has the greatest impact on the front side of the cups and the anemometer's rotation slows. This effect seems to occur over a range of wind directions when there are other tower effects present, so the effect of the lightening rod alone is difficult to isolate.

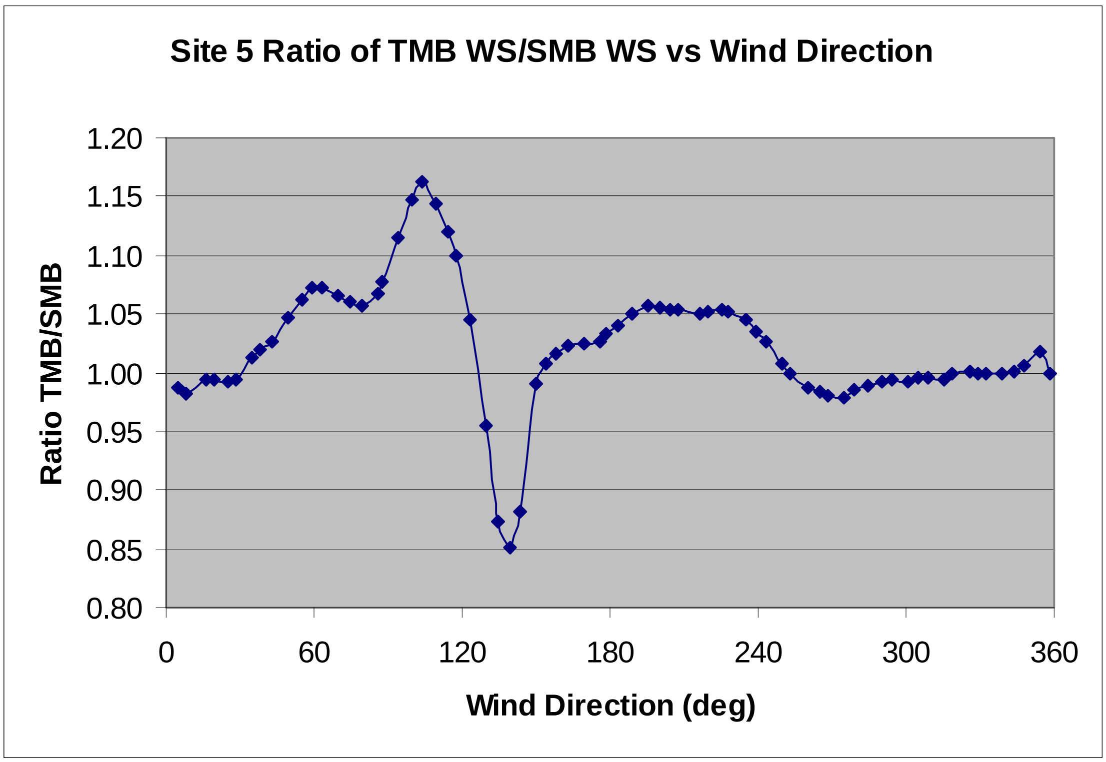


FIGURE 3. SMOOTHED RATIOS (TMB/SMB) OF WIND SPEED VERSUS WIND DIRECTION AT SITE 5.

The other sites all showed similar effects from the lightening rod but the other tower effects varied somewhat in clarity and magnitude. A number of the other sites showed a pattern in the wind speed ratios that suggested that some effect of the tower caused the TMB wind speed to read lower than the SMB when the wind blows from the direction that the TMB anemometer is mounted on the tower. That is, on the other four towers the TMB is mounted on the south side of the tower and when the wind blows from the south the TMB wind speed was in some cases observed to be lower than the SMB wind speed. However, one must consider the possibility that the observed dip in the wind speed ratios was the result, at least in part, of an acceleration of the wind at the crosswind position, as suggested by the data from Site 5 (Figure 3). At Site 4 both SMB would be oriented normal to the southerly flow. Whatever the cause, this effect is shown quite well in Figure 4 below. Also, on these other four towers, the lightening rod is mounted on the north side of the tower and its shadow effect is centered about due north.

Other than the similarity in the effects of the shadow of the lightening rod and the fact that some of the sites showed the effect described above, and presented graphically in Figure 4, the patterns in the ratios versus wind direction varied. Certainly, considering such variables as the installed height of the TMB anemometer above the tower, which may not have been exactly uniform at these sites, and the possibility of upwind/crosswind effects on the SMB, it is not surprising that the patterns are somewhat different. Depending on the positioning of a TMB at a site, its height above the top of the tower, the location of the lightening rod and the frequency of the wind directions, there could be a fair bit of variance in the errors in average wind speeds, as this data shows (see Table 1). Nonetheless, it appears that errors of three percent in average wind speed from using TMB anemometers on 50 m towers are possible if not likely. However, a rigorous analysis of the data could reveal the nature of the effects at a specific site.

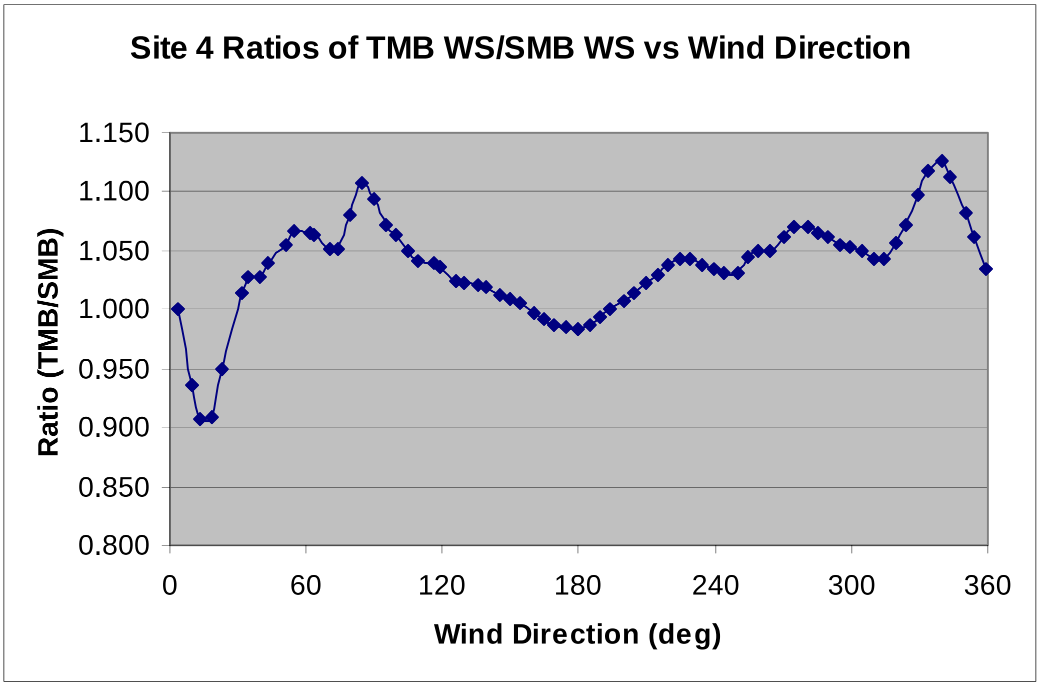


FIGURE 4. SMOOTHED RATIOS (TMB/SMB) OF WIND SPEED VERSUS WIND DIRECTION AT SITE 4.

## Ramifications

The wind speeds collected with the TMB in these data sets represents an overestimation of the wind resource. At Sites 1 through 4, where the errors in average wind speed from the TMB ranged from +2.5% to +3.4%, theoretical energy calculations for a 1.5 MW turbine that resulted from the TMB data were from four to six percent higher than what was obtained by using data from the SMB. These are significant errors in themselves, but things can get worse.

Frequently, proposed turbine hub heights are greater than the height of the tower used in the measurement program and it becomes necessary to estimate the wind speed and energy output at the proposed hub height. In order to do this, the observed data from a measurement site is used to project the wind speeds at the target hub height. In practice, on such a tower as the ones used in this study, wind speeds will be measured at 10 m, 30 m, and 50 m, and the change in wind speed with height, the vertical shear, is often characterized by the familiar $\alpha$ exponent, as in Equation 1 below.

$$\text{Equation 1. . } \alpha = \ln(U_2/U_1)/\ln(Z_2/Z_1).$$

In Equation 1, $U_2$ and $U_1$ represent wind speeds at heights $Z_2$ and $Z_1$, respectively, and we will assume that the wind speeds are from heights of 50 m and 30 m. The wind speed at some other height ($Z_3$) can be estimated using the $\alpha$ exponent obtained from Equation 1, as shown here in Equation 2.

$$\text{Equation 2 } U_3 = U_2 (Z_3/Z_2)^{\alpha}.$$

Of course, if the value of $U_2$ is erroneously high (TMB data), then the value of $\alpha$ will reflect that with an erroneously high value, as well. Then, when the TMB wind speed is used with the erroneous value of $\alpha$ to estimate the wind speed at some higher level, the errors are compounded, resulting in a seriously overestimated wind resource.

**Example Calculations**

The range of possible errors has been examined in the following test cases. We assume a site instrumented with SMB at 30 m and 50 m with an annual average wind speed of 8.0 m/s at the 50 m level. We consider a second tower at the same location, with the same wind conditions with SMB at the 30 m level but the tower was instrumented with a TMB instead of SMB at the 50 m level. Wind speeds at the 30 m level of both towers and at the 50 m level of the first tower are free of errors. The error in the TMB wind speed is assumed to be +3.0%, which is within the range of observed errors in the test data. Thus, the apparent 50 m wind speed would be 8.24 m/s. (Author's note: It is accepted that the anemometer is not capable of measuring the wind speed to this level of precision, but for the sake of argument, the wind speeds will be shown to one hundredth of a meter per second in these example calculations).

We will assume three cases of ambient (true) wind shear, with $\alpha$ values of 0.20, 0.25 and 0.30. These conditions will be used to estimate wind speeds and energy output for a 1.5 MW turbine with hub heights of 65 m and 80 m.

**Calculation of Shear $\alpha$ and Wind Speed Projections**

First, the assumed wind speeds are used to calculate the wind shear alpha. The 30 m wind speed is the same at both towers but varies with the value of $\alpha$. The wind speeds at 30 m and 50 m (TMB) are used to produce the apparent $\alpha$ exponent at the tower with the TMB. The results are shown below in Table 2.

TABLE 2. CALCULATIONS OF APPARENT SHEAR ALPHA FOR VARIOUS WIND SHEAR CONDITIONS.

| True alpha | 50 m SMB | 30 m SMB | 50 m TMB | Apparent alpha |
|---|---|---|---|---|
| 0.20 | 8.00 | 7.22 | 8.24 | 0.26 |
| 0.25 | 8.00 | 7.04 | 8.24 | 0.31 |
| 0.30 | 8.00 | 6.73 | 8.24 | 0.36 |

When the data from the TMB is used, the apparent shear alpha is considerably higher than the true shear alpha. Now the true and apparent shear alpha values will be used with the true (SMB) and erroneous (TMB) wind speed data to estimate average wind speeds at the two proposed hub heights of 65 m and 80 m. It is assumed for the purposes of this exercise that what is represented as the true shear alpha from 30 m to 50 m accurately reflects the shear from 50 m to the two target heights. The results are presented in Table 3

Remember that the 50 m wind speed from the SMB case was 8.00 m/s and 8.24 m/s in the TMB case. These are the base speeds that were used with the respective $\alpha$ exponents to project the wind speeds at 65 m and 80 m. The error in wind speed of 3.0% at 50 m becomes an error of 4.6% at 65 m and 5.8% at 80 m, which illustrates how the errors in TMB wind speed are amplified as the projection height increases. It turns out that the percentage error in the estimated wind speeds is a function only of the base error (3.0% in this case) and the projected height, and is independent of $\alpha$ value.

TABLE 3. PROJECTED WIND SPEEDS (M/S) AT HUB HEIGHTS OF 65 M AND 80 M USING TRUE (SMB) AND APPARENT (TMB) SHEAR ALPHA EXPONENTS.

| | Projected WS (SMB) | | Projected WS (TMB) | |
|---|---|---|---|---|
| True alpha | 65 m | 80 m | 65 m | 80 m |
| 0.20 | 8.43 | 8.79 | 8.82 | 9.30 |
| 0.25 | 8.54 | 9.00 | 8.93 | 9.52 |
| 0.30 | 8.66 | 9.21 | 9.05 | 9.75 |

Now the projected wind speeds are used to calculate energy output from the 1.5 MW turbine. Again, we assume that the "true alpha" accurately represents the shear up to the proposed hub heights, so those projections of hub height wind speed are accurate. The base wind speed distribution is assumed to be typical of wind conditions present in the plains of the United States. The results are shown in Table 4.

TABLE 4. ANNUAL ENERGY CALCULATIONS FOR A 1.5 MW TURBINE WITH HUB HEIGHTS OF 65 M AND 80 M USING PROJECTED WIND SPEEDS FROM SMB AND TMB FOR VARIOUS VALUES OF SHEAR ALPHA.

| | 65 m Energy (MWh) | | Ratio | 80 m Energy (MWh) | | Ratio |
|---|---|---|---|---|---|---|
| True alpha | SMB | TMB | TMB/SMB | SMB | TMB | TMB/SMB |
| 0.20 | 5,673 | 6,133 | 108.1% | 6,095 | 6,658 | 109.2% |
| 0.25 | 5,810 | 6,264 | 107.8% | 6,344 | 6,902 | 108.8% |
| 0.30 | 5,951 | 6,399 | 107.5% | 6,571 | 7,132 | 108.5% |

Using the projected wind speeds from the erroneous TMB data produces large errors in theoretical energy. The errors in theoretical energy at 50 m are almost doubled at the 80 m level.

## Conclusions

Test data from specially configured 50 m tubular anemometer towers has shown that the anemometer mounted on the top-mounted boom (TMB) was subject to effects which resulted in overestimations of wind speed compared to what was measured by an unobstructed side-mount boom at the same height. Localized flow deformation including perturbations in vertical inflow angle at the TMB are suspected to be at least partly responsible for the observed effects. The error in average wind speed using a TMB was a function of wind direction and the lightening rod was observed to cause significant errors in the TMB wind speed measurements. The cumulative errors in TMB wind speed are thus highly dependent on the wind direction frequency distribution and the positions of the anemometer and lightening rod on the tower. Before any quantitative estimates of wind speed errors at a specific site can be made, it would be important to consider the position of the lightening rod with respect to the TMB anemometer. A detailed analysis of wind shear versus wind direction may help in determining the magnitude and frequency of possible errors. The signature of the lightening rod can often be seen in such analysis.

In this study, the cumulative errors in TMB wind speed were observed to be on the order of +three percent. Errors in wind speed of this magnitude can result in errors in turbine energy output on the order of +five percent or more, depending on the wind speed distribution.

The erroneously high wind speeds observed with the TMB resulted in overestimations of vertical wind shear. If the erroneous data from a TMB is used with the resulting erroneous shear $\alpha$ to estimate wind speeds at higher levels, the errors in wind speed at the 50 m level are amplified and can result in some gross overestimations of theoretical energy from any wind turbine.

While these test data were collected on a 50 m tubular tower, it is quite likely, if not inevitable that similar effects, although possibly less severe, would be present when using TMB on other tubular towers of lesser height and diameter. Results from a similar study on 26 m tubular towers suggest that there are errors of +one percent from using TMB on these towers.

This study also showed that there are also effects due to tower shadow present on side-mount boom anemometers. Certainly downwind effects need to be considered, but there was also evidence of a wind speed deficit measured when the SMB was upwind of the tower, possibly coupled with an acceleration in the wind speed when the SMB is oriented normal to the wind direction.

**Recommendations**

The use of TMB for wind resource assessment is highly discouraged in favor of using SMB. Using a much longer TMB would alleviate such problems, however, avoiding effects from the lightening rod are paramount. In wind regimes with variable wind directions, having redundant sensors is recommended but the data need to be screened or filtered to eliminate at least the more severe effects downwind of the tower. In wind regimes with uni-directional winds it is recommended that the SMB be positioned at an angle of approximately 45° relative to the prevailing direction. At this position the theoretical effect of the tower is near zero.