FIELD COMPARISON OF MAXIMUM CUP, CLIMATRONICS AND MET ONE ANEMOMETERS

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Abstract

During the summer of 1998, a field comparison of three different anemometers was conducted. They were a Maximum Cup Type #40, a Climatronics Model F460, and a Met One Model 010C. Each was calibrated and placed on a common crossarm at three meters above ground level. Average wind speeds and standard deviations were collected on a 10-minute basis. Wind speeds from the Maximum Cup were interpreted three ways. Data were collected with and without the protective rubber boot on the Maximum Cup. The average wind speeds measured by the Climatronics and Met One sensors agreed quite closely. The Maximum Cup showed signs of performance degradation in wind speeds below approximately 8 m/s (18 mph) and its average speeds disagreed with the other sensors by up to several percent. These errors were amplified when the data were used to calculate theoretical energy with a turbine's power curve. Turbulence intensities at speeds > 9 m/s were essentially the same for all three anemometers. A method of correcting wind speed data from the Maximum Cup is presented, as well as a discussion of the impact of the performance of the Maximum Cup and its effect on energy projections at other sites.

Introduction

In wind energy project development, two of the key elements are wind speed data and the power curve for a prospective turbine. During the course of developing wind energy projects, and the wind turbines to be used in them, at least three different anemometers have been used by Enron Wind Corp. ("EWC", formerly known as Zond Systems), the Maximum Cup Type #40, Climatronics Model F460 and Met One Model 010C. The Maximum Cups have been used for resource assessment. The Climatronics and Met One sensors have been used for power curve measurements for turbines being developed by EWC. It has been recognized that if the three different sensors do not perform similarly, that is, indicate the speed of the same wind equally, errors in energy projections would be the result.

Maximum Cups have been used widely in resource assessment. While the performance of these sensors has been found to be quite consistent from unit to unit, and does not degrade significantly over time in the field, calibration results from various groups have differed. A recent study of the calibration of the Maximum Cup by Lockhart and Bailey [1] reconciled the results from various calibration studies and determined a "Consensus" transfer function to use for Maximum Cups if no specific calibration has been performed.

In measuring wind speeds for resource assessment with the Maximum Cup, the slope-and-offset transfer function used by EWC was different than the default transfer functions used in various commercial loggers and the Consensus transfer function. In fact, considering the results from Lockhart [1], the transfer function used by EWC would produce lower wind speeds than by using any of these alternatives. This would, of course, result in lower energy projections. More specifically, if the speeds measured by the Maximum Cup using the EWC conversion did not agree with those measured by the anemometers used in wind turbine power curve measurements, the energy projections thus derived would be in error.

An independent study of the wind speeds from all three of these sensors has been conducted, by performing a series of simultaneous field measurements. The method used was to collect average wind speeds from the three sensors at the same location, in the same wind, with a common data logger, and to compare the measured wind speeds to determine how these sensors perform relative to one another in the live atmosphere. Since the Climatronics and Met One sensors were used in determining power curves, the wind speeds measured by them serve as the benchmark. To simplify matters, the Climatronics will be considered the reference speed for the power curve and disagreement with its speeds (or theoretical energy derived from its wind speeds) will be considered to be in error. This does not suggest that the wind speeds measured by the Climatronics are an absolute wind speed reference.

Site Selection

The site selected for the measurements was on the EWC wind turbine project in the Altamont Pass. A well-exposed ridge on the north end of the project was selected. The axis of the ridge runs almost directly normal to the prevailing wind flow. The ridge is smoothly rounded on the crest and the terrain is covered with grass and thistle. There are no wind turbines upwind for approximately two km (1.2 miles).

The sensors were mounted on a crossarm on a 3 m (10 ft) mast. The separation between sensors was approximately 140 cm (56 in) or eight cup rotor diameters. The crossarm was oriented toward the north-northwest, such that it would be normal to the prevailing wind direction (~240°) at the test site. A wind vane was also mounted on the tower so that a reference wind direction could be recorded.

Sensors and Data Logging System

Brand new, calibrated sensors of each type were obtained. The calibration techniques varied. Met One ("Met1") and Climatronics ("Clim") used wind tunnels. Otech Engineering calibrated the Maximum Cup by mounting it on a rig attached to the front of a moving vehicle. The wind speed reference for all were National Institute of Standards and Testing (NIST) traceable anemometers. Met One and Climatronics used cup anemometers of the same type being calibrated and Otech used an R.M. Young propeller anemometer.

All sensors were wired into a Campbell Scientific model 21X data logger, which was programmed to sample the wind speeds, and direction once every second and record averages, standard deviations and maxima of the wind speeds, and average direction, every ten minutes. The Maximum Cup signal was interpreted three ways: using its calibration conversion ("MaxCal"), the Consensus transfer function ("MaxCons") and the EWC conversion ("MaxEWC"). Thus, every ten minutes five average wind speeds were recorded (three from the Maximum Cup) along with three standard deviations and three maximum wind speeds.

Below in Table 1 are the slopes and offsets used for the sensors to yield the wind speeds in m/s, with English equivalents in parentheses.

Two sets of data were collected. In the first set, the protective rubber boot for the Maximum Cup was present and in the second set it was not. After screening by wind direction (wind direction within ±30° of normal to the boom orientation) and eliminating records which were declared invalid, there were 1393 ten-minute data records in Data Set 1 (with the boot) and 1153 valid records in Data Set 2 (without the boot).

Table 1. LINEAR SLOPES AND OFFSETS USED TO MEASURE WIND SPEEDS.

	Slope	Offset

Sensor	m/s/Hz	(mph/Hz)	m/s	(mph)
Climatronics	0.0470	(0.1051)	0.224	(0.500)
Met One	0.0399	(0.0893)	0.246	(0.550)
Maximum Cup (calibrated)	0.7595	(1.6990)	0.516	(1.154)
Maximum Cup (consensus)	0.7649	(1.7110)	0.349	(0.780)
Maximum Cup (EWC)	0.7577	(1.6949)	0.000	(0.000)

Results from Data Set 1 (with boot)

All valid data records while the Maximum Cup had the boot were analyzed in a number of ways. First, the average wind speeds for all records were calculated and compared to the Climatronics wind speed. The five average speeds and their ratios to the reference speed in Data Set 1 are given below in Table 2.

Table 2. **AVERAGE WIND SPEEDS AND RATIOS TO CLIMATRONICS FOR DATA SET 1 (MAXIMUM CUP WITH BOOT).**

	Clim	Met1	MaxCal	MaxCons	MaxEWC
Avg. WS (m/s)	9.00	9.07	9.36	9.26	8.83
Avg. WS (mph)	(20.13)	(20.28)	(20.94)	(20.71)	(19.74)
Ratio to Clim	1.000	1.007	1.040	1.029	0.981

Not surprisingly, all sensors had a different result. The average wind speeds from the Climatronics and Met One sensors agreed the best. The average wind speed from using the Maximum Cup’s calibration transfer function had the largest error. One would naturally assume that using the calibration slope and offset would be more accurate, but this was not the case, at least not when compared to the Climatronics.

Analysis was performed to see how the wind speed ratios to the Climatronics varied as a function of wind speed. First, the data were sorted by wind speed using the Climatronics as the reference. Then ratios of each ten-minute wind speed to the Climatronics were calculated. Group averages of the Climatronics wind speed and the ratios were calculated in one m/s bins. The resulting mean ratios to the Climatronics wind speed were plotted as a function of Climatronics wind speed and are shown in Figure 1.

The average ratio of the Met One to Climatronics is largest at low wind speeds and decreases steadily as wind speed increases. At around 14 m/s their speeds are almost equal and at higher speeds the Met One reads slightly lower than the Climatronics. The wind speeds from the Maximum Cup are quite another story. This sensor clearly suffers from performance degradation in low wind speeds as evidenced by the declining ratios from MaxEWC, which has an offset of zero. The reason for the variance in behavior of the three curves for the various Maximum Cup speeds is primarily due to the offsets used (see Table 1). The MaxCal offset is 0.52 m/s (1.15 mph) and since its slope is nearly the same as the MaxEWC, its speed is nearly 0.52 m/s greater at all times. The offset becomes a greater percentage of the speed, and affects the ratios to the Climatronics to a greater extent, as the wind speed decreases. The MaxCons (offset = 0.35 m/s) ratios are affected in a fashion similar to the MaxCal, but to a lesser degree. The highest ratio to the Climatronics occurs with the MaxCal at around 4 m/s (9 mph) where the ratio is approximately 1.06.

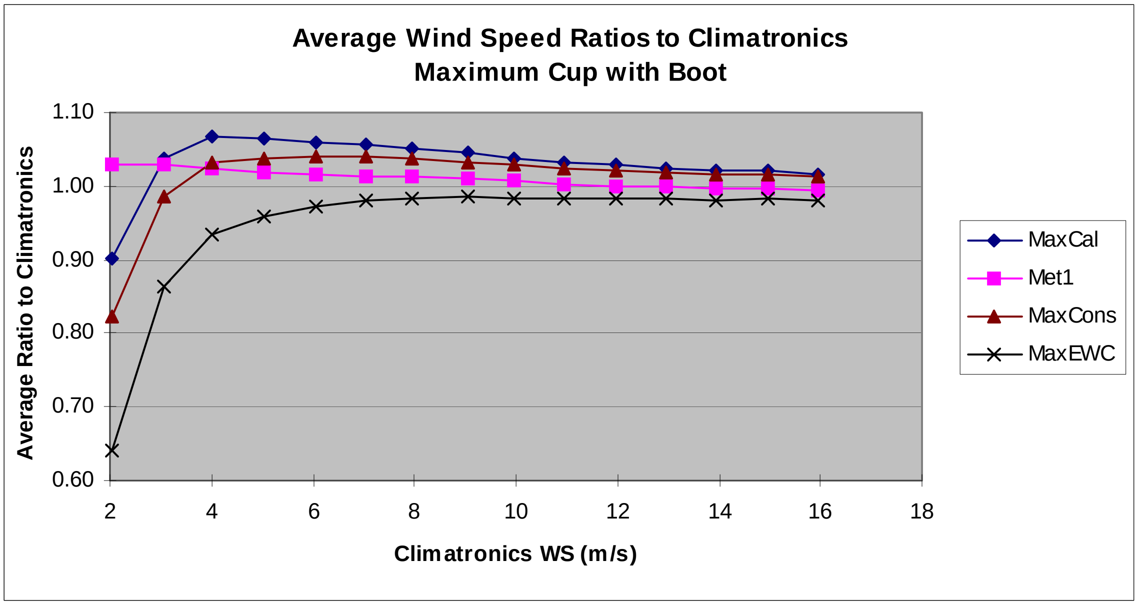

Figure 1. AVERAGE WIND SPEED RATIOS TO CLIMATRONICS WIND SPEED AS A FUNCTION OF CLIMATRONICS WIND SPEED.

It is suspected that the non-linear response of the Maximum Cup in low wind speeds is a result of being in a turbulent atmosphere (as opposed to a wind tunnel) and the higher coefficient of friction in the sensor's nylon bushings. This anemometer has a higher starting threshold (~1 m/s) than the Climatronics and Met One sensors, which use ball bearings. Other, perhaps inertial, effects may contribute, as well.

The observed differences in wind speed would obviously affect the theoretical energy calculations made with the data. Such a calculation was made using all five sources of wind speed in this data set. The power curve was for a 750 kW turbine that is assumed to use the Climatronics speeds as a reference, as EWC did. The theoretical energy values thus obtained and their ratios to the Climatronics theoretical energy values are shown below in Table 3.

Table 3. **THEORETICAL ENERGY CALCULATION BY METHOD OF BINS FOR 1393 TEN-MINUTE AVERAGES OF THE FIVE WIND SPEED SOURCES USING A 750 kW TURBINE POWER CURVE. MAXIMUM CUP WITH BOOT.**

	Clim	Met1	MaxCal	MaxCons	MaxEWC
Theo. kWh	74,131	75,368	80,468	78,717	71,396
Ratio to Clim	1.000	1.017	1.085	1.062	0.963

The theoretical energy values that result from using the MaxCal speeds are more than eight percent greater than those obtained from using the Climatronics wind speeds. The MaxEWC values were almost four percent lower than Climatronics. The Climatronics and Met One energy calculations differed by almost two percent.

The theoretical energy ratios shown in Table 3 would not apply to all sites, nor would the average wind speed ratios shown in Table 2. Because the ratios of Maximum Cup wind speeds to the reference are not constant for all wind speeds, the average wind speed ratios and theoretical energy ratios at some other site could be larger or smaller than those shown here. The magnitude of the difference in wind speeds would depend upon the wind speed distribution of a given data set and the slope and offset that was used. The same holds true for the Met One sensor, but to a lesser extent.

Results from Data Set 2 (without boot)

Since approximately May 1995, NRG Systems (the distributor of the Maximum Cup anemometer) has supplied the protective rubber boot with all units sold. Comparison of test results by Lockhart [1] has shown that the rubber boot increases the rotation rate of the cups given the same wind speed. Therefor, given the same ambient wind speed and using the same transfer function, a booted cup will indicate a higher wind speed than the cup would without the boot. Conversely, everything else being equal, removing the boot would result in the cup slowing, thus indicating lower wind speeds. In Lockhart's study [1], having no boot was reported to have the effect of slowing the rotational rate by approximately two percent, compared to a booted cup. Since the EWC transfer function was used before the boots were available, a second set of data was collected to see what effect the absence of the boot would have on the MaxEWC wind speed. The boot was removed from the Maximum Cup and monitoring continued using the same transfer functions as before. The data was again screened by wind direction and the 1153 valid data records were used in the subsequent analysis. The average wind speeds and ratios to the Climatronics are shown below in Table 4.

Table 4. AVERAGE WIND SPEEDS AND RATIOS TO CLIMATRONICS FOR DATA SET 2 (MAXIMUM CUP WITHOUT BOOT).

	Clim	Met1	MaxCal	MaxCons	MaxEWC
Avg. WS m/s	9.59	9.63	9.79	9.69	9.25
Avg. WS mph	(21.45)	(21.53)	(21.90)	(21.67)	(20.69)
Ratio to Clim	1.000	1.004	1.021	1.010	0.965

Following the same comparison procedures as with the booted-cup data set, the non-booted data were sorted by Climatronics wind speed and ratios of the other wind speed parameters calculated relative to the Climatronics. These ratios were averaged in one m/s bins. A graph of wind speed ratios versus wind speed bears a strong resemblance to Figure 1. The patterns are the same, but the ratios from the Maximum Cup wind speeds have decreased, which is consistent with what was expected. The ratios of the Met One to Climatronics were very close to those in the first data set. The ratio of the MaxEWC speed ratios (data sets 1 / data set 2) would be indicative of the change in performance of the Maximum Cup. The average ratios suggested a decrease in rotational speed of ~1.3 percent, on the same order as the expected change of 2 percent. A detailed analysis of the rotational speed of the Maximum Cup relative to the Climatronics revealed that, in these data sets the Maximum Cup spun slightly faster without the boot at speeds below ~4 m/s (Climatronics). At higher speeds the Cup spun slower without the boot.

The data without the boot were used to calculate theoretical energy for the same 750 kW wind turbine. The calculations are shown below in Table 5. The Table includes the gross kWh calculated from each wind speed parameter and the ratios to the Climatronics theoretical energy. The theoretical energy calculations from the Climatronics and Met One wind speeds were very close to one another, within one percent. The energy ratios from the Maximum Cup wind speeds all decreased relative to the Climatronics, compared to the energy ratios in Data Set 1. However, if one had followed the recommendation by Lockhart [1] for non-booted Maximum Cups, and increased the slopes in the three Maximum Cup equations by two percent, the errors would likely have been similar or greater in magnitude than those observed in Data Set 1.

Table 5. THEORETICAL ENERGY CALCULATION BY METHOD OF BINS FOR 1153 TEN-MINUTE AVERAGES OF THE FIVE WIND SPEED SOURCES USING A 750 kW TURBINE POWER CURVE. MAXIMUM CUP WITHOUT BOOT.

	Clim	Met1	MaxCal	MaxCons	MaxEWC
Theo. kWh	72,068	72,543	74,702	73,559	68,637
Ratio to Clim	1.000	1.007	1.037	1.021	0.952

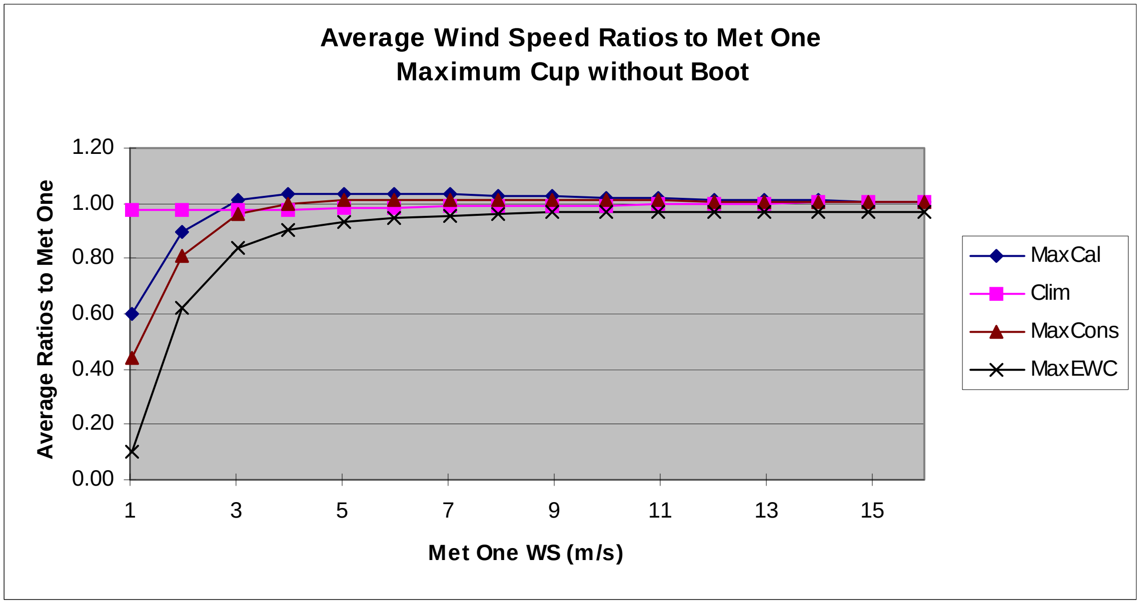

Figure 2. Wind speed ratios to Climatronics versus Climatronics wind speed.

Turbulence Intensity

Turbulence intensity, Ti, is defined as the standard deviation of the wind speed over some time interval divided by the average wind speed over the same interval. The standard deviation of the wind speed was measured for all three sensors and Ti as a function of wind speed was analyzed. For all three anemometers, Ti decreased as wind speed increased. In speeds below about 9 m/s (20 mph) the Ti measured by the Maximum Cup was higher than the Ti measured with the Climatronics and Met One sensors and the difference increased in magnitude as wind speed decreased. At speeds above 9 m/s the Ti from all sensors was almost identical (Ti $\approx$ 0.07 at 15 m/s). The Ti measurements from the Maximum Cup without the boot were very similar to those with the boot.

Method of Correction of Maximum Cup Data

It may be desirable to make corrections to wind speeds gathered with the Maximum Cup, to make them consistent with wind speeds collected with the Climatronics anemometer. Since the Climatronics and the Met One sensors performed similarly, there is evidence that other anemometers that use ball bearings may perform more like the Climatronics and Met One sensors than the Maximum Cup. If sensors with similar performance are used in power curve measurements, errors in energy estimates could result when wind speed data collected using Maximum Cups is used in theoretical energy calculations. Analysis of Data Sets 1 and 2 resulted in an effective way of making such a correction.

The maximum ratio of Maximum Cup rotational speed to the Climatronics was observed at a speed (as indicated by the Climatronics) of approximately 8 m/s (18 mph). At speeds higher and lower than this the relative rotation rate of the Maximum Cup was slower. In the lower speed range, below 8 m/s, the performance degradation was non-linear and in the higher speed range the degradation appeared to be quite linear. An adjustment to each range of speeds was therefor derived from the data in Sets 1 and 2, appropriate for data collected with and without the protective boot on the Maximum Cup.

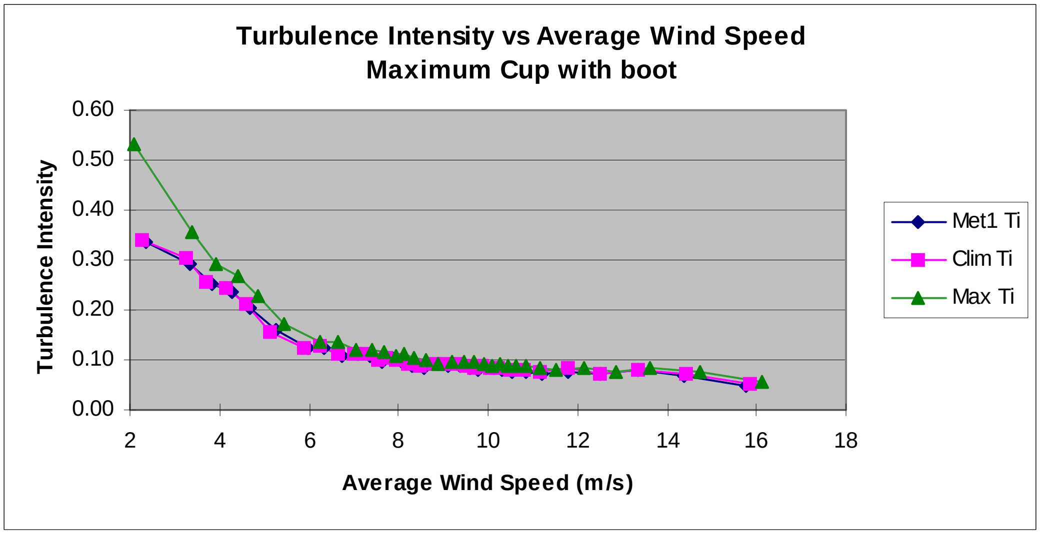

Figure 3. Ti versus wind speed for all three sensors.

First the linear slope-and-offset equation for the MaxCons was inverted and the wind speeds converted to average Hz. Then in the lower speed range, ≤ 8 m/s (Maximum Cup Hz ≤ ~10.3/sec), a third-order polynomial was fitted to the Maximum Cup average Hz versus Climatronics average wind speed. In the upper speed range, ≥ 8 m/s (Maximum Cup Hz ≥ ~10.3/sec), a linear regression was performed between the Maximum Cup Hz and Climatronics wind speed. This yielded a slope-and-offset equation. Below in Table 6 are the polynomial coefficients and the slope and offset for both of the data sets, with and without the boot. In Table 6, the polynomial coefficient C0 is the constant term and C1, C2, and C3 are the first-, second-, and third-order terms, respectively.

For the booted Maximum Cup the polynomial is valid for wind speeds greater than the minimum speed in the range analyzed, 2 m/s by the Climatronics. At this speed the Maximum Cup Hz ≈ 1.7/sec. The non-booted polynomial is valid for average Hz ≥ 0.1/sec, where the Climatronics speed ≈ 1 m/s.

Table 6. **POLYNOMIAL COEFFICIENTS AND LINEAR SLOPES AND OFFSETS TO CORRECT MAXIMUM CUP WIND SPEEDS TO AGREE WITH CLIMATRONICS, IN M/S (MPH), FOR BOOT AND NO-BOOT DATA.**

	Max Cup Hz ≤ 10.3/sec				Max Cup Hz ≥ 10.3/sec	
	C0	**C1**	**C2**	**C3**	**Slope**	**Offset**
with boot	1.158	0.4344	0.0358	-0.00137	0.7742	-0.053
	(2.591)	(0.9719)	(0.0801)	(-0.00307)	(1.732)	(-0.118)
no boot	0.956	0.5329	0.0227	-7.52E-4	0.7915	-0.148
	(2.128)	(1.1921)	(0.0508)	(-1.68E-3)	(1.771)	(-0.330)

This technique was tested in the field on the same apparatus as for Data Sets 1 and 2, however, an old, well-used Maximum Cup was substituted for the new one used in the original testing. Data were collected using the same slopes and offsets as in Data Sets 1 and 2 and by using the polynomial or slope-and-offset correction above. The old Maximum Cup showed the same performance degradation in low wind speeds (conventional signal processing) and, relative to the Climatronics, was almost identical to the brand new sensor. The average corrected wind speeds (using the polynomial/linear technique) were within approximately one percent of the Climatronics wind speeds with the old Maximum Cup.

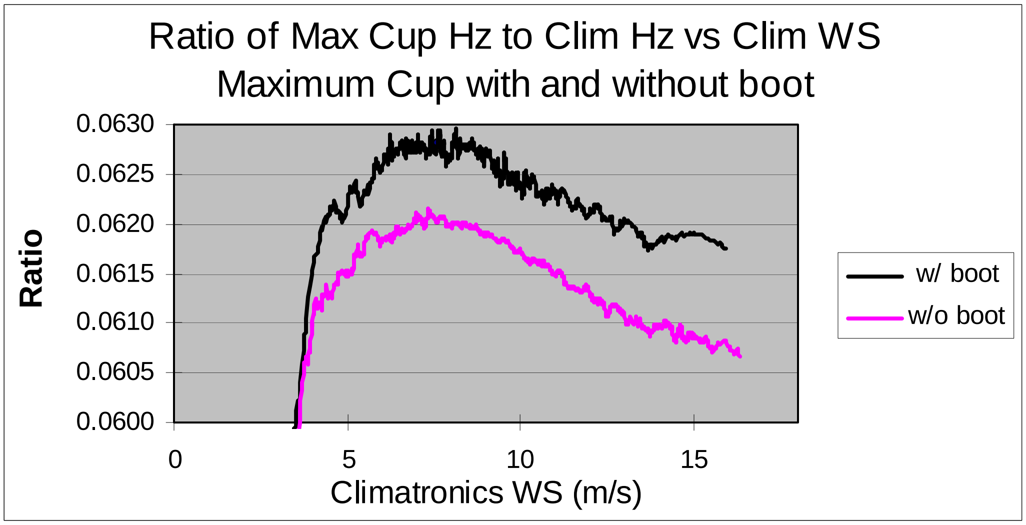

Figure 4. Comparison of rotational speed of old, used Maximum Cup and new Maximum Cup to Climatronics.

Implications for Wind Resource Assessment

The results of this comparison have disturbing implications. Wind speed measurements made with Maximum Cups could be in error compared to the wind speeds measured in power curve testing. No claim is made that the Climatronics or Met One sensors measured the true wind speed, although it would not be unreasonable to assume that they are closer to measuring it than the Maximum Cup. The point is that if the sensors used in resource assessment do not perform similarly to those used in power curve testing, errors in speed and energy projections will result. If the performance characteristics of the Climatronics and Met One sensors used here are representative of the performance of anemometers typically used in power curve testing, any resource assessment work performed using Maximum Cups could produce significant errors, when used with those curves.

Thousands of Maximum Cups that have been used in resource assessment activities around the world. They have been used in collecting wind speed data with a variety of data loggers. Many Maximum Cups have been calibrated, but often data is collected using the default transfer functions in the various loggers. To complicate matters, the default slopes and offsets used in commercially available data loggers are different from one another. One wonders what kinds of errors may be possible when the default slopes and offsets in commercial data loggers are used with Maximum Cups. Two data loggers, those available from NRG Systems and Second Wind, have been used extensively for many years. NRG Systems has used the same default slope and offset in all of their loggers, while Second Wind has used three different sets of slopes and offsets in different versions of their NOMAD logger. Below is Table 7 showing the slopes and offsets used in these loggers.

The errors shown in Tables 2 through 5 pertain to the data collected as part of this test. The test data are site-specific and were collected during the high wind season, so the errors are not representative of those that might result from resource assessment activities for an entire year at another site. Any such errors would depend upon the wind speed frequency distribution at the site and the slope and offset used in collecting the data.

Table 7. **DEFAULT SLOPES AND OFFSETS USED IN NRG AND SECOND WIND NOMAD DATA LOGGERS.**

Slope	Offset

	m/s/Hz	mph/Hz	m/s	mph
NRG	0.7637	(1.708)	0.000	(0.000)
NOMAD 1	0.7617	(1.704)	0.000	(0.000)
NOMAD 2	0.7689	(1.720)	0.402	(0.900)
NOMAD 3	0.7734	(1.730)	0.483	(1.080)

As a test of the effect of using Maximum Cups with these loggers, hourly average wind speeds from four different wind regimes were used to characterize the magnitude of possible errors. It is assumed that the original data was collected using a Maximum Cup (with boot) using the Consensus transfer function. The wind speeds were converted to average Hz and then processed to produce wind speeds that would have been recorded using the four slopes and offsets presented in Table 7, and also using the calibrated slope and offset from Table 1. The resulting average speeds and theoretical energies were then compared to those generated using the polynomial/linear regression equations to simulate the speeds measured by a Climatronics F460, which was used as a reference.

The four sites were one from the Altamont Pass (ALT), and three from the DOE Candidate Site Program, Cold Bay, Alaska (COL), Culebra, Puerto Rico (CUL), and Finley, North Dakota (FIN). Of these, the Finley site had the highest mean speed, on the order of 9 m/s. Cold Bay had a mean speed of around 7.5 m/s and the other two had mean speeds just under 7 m/s. Despite the similarities that there may have been in mean speed, the wind speed distributions were all quite different. Table 8 lists the deviations of average wind speed, in percent, from the simulated Climatronics wind speed.

Table 8. **DEVIATIONS OF AVERAGE WIND SPEEDS FROM THE AVERAGE SPEED FROM A SIMULATED CLIMATRONICS F460 IN FOUR WIND REGIMES. CALCULATED FOR VARIOUS WIND SPEED TRANSFER FUNCTIONS: THE CONSENSUS (CONS), NRG DEFAULT (NRG), THREE NOMAD DEFAULTS (NOM1, NOM2, NOM3) AND USING THE CALIBRATED CONVERSION FROM OTECH (CAL).**

	Deviations of Avg. Wind Speed from Simulated Climatronics					
	Cons	NRG	NOM1	NOM2	NOM3	Cal
ALT	1.6%	-3.7%	-3.9%	2.9%	4.6%	3.4%
COL	2.2%	-2.6%	-2.8%	3.5%	5.1%	3.8%
CUL	3.3%	-2.0%	-2.2%	4.6%	6.3%	5.0%
FIN	2.4%	-1.6%	-1.9%	3.5%	5.0%	3.5%

A theoretical energy calculation was performed with the year of hourly data of the various origins. The annual totals were compared to the total from the simulated Climatronics data. The percent deviations from the Climatronics annual total are presented below in Table 9.

The largest differences in wind speed and theoretical energy are found to be between the simulated Climatronics and the NOM3 default transfer function. Sizeable deviations are observed using both the NOM2 and the Calibrated transfer functions, as well. The wind speed distribution at the Trade Winds site was particularly susceptible to deviations in wind speed and to an even greater extent, theoretical energy.

Table 9. **DEVIATIONS OF ANNUAL THEORETICAL ENERGY FROM THE THEORETICAL ENERGY DERIVED FROM A SIMULATED CLIMATRONICS F460 IN FOUR WIND REGIMES. CALCULATED FOR VARIOUS WIND SPEED TRANSFER FUNCTIONS: THE CONSENSUS (CONS), NRG DEFAULT (NRG), THREE NOMAD DEFAULTS (NOM1, NOM2, NOM3) AND USING THE CALIBRATED CONVERSION FROM OTECH (CAL).**

	Deviations of Theoretical Energy from Simulated Climatronics					
	Cons	NRG	NOM1	NOM2	NOM3	Cal

ALT	5.7%	-2.2%	-2.5%	7.8%	10.5%	8.2%
COL	5.4%	-2.6%	-3.0%	8.2%	10.4%	8.6%
CUL	9.8%	-1.7%	-1.9%	14.8%	17.8%	15.3%
FIN	4.6%	-1.6%	-2.0%	6.2%	8.5%	6.5%

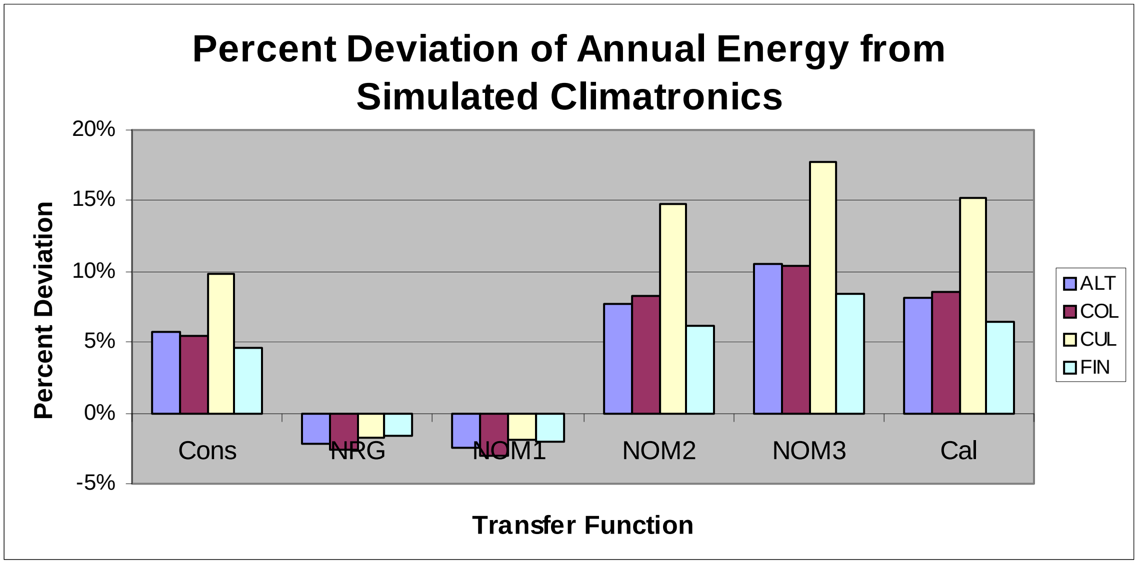

Figure 5. Percent deviation in theoretical energy from simulated Climatronics for different Maximum Cup transfer functions.

Conclusions

Two sets of 10-minute average wind speed data from three anemometers, a Maximum Cup Type #40, a Climatronics Model F460 and a Met One Model 010C, have been collected and analyzed. In the first set of data the Maximum Cup had its protective rubber boot in place, in the second set, the boot had been removed. All three anemometers were calibrated and their calibration slopes and offsets were used to measure the wind speed. The wind speed from the Maximum Cup was also recorded using two additional slopes and offsets: the “consensus” transfer function, and one used by EWC in resource assessment activities. The Climatronics and Met One sensors had been used by EWC for power curve measurements and the Maximum Cup used in resource assessment. The data from the Climatronics sensor was used as the reference in wind speed and theoretical energy comparisons. Deviations from the reference values were considered to be errors.

A free-atmosphere comparison of different anemometers has revealed some subtleties in performance that had not been observed previously, or anticipated by this investigator. Testing of anemometers in the static flow conditions of a wind tunnel would probably not show the same result. The wind speeds measured using the Climatronics and Met One sensors agree very well with one another (within one percent of average wind speed) and the wind speed ratios between these two varied in essentially a linear fashion over the range of wind speeds measured. The wind speeds measured using the Maximum Cup anemometers did not agree with the Climatronics and Met One sensors as well as the Climatronics and Met One did with each other. Depending on which slope and offset that was used with the Maximum Cup, the average wind speed was either overestimated or underestimated by as much as four percent. Furthermore, the Maximum Cup exhibited a non-linear degradation in performance at speeds below approximately 8 m/s. As the wind speed decreased below this threshold, the Maximum Cup spun progressively slower compared to the other two.

Without the boot, the Maximum Cup ran slower than it did with the boot in place. The magnitude of the decrease in rotational speed was approximately 1.3%. However, the change in rotational speed was not constant, either. At speeds < ~4 m/s the non-booted cup ran a bit faster than the booted cup, relative to the Climatronics anemometer.

The errors in average wind speed and theoretical energy observed in this study are not necessarily representative of errors that would be observed at potential development sites. This is because the ratio between the Maximum Cup wind speed and either the Climatronics or Met One speeds is not constant over the range of observed speeds. The error in average wind speed would depend upon the frequency distribution of the measured speeds and the transfer function used. Errors in theoretical energy would further depend upon the power curve that was used.

A method of correcting the Maximum Cup wind speed data, to make it consistent with the Climatronics over the range of observed speeds, was developed. It uses the combination of a third-order polynomial and a linear, slope and offset, transfer function.

A simulation of potential errors in wind speed and theoretical energy from using default transfer functions in two commercially available data loggers (NRG and Second Wind) and the Consensus and Calibrated slopes and offsets was performed. The comparison used estimated Climatronics speed, as a reference, and one year of hourly average wind speeds from four sites with varying wind characteristics. The largest errors in wind speed and theoretical energy (overestimates) were obtained using the default slope and offset in the latest version of the NOMAD. The Calibration slope and offset had the next highest errors. The lowest errors were found with the NRG default slope and offset and the earliest version of the NOMAD, both of which underestimated the speed and energy by a few percent.

Turbulence intensity measurements from all three sensors at average speeds above 9 m/s (20 mph) were almost identical. At speeds below 9 m/s the turbulence intensity from the Maximum cup was higher than from the other two anemometers, with the difference increasing as wind speed decreased.

Recommendations

Side-by-side comparison of sensors to be used for different purposes (power curve measurement and resource assessment) is recommended to eliminate, or at least reduce, potential errors in energy estimations. This research shows that significant errors are possible, if not expected, in the absence of such a comparison.

Similar, comparative testing of other anemometers with ball bearings and the Maximum Cup are recommended, to see if similar results are obtained. Consistent use of the same type of anemometer throughout power curve testing and resource assessment would go a long way toward alleviating the kinds of problems demonstrated here, although it would probably be more expensive. It would be advisable to carefully consider whether to use a Maximum Cup for power curve testing, considering its performance.

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